Title: Is there a role for Central Banks in the low-carbon transition? A Stock-Flow Consistent modelling approach

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Abstract

Climate change was recognized as a risk for ecosystems and the economy, and recently for the stability of the financial system. Tackling climate change requires urgent investments in the low-carbon energy transition. However, capital is not flowing at the pace and amount needed, exposing public and private investments to the risk of stranded assets. Central banks' influence in the economy soared since 2008 but their role in the low-carbon transition has been mostly neglected so far. In this article, we display under which conditions central banks could contribute to meet the interlinked goals of sustainability and financial stability by influencing the timing and magnitude of the low-carbon transition. By further developing the EIRIN Stock-Flows Consistent, flow-of-funds behaviorual model[2] we simulate three scenarios, i.e. an unconditioned Quantitative Easing (QE), a green QE conditional to the purchase of green sovereign bonds, and conventional monetary policies. For each scenario, we analyze the impact on green investments and jobs, credit conditions, green/brown bonds market, and inequality across heterogeneous households and sectors, identifying main feedback loops and transmission channels. We find that, under the model's conditions, a green QE promotes a faster development of the green bonds' market, with positive spillovers on green investments, employment, commercial and central banks' reserves, and on decreasing risk of stranded assets for the financial system. However, in all scenarios we find that wealth concentration in the credit sector and in the wealthiest household increases, with undesirable effects on income inequality, financial stability and aggregate demand.

Keywords: central banks, green Quantitative Easing, green sovereign bonds, Stock-Flows Consistency, financial stability, inequality.

Introduction

Climate change is one of the most impelling challenges that human societies has faced and will face in the future, and it was recognized as a main source of risk for current and future generations (IPCC 2014; Gaffney and Steffen 2017). Its impact is also expected to have serious distributive consequences by affecting poor and vulnerable households the most, also in high-income countries (Hallegatte et al. 2016; Hsiang et al. 2017). To limit the negative impact of human activities on the climate, the European Union (EU) signed, in December 2015, the 'Paris Agreement' aimed at stabilizing global temperature on (or below) 2°C above pre-industrial levels (UNFCCC 2016). Meeting this goal requires urgent and massive investments in renewable energy, estimated for the EU alone in roughly 180 billion (bn) EUR per year by 2050. However, capital is not flowing in low-carbon projects at the pace and amount needed to meet these goals.

On the one hand, the misalignment between public and private financial flows and sustainability prevents the mobilizing of capital into low-carbon investments and to increase climate risks (Buchner et al. 2015). On the other hand, it exposes the financial sector to potential losses in assets' values from the so-called "carbon stranded assets", in particular in the scenario of a sudden and disorderly transition to a low-carbon economy (Caldecott and McDaniel 2014). Such losses could be substantial not only for individual investors but could also have negative implications at the macroeconomic level. The global climate "Value at Risk" due to climate-induced physical damages has been estimated in

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[2] Monasterolo and Raberto 2017.

approximately 24.2 trillion (trn) USD of lost financial assets (Dietz et al. 2016). In addition, Battiston et al. (2017) show that the exposure of financial actors' equity holdings portfolios to carbon-intense sectors is considerable, in particular for pension funds and investment funds in the Euro-Area (respectively 45% and 47% of their equity portfolio). Furthermore, financial actors' interconnectedness could amplify risk through reverberation effects on the interbank market in the financial network, with potential implications on systemic risk (Battiston et al. 2017; ESRB 2016).

Recently, the tight relationship between sustainability and financial stability was recognized (HLEG 2017). Several central banks started to address climate change as a risk for the performance of the real economy and for the stability of the financial system, which is a main objective of central banks' mandates (Carney 2015; Schotten et al. 2016; Signorini 2017; Draghi 2017). In its interim report, the High-Level Expert Group on Sustainable Finance highlights the key role of the financial sector in accelerating the shift to a low-carbon and resource efficient economy, and provides preliminary recommendations to align the financial system to sustainability (HLEG 2017).

However, a key financial actor is missing from the HLEG's narrative, i.e. central banks. In the aftermath of the last financial crisis, the role and influence of central banks on the real economy became more visible and significant. A growing number of central banks introduced new unconventional tools to boost economic activity, and implemented new macroprudential policies to foster future financial stability (Monnin 2017). In particular, the European Central Bank (ECB) engaged in unconventional monetary policies, such as the Quantitative Easing (QE) assets' purchase program aimed at restoring growth and employment by injecting cheap liquidity in the Euro-Area (EA). The QE started in March 2015 and has injected new liquidity for roughly 2 trn EUR in the EA (August 2017). The preliminary analyses of the ECB's QE show a strong bias towards carbon-intense assets, and thus a clear misalignment to the Paris Agreement and the EU sustainability agenda (Barkawi 2017). In addition, it was highlighted that the ECB's QE may have played a not negligible role on the increase in wealth concentration and inequality in the EU. Indeed, by pushing-up assets' prices, the QE mostly benefitted the wealthiest and most sophisticated actors in the market (Fountan and Jourdan, 2017).

On the regulatory side, the Basel III regulation introduced to promote financial stability does not consider yet climate among the risks that banks' capital could face.

Current obstacles to invest in the low-carbon transition in the EA have more to do with the presence of conflicting incentives and regulations than with a lack of available liquidity on the market. Thus, aligning ECB's monetary policies to the EU sustainability agenda appear to be key to strengthen the EU economy and the coherence of its political agenda, as well as to comply with the ECB's mandate, as laid down in Article 127 of the Lisbon Treaty[3].

Therefore, academics and practitioners are discussing the role that central banks could play to promote sustainability and financial stability via targeted unconventional monetary policies, such as a green Quantitative Easing (QE), and green macroprudential regulations, such as the increase of capital requirements for banks' carbon intense investments (Campiglio 2016; Monnin and Barkawi, 2015; Ryan-Collins and Van Lerven 2017; Volz 2017).

Nevertheless, the assessment of such policy tools is still at a developing stage. In order to understand the timing and magnitude of their policies and regulations, as well as their potential unintended

[3] Art. 127, Lisbon Treaty: "The primary objective of the European System of Central Banks (hereinafter referred to as "the ESCB") shall be to maintain price stability. Without prejudice to the objective of price stability, the ESCB shall support the general economic policies in the Union with a view to contributing to the achievement of the objectives of the Union as laid down in Article 3 of the Treaty on European Union."

effects, central bankers need to assess the direct and indirect policies' transmission channels and feedbacks on markets and agents' expectations, and on investments' decisions. There is growing concern among academics and practitioners that models currently used for analyzing economic and monetary policies, i.e. Dynamic Stochastic General Equilibrium Models (DSGEs) are not appropriate to analyse the microfoundations of complex systems (Fagiolo and Roventini 2017).

In this article, we propose the EIRIN Stock-Flows Consistent flow-funds behaviorual model as an alternative approach to DSGEs to analyze under which conditions central bank's (un)conventional monetary policies could help to scale-up investments in renewable energy without triggering instability in the credit market, and unintended distributive effects (i.e. inequality). For each monetary policy scenario, we identify the changes in level and composition (green/brown assets) of the agents' balance sheets, including the central bank's one, and thus their potential exposure to carbon stranded assets. Then, we look at the cross-sectors feedback loops and the transmission channels from the financial system to the (green) real economy, and their distributive effects on wealth concentration and income inequality across heterogeneous households.

EIRIN introduces structural and behavioral advances on DSGEs. First, it combines Stock-Flows Consistent (SFC) and Agent-Based (ABMs) models' features, while being parsimonious in terms of complexity, in order to identify the causality chains. SFC and balance sheet accounting (Lavoie 2014) are fundamental to assure models' transparency and accountability because they allow to track all transactions, and to display changes in agents' balance sheets as a consequence of endogenous dynamics. In addition, they allow us to represent how central banks' balance sheet composition changes as a consequence of (un)conventional monetary policies, and the flows that they generate in the economy. Second, not being forced to rely on equilibria, EIRIN allows to display emerging, often unexpected macroeconomic dynamics, which are determined by the interaction of heterogeneous agents characterized by bounded rationality and intertemporal optimization. These features contribute to analyse the presence of feedback loops and of endogenously generated macro-financial booms and busts cycles. Third, by distinguishing between credit, bond and capital market for funding green investments, EIRIN allows to compare conventional monetary policies implemented via bank lending with unconventional ones, and assess their effect on the stability of the credit sector and on the bond market. Fourth, by disaggregating households in terms of income sources, investing and saving behaviors, and access to financial markets, it allows us to represent the origins and consequences of income inequality and wealth concentration. As main novelties on the previous version of the model (see Monasterolo and Raberto 2018), we introduce a full energy sector and an energy market, as well as a bonds' market. These innovations are fundamental for the analysis of (un)conventional monetary policies in the low-carbon transition.

This manuscript is organized as follows. Section 2 discusses the development of ECB's monetary policies in the aftermath of the financial crisis and their implications on sustainability and inequality in the EA. Section 3 describes the features of the expanded EIRIN model, explaining its methodological advances on DSGEs for the analysis of the impact of (un)conventional monetary policies. Section 4 describes (un)conventional monetary policies' scenarios and compares the results in terms of effects on sustainability, financial stability and inequality. Section 5 concludes.

2. Central banks' monetary policies after the crisis: challenges and implications for sustainability

In the aftermath of the last financial crisis, CBs engaged in a series of expansionary monetary policies with the aim to restore stable growth, and considered new macroprudential policies aimed to foster future financial stability. In the EA, the ECB introduced Long-Term Refinancing Operations in 2011 that

supplied 523 banks with 489 bn EUR to for 3 years at 1% interest rate, accepting loans and government securities as a collateral. However, since the expected effects on new investments in the real economy did not materialize, on 11th March 2015, the ECB's Governor Mario Draghi reassured financial markets, investors and governments that the ECB would have done *whatever it takes* to restore growth and save the Euro. Since then, the ECB started its assets purchase program, known as QE, through which it kept buying financial securities from commercial banks with the aim to stimulate private sector's spending. Indeed, by replacing commercial banks' illiquid assets with new liquidity, the ECB expected a decrease in interest rates and an increase in non-financial corporations' borrowing as a result of cheaper loans, thus stimulating economic growth and restoring a close to 2%[4] inflation in the EA.
The initial assets purchase program worthy 80 bn EUR per month and targeting government bonds was then extended to corporate bonds in June 2016, while reducing the monthly purchase to 60 bn EUR. This amount overtakes by roughly three times the monthly amount of investments into renewable energy projects in 2016 (24 bn USD/month, FS-UNEP and BNEF 2016). Table 1 shows the value and breakdown of assets purchased under the QE for 2,063,151 on 31st August 2017. The public sector purchase programme (PSPP) represents the main voice of spending, standing at 1,704,041 million (mn) EUR, followed by the covered bond purchase programme 3 (CBPP3).

	Mar-15	Aug-17
Asset-backed securities purchase programme (ABSPP)	4,622	24,424
Covered bond purchase programme 3 (CBPP3)	63,603	227,788
Corporate sector purchase programme (CSPP)	0	106,898
Public sector purchase programme (PSPP)	47,356	1,704,041
Total Asset Purchase Program	115,581	2,063,151

Table 1 QE's purchases (in mn EUR). ABSPP, CBPP3 and CSPP include both primary and secondary holdings. Source: ECB.

The expected change in inflation, growth and unemployment in the EA did not materialize. Inflation remained well below the 2% target (+1.3% in July 2017) while GDP growth and unemployment respectively increased and decreased slightly since March 2015 (see Figure 1). The US economy performed better in the same period.

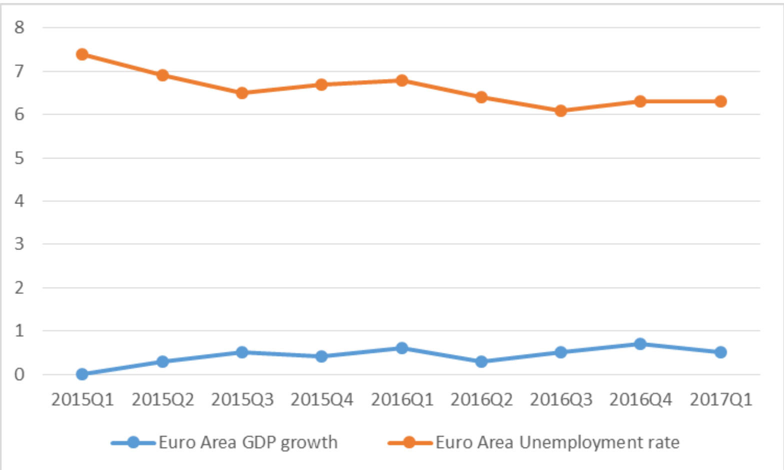

Figure 1 Quarterly GDP growth and unemployment rate in the EA, 2015 – 2017. Source: Eurostat.

[4] https://www.ecb.europa.eu/explainers/show-me/html/app_infographic.en.html

It follows that when needed, the ECB is ready and willing to take measures that were previously considered *unconventional* to reach its objectives. Nevertheless, there is growing concern on the implications of such policies on sustainability and inequality in the EA. Indeed, despite the ECB claimed the sector-neutrality of assets purchase program, recent analyses of the QE's composition show that it is severely biased towards large companies that are active in carbon-intense sectors, in particular automotive, fossil fuels and utility companies (Matikainen et al., 2017). This means that the expansion occurred in ECB's balance sheet as a consequence of the QE is not aligned neither with the EU 2030 sustainability agenda nor with the macroprudential regulation developed after the last financial crisis (e.g., the Basel III Accord[5]) and aimed at mitigating the systemic risk of the financial system. Indeed, it contributes to maintain investors' exposure to climate risk and to slow-down divestment from the so-called carbon stranded assets (Caldecott and McDaniels, 2014) by affecting expectations on investments' risk and return. In addition, it exposes the ECB itself to the risk of stranded assets, having its balance-sheet expanded mostly towards carbon-intense assets.
Moreover, the implications of the ECB's QE on income inequality and wealth concentration started to be analysed. Fountan and Jourdan (2017) highlighted that the QE benefitted the wealthiest households by increasing the prices of the financial assets that they mostly own, with little benefits for lower incomes households. Then, by limiting the number of safe assets in the financial markets, the QE re-channels investment towards housing assets, thus increasing their prices, at the expenses of low-income earners. Inequality is one of the main societal challenges and has been associated to a specific Sustainable Development Goal (SDG) (i.e. SDG 10 Tackling inequality) within the UN 2030 sustainability agenda (UNDP 2016).
The implications on widening income inequality of a delayed low-carbon transition have received attention. High levels of inequality prevent poor and vulnerable households, who are the most exposed to climate risk, to adequately cope with that due to the lack of financial endowments (Hallegatte et al. 2016). Over the past three decades, income inequality has increased in most advanced economies, in particular after the last financial crisis (Alvaredo et al., 2017). Recent studies show that high levels of inequality hamper durable growth and financial stability Ostry et al. (2014). Indeed, the low- and middle-income households who cannot rely on their sole wage anymore to maintain their lifestyles, start to increasingly rely on borrowing, which eventually triggers private debt crisis (Turner 2016) and a sequence of events that characterized the run-ups to both the Great Depression and the Great Recession (Kumhof et al. 2013). The increase in global inequality was associated to the relevance that the financial sector has assumed with respect to the real economy since the end of the 1980s, a process known as *financialization* (Epstein 2005; Palley 2007). The concentration of investments in financial markets determined the concentration of gains in few mighty actors of the financial sector who could access higher yield investments on financial market. Then, it contributed to depress wages and returns from investments in the real economy. As a result, the gap between the top 1% of the income distribution and the middle and low-income class widened.
Recently the ECB recognized that capital gains in bonds and equity markets, which were fuelled to a large extent by its QE, mostly benefitted the net wealth of the richest 20% EA's households that increased by 30%[6], and that *such side-effect should be tolerated*[7]. At the same time, the ECB's vice

[5] http://www.bis.org/bcbs/basel3.htm
[6] https://www.ecb.europa.eu/pub/annual/html/ar2016.en.html#IDofChapter1_2_1_Box5
[7] https://www.ecb.europa.eu/press/key/date/2014/html/sp141017_1.en.html

President stated that ECB's monetary policies contributed to compress inequality by lowering unemployment, thus increasing the disposable income for Europe's poorest households[8].
Uncertainty on the role of unconventional monetary policies prevails. Being the future of the ECB'S QE still unknown, the development of models able to understand its influence on the connected dimensions of sustainability, financial stability and inequality – i.e. what we could call the climate-finance-inequality nexus - is fundamental.

3. Methodology

3.1 Review of the state of the art

Despite the growing attention by academics and practitioners on the role of central banks' unconventional monetary policies on sustainability and financial stability, their assessment is still at initial stages. There is growing concern about the ability of the models currently used by central banks and academics – i.e. DSGEs – to identify monetary policies' transmission channels and the feedback loops generated along the climate-finance-inequality nexus. DSGEs have been recently criticized for their inability to recognize and analyse the last financial crisis, and to provide relevant policy recommendations to decision-makers (Blanchard 2016; Romer 2016; Stiglitz 2017) because they exclude key structural and behavioural drivers of endogenous feedbacks (Fagiolo and Roventini, 2017). On the one hand, DSGEs have contributed to increase the general knowledge about micro and macro-economic stylised facts. Recently, they have also been complemented with relevant features previously missing, such as endogenous money creation (Jakab and Kumhof 2014), households' heterogeneity (Ahn et al. 2017), and a focus on environmental issues (Annicchiarico and Di Dio 2016). On the other hand, DSGEs have been recently criticized for not beeing able to fully address the following key macroeconomic issues:

- The origin and the impact of income inequality. In particular, its increase over time in the last three decades (Piketty 2014; Stiglitz 2015), its relation to growing private debt and financial markets (Kay 2015), and its implications on the performance of the real economy.
- The origin of instabilities in the financial system, and the feedbacks through which financial shocks cascade on the real economy (Stiglitz 2017).
- The impacts of climate change on the stability of the financial system and on the real economy, as well as the impact of the financial system on the climate, e.g. via capital reallocation.
- Understanding the central banks' unconventional monetary policies and their consequences in a quasi-zero lower-bound environment (Palley 2016).
- The endogenous explanation of business cycles, which are key to understand the emergence of boom-and bust cycles in advanced economies (Minsky 1986).

These issues matter when we want to understand the impact that different sets of (un)conventional monetary policies on sustainability, financial stability and inequality. In particular, the analysis of distributive effects requires an understanding of the interaction between the policy drivers and markets and agents' behavioral responses in terms of allocation of resources (in particular between consumption/saving, and different types of investments), thus going beyond the simple representation of households' income levels.

In addition, DSGEs have been considered inadequate to account for the structural and behavioural drivers of endogenous feedbacks between interconnected actors and not fully rational and coordinated heterogeneous agents (Fagiolo and Roventini 2017).

[8] https://www.ecb.europa.eu/press/key/date/2017/html/ecb.sp170822.en.html

On the one hand, the analysis of the effects of feedback loops at work in the economy through direct and indirect shock-transmission channels is important to assess the impact of (un)conventional monetary policies on the climate-finance-inequality nexus for several reasons. First, shocks on the financial sector, due e.g. to monetary policies, are transmitted to the real economy (in terms of investments) and to the climate (in terms of emissions). Second, shocks on the climate and the real sector are transmitted to the financial sector. Third, understanding the feedback structure of a system allows to identify the presence of (i) time delays between the imposition of a shock and the agents' response to that, (ii) tipping points beyond which the characteristics of the system change dramatically, and (iii) reinforcing feedbacks, which often give rise to problems of path-dependency. Furthermore, the analysis of the dynamic interplay of feedback loops contributes to explain emerging non-linear behaviours that are not necessarily intuitively understood.

On the other hand, in the case of shocks previously not considered in the context of the low-carbon transition, the standard assumption on rational expectations of the agents has to be relaxed because economic actors may fail to fully anticipate (even in expected values) the impact of such type of shocks. At this regard, there is a growing stream of research in behavioural economics that analyses the conditions under which a departure from rational expectations could occur (Dosi et al. 2015), including deep uncertainty on the probability of events and the distribution of outcomes (Knight 1921), multiple equilibria and coordination failures (Keynes 1936), unequal access to information (Greenwald and Stiglitz 1986), endogenous shocks and radical changes in policies (Stiglitz 2011). Moreover, the interaction of heterogeneous agents reacting across different spatial and temporal scales could give rise to the emergence of aggregate properties that cannot be deduced by the simple aggregation of individual ones (Tesfatsion and Judd 2006).

3.2 The EIRIN model's contribution to assess the impact of monetary policies on sustainability, financial stability and inequality

The structural and behavioural characteristics of the EIRIN model are designed to allow the analysis of the impact of green fiscal, monetary and macroprudential policies on the interconnected dimensions of sustainability and financial stability, and analyzing the distributive effects. These characteristics constitute an innovation on DSGEs and let us identify EIRIN as a complementary tool to such models.

EIRIN is a demand-driven Stock-Flow Consistent (SFC) model rooted on a neo-Schumpeterian, Post-Keynesian tradition (Naqvi 2015; Dafermos et al. 2017; Bovari et al. 2017). EIRIN adopts a balance sheet accounting approach (Lavoie 2014) that allows us to track all the transactions among the economic agents and sectors, and the relations between the changes in stocks of assets and liabilities with the changes in the corresponding flows, thus increasing results' accountability. In the Post-Keynesian tradition, the model embraces endogenous money creation (McLeay et al. 2014) and modern money theory (Wray 2015). EIRIN adopts a Leontief production function with no substitution of the four production factors (Labour, Capital, Energy and Raw Materials). We chose to use a Leontief to highlight the non-substitution of the four production factors in the short-term period, consistently with the short-term focus of our model (i.e., a decade). Moreover, it allows us to account for the difference in business models between renewable energy sources, which work on quasi-zero marginal costs, and fossil fuels, which instead are subject to decreasing marginal costs.

EIRIN distinguishes between credit and bond markets for funding green investments. This distinction is fundamental because it allows us to compare conventional monetary policies implemented via the bank lending channel with unconventional ones (i.e. a QE) via the interest rate channel (which influences the Net Present Value (NPV) and the bonds' yields) both on the stability of the banking sector and the stability of the debt (or bond) market. Then, it allows us to assess the feedbacks from the introduction of monetary policies on the borrowing conditions for green/brown investments, and to represent the separate transmission channel for monetary policy, as well as firms' heterogeneous access to capital. Finally, we distinguish between liquidity created by the commercial bank through endogenous creation in the credit system (which represents roughly 97% of the liquidity currently created, McLeay et al., 2014) and that created by the CB through unconventional monetary policies. This distinction is important to understand the drivers of the change and composition of debt levels in the economy, and to assess the impact of unconventional monetary policies on debt and liquidity.

In addition, EIRIN explicitly models green bonds. Green bonds are fixed income securities that finance investments with environmental or climate-related benefits and thus represent a key component of green finance. We chose to focus on green sovereign bonds as an eligible asset for CB's green QE for several reasons. First, green bonds surged in the last couple of years, reaching 895bn USD outstanding in 2017, a jump of 201bn USD from 2016 (Climate Bonds Initiative (CBI), 2017). Green bonds were recently recommended by the High-Level Experts Group on Sustainable Finance, which is charge of developing the EU vision of sustainable finance, as a powerful tool to finance the low-carbon transition by decreasing the cost of capital for green investments for companies and governments, while keeping investment's risk low (HLEG, 2017). Municipalities and recently national governments started to issue green bonds to finance low-carbon infrastructural investments (see for instance Poland and France in the EU), while CBs in emerging countries (e.g. in Morocco and in China) started to buy green bonds and to support green repo. Then, sovereign bonds represent around 40% of the global bonds market (versus only 7% of corporate bonds) and are at the core of the ECB's assets purchase program started in March 2015 (90% circa[9]). Finally, they represent a tool through which a 'green' entrepreneurial state, recently advocated by Mazzucato (2015) could open the green market via mission-oriented investment.

These solutions allow EIRIN to assess under which conditions (un)conventional monetary policies could foster or hinder investments reallocation to low-carbon sectors, the effects on green growth and the (sound) expansion of green bonds' market.

3.3 Agents and sectors of the EIRIN economy

The EIRIN economy is shaped upon the EA and is populated by heterogeneous sectors and agents[10]:

- *Heterogeneous households*: by building on Goodwin (1967) and the Lotka-Volterra's predator-prey model, the households' sector includes a worker (Hw) and a capitalist (Hk) income class. Households (HH) are heterogeneous not only in terms of income level and source but also in terms of access to financial markets (i.e., by type of financial product and their yield), and of investment/saving/consumption behaviours. Hw lives on wages, while Hk earns his wealth out of land rent and financial markets through government bonds. Hk receives dividends from mining and utility companies (except in the case of negative liquidity), and from the bank. HH's consumption plans are based on the buffer-stock theory of savings (Deaton 1991; Carroll 2001) and their share of consumption on total income decreases with the increase in income levels. Such level of detail of households' heterogeneity is functional to analyse the role that different access to financial markets played on inequality in the last two decades, and its effects on missing aggregate demand in high-income economies and on financial instability. Second, it allows to assess the distributive effects of single or suites of policies on the channels of inequality in the EU.

[9] https://www.ecb.europa.eu/mopo/implement/omt/html/pspp.en.html

[10] See Monasterolo and Raberto (2018) for the description of the core equations of the EIRIN model.

- *Heterogeneous capital goods* characterized by different resource and emissions intensity. Capital goods set the consumption goods producer (CGP) production's capacity and technology endowment, reflecting different levels of resource efficiency. Green capital goods allow a more resource-efficient, low-carbon production process than brown goods. We introduce a parameter α of resource intensity that depends on the raw materials intensity of the production process. In so doing, we explicitly model the role of raw materials' cost on CGP's investments decisions.
- *Heterogeneous capital (KGP) and consumption goods producers* (CGP) who make their investments decisions – in either brown (carbon-intense) or green (resource resilient) goods – based on the Net Present Value (NPV), which is in turn influenced by the interest rate set by the central bank, and by the government's fiscal policy and subsidies. This point is particularly important because (i) it allows us to understand agents' intertemporal behaviour by comparing short-term costs with long-term benefits, (ii) it supports the representation of endogenous decision-making (e.g. the NPV of brown versus green investment decisions) and endogenous money creation in the credit market. We use NPV calculations to compare the present cost of investments, which are higher in the case of green capital goods (reflecting higher initial cost of capital and salaries), with the present value of future expected positive or negative cash flows. In so doing, we display endogenously generated GDP and the shifting to low-carbon investments.
- *Heterogeneous skills* for workers employed in the brown/green sectors. We assume that skills are uniformly distributed among workers and that the green sector always employs the workers with the highest skills, in exchange of higher salaries, to support initial R&D. Wages in the brown and green capital goods production sectors are endogenous and set according to the average workers' skills in each sector.
- *An energy sector* based on the Global Change Assessment Model (GCAM) (Calvin et al. 2013) that has a granular representation of energy and electricity producers (fossil fuels, renewable energy). The energy sector is composed by a mining company that extracts fossil fuels, a brown utility company that produces electricity out of fossil fuels, and a green utility company that produces electricity out of renewable energy sources. Agents produce to meet the internal demand for energy either through fossil fuels or renewable energy sources (i.e. solar and wind). Energy production is demand driven and we assume fixed HH's demand for daily uses such as heating and transportation. The brown utility sets the energy price based on a mark-up on its unit costs, given by the price of oil and the cost of debt service. The electricity price is unique and endogenously set by the brown utility company based on a mark-up on its unit costs. Hw and Hk subtract the energy bill from their wage bill as shown by their disposable income.
- *A credit sector* represented by a commercial bank (BA) that provide loans to the firms, the mining and utility companies, financing them through endogenous money creation. The bank has a leverage target (ratio between risk weighted assets and equity) to meet Basel III requirements, and a Capital Adequacy Ratio to build resilience against shocks and avoid risk of default as a consequence on non-performing loans.
- *A foreign sector* (RoW) that provides raw materials to the domestic economy in infinite supply and at a given (constant) price to meet the production needs in the brown sector.
- *A government* that decides on the fiscal policy with the purpose to keep the budget balance aligned to the Maastricht criteria, issues brown bonds to cover its regular expenses, and issues green bonds to support capital investments in renewable energy production.
- *A Central Bank (CB)* engaging in (un)conventional monetary policy. The CB sets the interest rate according to a Taylor like rule. The interest rate depends on the inflation and output gap, measured as employment gap, i.e. the distance to a target level of employment, and influences agents'

expectations and investments through NPV. In addition, the CB provides liquidity to BA in case of shortage of liquid assets, and accepts green/brown bonds as eligible asset in case of QE.

Figure 2 displays the composition of the balance-sheet of each agent of the EIRIN economy

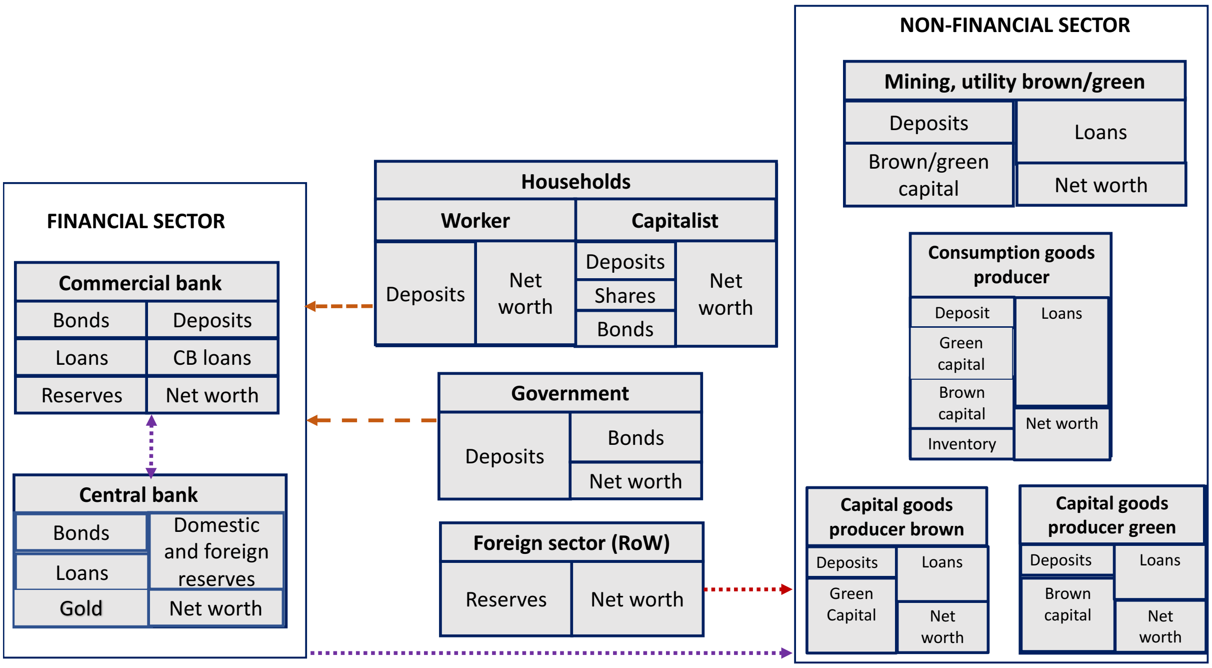

Figure 2: Balance sheet matrix of the EIRIN model according to the Godley-Lavoie framework (2007). For each sector and agent, a representation in terms of assets and liabilities is provided, as well as an initial selection of shock (e.g. (un)conventional monetary policy) transmission channels. Purple dotted lines: shock transmission to the credit sector via financial exposure. Orange dotted lines: shock transmission via investments (shock transmitted against the direction of the arrow). Red dotted line: fossil fuels' export by the foreign sector to the EU. Black line: potential climate impact on households, economic sectors, and then to the credit sector (i.e. physical and financial stranded assets). The impact of the financial sector on the climate is indirect (through financial investments in the brown real economy, brown assets, and loans).

In addition, Figure 3 displays the capital and current account flows of the EIRIN economy.

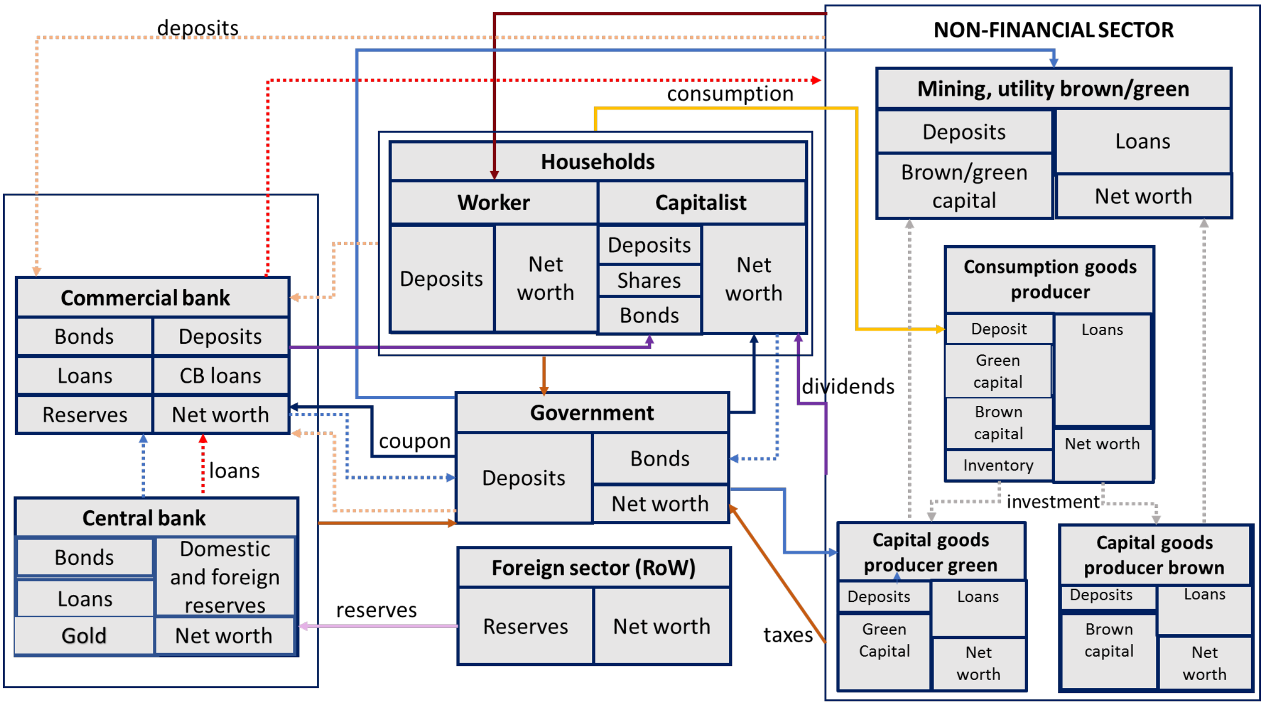

Figure 3 Capital and current account flows. As a difference from the balance sheet matrix, which displays capital accounts balance sheet entries (stocks), Figure 3 reports all EIRIN's flows in capital and current accounts. The dotted lines represent the capital account flows; the straight lines represent the current account flows. Each arrow is oriented according to the money flows that it represents in the model. The government collects taxation, decides on the fiscal policy (budget balance constraint), issues bonds, and provides subsidies. All economic actors pay taxation and have deposits in the BA. KGP and CGP pay BA an interest on debt, pay dividends to Hk, and pay wages to the labour force. BA pays interests on loans to CB for borrowing in case of need of liquid assets, and pays dividends to the Hk. HH are heterogeneous in terms of income sources: only Hk has access to dividends from bank and firms, and can purchase bonds. Hw has wages as the only source of income. Both HH consume. KGP produces green capital goods out of green electricity provided by the green utility company, and brown capital goods out of brown electricity provided by the brown utility company, which uses mining company's fossil fuels. KGP provide green/brown capital goods to the CGP. CB accepts sovereign (green/brown) bonds as eligible asset for its purchase program, and purchases them from BA. The government pays an interest on (green/brown) bonds coupons. The government also provides subsidies to the CGP and to the utility company for green investments.

Finally, Table 2 (below) displays the balance-sheet matrix of the EIRIN economy according to the Godley-Lavoie framework (Godley and Lavoie, 2007).

	Households (H)		CGP (C)	Mining Company (mi)	Utility (U)		KGP (Kgreen/ Kbrown)	Bank (BA)	Government (G)	Central Bank (CB)	Foreign Sector (ROW)	Σ
	Worker (Hc)	*Capitalist (Hk)*			Brown (BU)	Green (GU)						
Tangible capital			$+p_{K_g}K_{C,g}$ $+p_{K,_b}\ K_{C,b}$	$+p_{K_b}\ K_{mi,b}$	$+p_{K_b}\ K_{BU,b}$	$+p_{K_g}\ K_{GU,g}$						$+p_{K_g}K_{(C,GU)g}$ $+p_{K_b}\ K_{(C,BU,mi)b}$
Inventories			$p_C\ I_C$									$p_C\ I_C$
Gov. bonds $n_{bB}\ n_{gB}$		$+n_{gB}^{Hk}\ p_{gB}$ $+\ n_{bB}^{Hk}p_{bB}$						$+n_{gB}^{BA}p_{gB}$ $+n_{bB}^{BA}p_{bB}$	$-(n_{gB}p_{gB}+$ $n_{bB}p_{bB})$	$+n_{gB}^{CB}p_{gB}$ $+\ n_{bB}^{CB}p_{bB}$		*0*
Debt/credit			$-\ Loans_C$	$-\ Loans_{mi}$	$-\ D_{BU}$	$-\ D_{GU}$		$+Loans_{(C,mi)}+D_{(BU,GU)}$ $-\ Loans_{CB}$		$+\ Loans_{CB}$		0
HH, CGP, KGP, Gov deposits	$+M_{Hw}$	$+M_{Hk}$	$+M_C$	M_{mi}	M_{BU}	M_{GU}	$+M_k$	$-\ Deposits$	$+M_G$			0
Domestic reserves								$+M_{BA}$		$-\ Deposits_{CB}$		0
RoW reserves										$-\ ForeignLiab_{CB}$	$+\ M_{ROW}$	0
Gold in the vault*										$+M_{CB}$		$+M_{CB}$
Equity shares/		+CGP shares value + mi shares value + BU shares value + GU shares value + KGP shares value +B shares value	$-\ E_C$	$-\ E_{mi}$	$-\ E_{BU}$	$-\ E_{GU}$	$-\ E_K$	$-\ E_B$				0 0 0 0 0 0
Equity (Net worth)	$-\ E_{Hw}$	$-\ E_{Hk}$							$-E_G$	$-\ E_{CB}$	$-\ E_{ROW}$	$-\ E_{Hw} - E_{Hk} - E_G - E_{CB} - E_{ROW}$
Σ	0	0	0	0	0	0	0	0	0	0	0	0

3.4 EIRIN's markets

EIRIN's representative agents/sectors interact with each-others and with the foreign sector through a set of markets, i.e. consumption and capital goods markets, labour, energy, oil and raw materials markets. EIRIN makes also explicit consideration of the credit and bonds market and their interactions with the energy sector, the real economy and the government.

Demand and supply formation, as well as pricing in each market, with the exception of the credit market, are independent from each other at any given simulation step. In the credit market, demand depends on the demand for capital goods. The demand rationing affects the effective demand of capital goods by the CGP, the oil company and the green utility company. In each market, pricing is generally made by the supply side as a mark-up on unit costs, with the exception of the average price of labour, i.e. the average nominal wage, which is determined according to a Phillips curve-like rule, as in Keen (2013).

The key sequence of events occurring in each simulation step is the following:

1. Policy makers take their policy decisions, i.e. CB sets the policy rate according to a Taylor-like rule while the government adjusts the tax rates on labour and capital income, and on corporate earnings, to meet its budget deficit targets. Further details are provided in Monasterolo and Raberto (2018).
2. All markets, exception for the credit market, open in parallel. Prices of the exchanged goods or services are determined, then the nominal or real demand and supply are provided by the relevant agent in each market. Finally, transactions occur generally at disequilibrium, i.e. at the minimum between demand and supply, with the exception of the bond market which is characterized by an equilibrium pricing. The credit market opens after the capital goods markets. The possible rationing of credit supply affects the effective demand in the capital goods market by the consumption goods producer, the oil company and the green utility.
3. All transactions and monetary flows are recorded and the balance sheets of the representative agents/sectors of the EIRIN economy are updated accordingly.

3.4.1 Consumption and capital goods markets.

The consumption and capital goods markets are mainly characterized by the same behavioral equations considered in the first version of the EIRIN model (see Monasterolo and Raberto 2018 for the technical details). In particular, both the representative worker (Hw) and the representative capitalist (Hk) set their nominal demand for the homogeneous consumption good according to the buffer stock theory of consumption (Deaton 1991; Carroll 2001), i.e. based on both net income and liquid wealth. As a difference with the previous version of the model, we consider the disposable net income, being the newly-introduced energy expenses subtracted from net income to determine the consumption budget for goods.

The consumption goods production sector (CGP) supplies an amount of the homogeneous consumption goods, according to a Leontief technology, based on the inputs made available at the previous step, i.e. the share of employed workforce, and the endowment of physical capital. Raw materials imported from the foreign sector at an exogenously given constant price represent the third input used by the CGP. However, assuming raw materials in infinite supply, the CGP is never rationed on its import. Thus, raw materials are not binding for the production plans but influence the unit costs of production. The CGP sets prices as a fixed mark-up on unit costs, which include the labour unit costs, the raw material unit costs and the interest expenses on outstanding debt per unit of output. The transaction takes place at the minimum between demand and supply, and one of the two sides of the market is usually rationed. If rationing applies to the demand side, then this is distributed to the Hw and Hk proportionally to their demand. Finally, based on its sales and inventory level, the CGP makes the production plan for the next simulation step.

As for the capital goods market, there are two new actors on the demand side with respect to the first version of the EIRIN model, i.e. the green utility company and the oil company, where the former demands green capital goods whereas the latter demands brown ones. Further details are provided in the paragraph on the energy markets. On the supply side, there are the two capital goods production sectors, green and brown, which produce on demand by using labour as the only production factor and set their respective capital goods prices, $p_{K_{green}}$ and $p_{K_{brown}}$ based on labor unit costs, considering the higher money wage rate in the green sector, i.e. $w_{green} > w_{brown}$.

In addition, the demand side in the capital goods market is made by the consumption goods sector. In particular, based on its production plan and the Leontief technology, the CGP determines its target level of capital endowment and then accordingly, considering its present endowment of physical capital as well as the capital depreciation rate, it sets the level of investment, i.e. the demand for capital goods either brown or green. Then, the choice between investing in green or brown capital goods is made according to the highest Net Present Value (NPV) between green and brown expected investment cash flows.

Further details and the behavioral equations related to the capital goods producers and the investment demand of the CGP are provided in Monasterolo and Raberto (2018).

3.4.2. Labour market.

The demand side of the market is made by the consumption and the capital goods sectors, plus the government. For the sake of simplicity, we assume that both the brown and green utilities as well as the oil company do not employ workers as a production factor. The labor demand by the government is a new feature of this enriched version of the EIRIN model. It has been introduced not only for the sake of realism but also for taking into account i) a baseline level of expenses by the public sector, other than interests on debt or green subsidies, and ii) a baseline source of income for Hw. In particular, we assume that the government demands a constant fraction γ_G of the total workforce provided by Hw at the w_{brown} wage rate. The labour demand by the CGP is set according to its production plans and the Leontief production technology. Labour demand by both the KGPs, either green or brown, depends on the demand for investment received on the previous time step and on labor productivity. The labour force, which is supplied by Hw, is fixed, inelastic to wages and characterized by a continuum of skills uniformly distributed from a lower to an upper bound. The average nominal wage is determined according to a Phillips curve-like rule, as in Keen (2013), where the percentage change in the nominal wage depends on the level of unemployment recorded in the previous time step. The wage levels in the brown (government, CGP, KGP brown) and in the green sectors (KGP green), i.e. w_{brown} and w_{green}, are then determined based on the average nominal wage and on a minimum wage (set as a parameter in the model). It follows that the condition $w_{green} > w_{brown}$ always holds and the wage bill of the economy, consistently with the setting mechanism for the average wage, does not depend on the labour force allocation in the brown/green sectors but only on its employment level.

The labour transaction is set at the minimum between demand and supply. In the case of rationing on the demand side, we assume that the public sector has priority over the private sector agents, then the green KGP has priority on labour supply over the brown one, which in turn has priority on the CGP sector. Finally, we assume that the KGP green always hires the skilled fraction skilled fraction of the labour force.

The technical details on the wage setting and the distribution of skills over the labour force are given in Monasterolo and Raberto (2018).

3.4.3 Energy sector

Energy demand q_e is given by the sum of workers q_e^{Hw} and capitalists q_e^{Hk} energy demands, i.e. $q_e = q_e^{Hk} + q_e^{Hw}$. Both energy demands are assumed to be constant, consistently with the short-term horizon of our simulations. For the sake of simplicity, we don't consider the contribution of the production sector to the demand of energy, in order to detach the performance of green subsidies from the effects of the business cycle. In the further development of the model, we will include the production sector into the energy demand function.

The supply side is made by both a non-renewable (brown) q_e^{nr} and a renewable (green) q_e^r contribution, supplied by the brown and the green utility companies, respectively. We assume that the green utility has priority in the grid and that the brown utility is always able to meet the residual energy demand, i.e. $q_e^{nr} = q_e - c$ (1)

The green utility supply of renewable energy is set by its green capital endowment (i.e. the number of solar panels, n_{sp}), i.e. $q_e^r = \varepsilon_{sp} n_{sp}$, where ε_{sp} is the amount of energy produced by each solar panel each simulation step. The brown utility produces electricity q_e^{nr} by means of a non-renewable resource (e.g. oil), which is supplied by the oil company, and a production technology characterized by constant returns to scale, i.e. $q_e^{nr} = \varepsilon_o q_o$, where q_o is the quantity of oil necessary to produce q_e^{nr} units of energy and ε_o is the efficiency of the oil to energy transformation process.

The brown utility company sets the energy price p_e based on a mark-up μ_e on its unit costs c_e, given by the oil price p_O, and the cost of debt service, i.e.

$$c_e = \frac{p_o q_o + r_D D_{BU}}{q_e^{nr}} = {p_o}/{\varepsilon_o} + \frac{r_D D_{BU}}{q_e^{nr}} \qquad (2)$$

Accordingly, the energy price p_e is set as

$$p_e = (1 + \mu_e) c_e \qquad (3)$$

The oil price is assumed to be determined in international markets (considering that the EU is a net importer of fossil fuels) and thus is modelled as an exogenous variable characterized by a constant growth rate μ_o.

The green utility company may undertake green investments to increase its renewable energy production capacity by acquiring new units of solar panels, i.e. Δn_{sp}, which are identified in the model as new units of green capital goods. In particular, the green utility company computes at any time step the NPV of acquiring Δn_{sp} units of solar panels at the price $p_{K_{green}}$ subsidized for the γ_{sp}% by the government, assuming to be able to sell the new renewable energy produced at a constant price p_e, and considering a negligible depreciation of solar panels in the short-term (5 years).

The NPV is then given by:

$$NPV = -\left(1 - \gamma_{sp}\right) p_{K_{green}} \Delta n_{sp} + \frac{p_e \varepsilon_{sp} \Delta n_{sp}}{r_D} \qquad (4)$$

where r_D shall be considered as the cost opportunity of capital and used to discount future cash flows, which are proxied by the cost of debt.

The sign of the NPV determines the decision to undertake the investment or not, whereas its size, i.e. Δn_{sp}, being NPV increasing monotically with the number of new acquired panels, is set by the available liquidity of the green utility company, i.e. M_{GU}, plus the possibility to take new debt ΔD_{GU} with the bank given a constraint on the maximum allowed leverage α_{GU}. Accordingly, if $NPV > 0$ we have:

$$\Delta n_{sp} = \frac{M_{GU} + \Delta D_{GU}}{p_{K_{green}}} \text{ holding that } \Delta D_{GU} + D_{GU} \leq \alpha_{GU} E_{GU} \qquad (5)$$

otherwise if $NPV \leq 0$, then $\Delta n_{sp} = 0$. It is worth noting that investments in renewable production capacity are positively influenced by the green subsidy rate γ_{sp} to green capital investments, i.e. a policy parameter, and by the cost of energy p_e.

Concerning the brown utility company, for the sake of simplicity, we assume that no investments and no capital depreciation occur in the short-term space of our simulation. Accordingly, we assume that the level of (brown) physical capital and debt remain constant. Profits made on the mark-up on the oil price are paid out to Hk as dividends. As far as the oil company, we assume new investments in brown capital aimed to cover depreciation are covered by means of the proceedings of oil sales. Net profits are paid out in part to domestic capitalist shareholders and in part to foreign capitalist shareholders. The share of profits γ_O paid out to foreign shareholders sets the financial dependency on the foreign sector of the EIRIN economy for the provision of non-renewable energy sources.

3.4.4 *Credit market*.

BA is subject to a capital adequacy requirement (CAR) constraint, consistently with Basel III. Thus, credit may be rationed due to insufficient equity capital on the BA's side. In case of rationing, credit is allocated proportionally to the demand schedules of the CGP, the green utility and the oil company. Then, the three agents revise their investment plans downward accordingly and reduce the capital goods demand, either brown or green. In the case of credit rationing, BA stops paying dividends in order to increase its equity capital.

3.4.5 *Bonds market*.

We distinguish between green and brown sovereign bonds. Both green and brown bonds are infinitely-lived assets and pay a fixed coupon c_{bond} at every simulation step. Green bonds are issued by the government to support investments in renewable energy production (e.g. the utility companies' purchase of solar panels for the production of electricity out of renewable energy), while brown bonds are issued to cover the government's current expenditures. Hk and BA purchase and trade the (green/brown) sovereign bonds. Hk and BA reallocate at each time step their financial wealth W_a $(a = Hk/BA)$ among green (*gB*) and brown bonds (*bB*), as well as their deposits (M), based on the desired weights - $\widehat{\omega}_a^{bB}$, $\widehat{\omega}_a^{gB}$, $\widehat{\omega}_a^{M}$ $(a = Hk/BA)$ – of the three asset classes.

In particular, the financial wealth of both Hk and BA agents is given by:

$$W_a = n_{bB}^a p_{bB} + n_{gB}^a p_{gB} + M_a \; (a = Hk/BA) \tag{6}$$

where n_{bB}^a, n_{gB}^a are the holdings by agent a of brown and green bonds, respectively, at the market prices p_{bB} and p_{gB}, and M_a is the amount of bank deposits. The central assumption of our model is that both agents aim to allocate the amount of money invested into the three asset classes so to mimic the relative asset market capitalization of an ideal market portfolio, where the "ideal" market capitalization of each asset class is determined by the amount of units outstanding, times a "rational" price for bonds. The rational price of green and brown bonds, $\bar{p}_{gB}^a \; and \; \bar{p}_{bB}^a$, is determined by the present value of the infinite stream of coupons c_{bond}:

$$\bar{p}_{bB}^a = \bar{p}_{gB}^a = \frac{c_{bond}}{r_{CB} + \delta_a} \tag{7}$$

where δ_a $(a = Hk/BA)$ is the risk spread.

Given the relative share of asset capitalization of the ideal market portfolio, the desired weights $\widehat{\omega}_a^{bB}, \widehat{\omega}_a^{gB}, \widehat{\omega}_a^{M}$ by any of two sectors/agents $(a = Hk, BA)$ for each asset class (brown/green bonds and BA deposits) are defined:

$$\widehat{\omega}_a^{bB} = \frac{n_{bB}\bar{p}_{bB}^a}{n_{bB}\bar{p}_{bB}^a + n_{gB}\bar{p}_{gB}^a + M_{Hk} + M_{BA}} + \varepsilon \quad (a = Hk/BA) \tag{8}$$

$$\widehat{\omega}_a^{gB} = \frac{n_{gB}\bar{p}_{gB}^a}{n_{bB}\bar{p}_{bB}^a + n_{gB}\bar{p}_{gB}^a + M_{Hk} + M_{BA}} + \varepsilon \quad (a = Hk/BA) \tag{9}$$

$$\widehat{\omega}_a^{M_a} = 1 - \widehat{\omega}_a^{bB} - \widehat{\omega}_a^{gB} \quad (a = Hk/BA) \tag{10}$$

where n_{bB} and n_{gB} are the amounts of brown and green bonds outstanding, respectively, and ε is a normally distributed random shock with mean zero and standard deviation σ_ε.

The desired asset weights along with the financial wealth of Hk and BA set the amount of financial resources that Hk and BA commit to each asset, i.e.

$$\widehat{W}_a^x = \widehat{\omega}_a^x W_a \tag{11}$$

where $a = \frac{Hk}{BA}, x = bB, bB, M$

The total financial resources committed in the market to each bond, either brown or green, depends also on i) the money drawing requests by the government ($-\Delta M_G$), which needs to issue new bonds (green/brown) to finance its activities, and ii) the unconventional monetary operations put in place by the CB, which injects new money, $+\Delta M_{CB}^{bB}$ and/or $+\Delta M_{CB}^{gB}$ to purchase brown and/or green bonds.

In the same fashion of Tobin (1969), the prices of both brown and green sovereign bonds are set at the equilibrium value given by the ratio of total financial resources committed to each asset and their outstanding number. The bonds' portfolio allocation (green/brown) depends on Hk and BA's preference structure and the bonds' yields given the current market price.

4. EIRIN scenarios and computational results

4.1 Using the software *Matlab,* we simulate and compare three scenarios, one characterized by conventional monetary policies, and two characterized by unconventional monetary policies:

1. *Conventional monetary policies (CMP)*: the government issues green bonds to support private investments in renewable energy production (i.e. new solar panels purchased by the utility company), CB sets the interest rate following a Taylor rule (black scenario);
2. *Unconditioned QE (UQE)*: the government issues green bonds to support private investments in renewable energy production (i.e. new solar panels purchased by the utility company); the CB starts an assets purchase program accepting sovereign bonds (either green or brown) as eligible asset (blue scenario). In particular, the CB purchases at each simulation step a γ_{UQE} share of the outstanding sovereign bonds, both brown and green, from BA, which is the sole financial intermediary of the EIRIN economy.
3. *Green QE (GQE)*: the government issues green bonds to support private investments in renewable energy production (i.e. new solar panels purchased by the utility company); the CB starts an assets purchase program accepting only green sovereign bonds as eligible asset for its green QE (green scenario). In particular, the CB purchases at each simulation step a γ_{GQE} share of the outstanding green sovereign bonds from BA, which is the sole financial intermediary of the EIRIN economy.

For each policy scenario, we discuss the two following points:

- To what extent each policy pathway would contribute to scale-up green investments, in particular into renewable energy production?
- Under which conditions could potential distributive effects of such policies on income inequality and wealth concentration emerge?

Figure 4 displays the effects of CB's unconventional monetary policies (UQE, GQE) on CB and BA's balance-sheets.

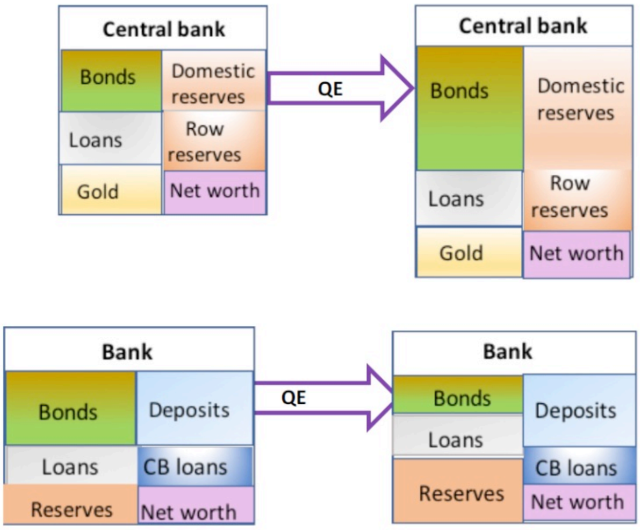

Figure 4 Change in CB and BA's balance-sheets as a consequence of unconventional monetary policies. The CB purchases sovereign bonds from the BA, and pays it by creating new reserves, thus increasing its assets and liabilities by equal amounts. In contrast, the BA purchases the sovereign bonds (green/brown) bonds from the government and sells them to the CB, thus modifying its asset side. The bonds' value sold to the CB is replaced by an equal amount of reserves deposited at the CB. The BA decides how to use new reserves by looking at the assets' return, which are given by the expectations on the CB's interest rate.

4.2 Simulations and discussion of results

Figure 5 displays the transmission channels from *CMP* in the EIRIN economy. Conventional monetary policies work through the interest rate channel (Taylor rule) with effects on the increase/decrease of the cost of capital for investments and on the interest paid on deposits, in order to slow down/foster investments and meet the unemployment and the inflation targets (e.g. 2% in the EA).

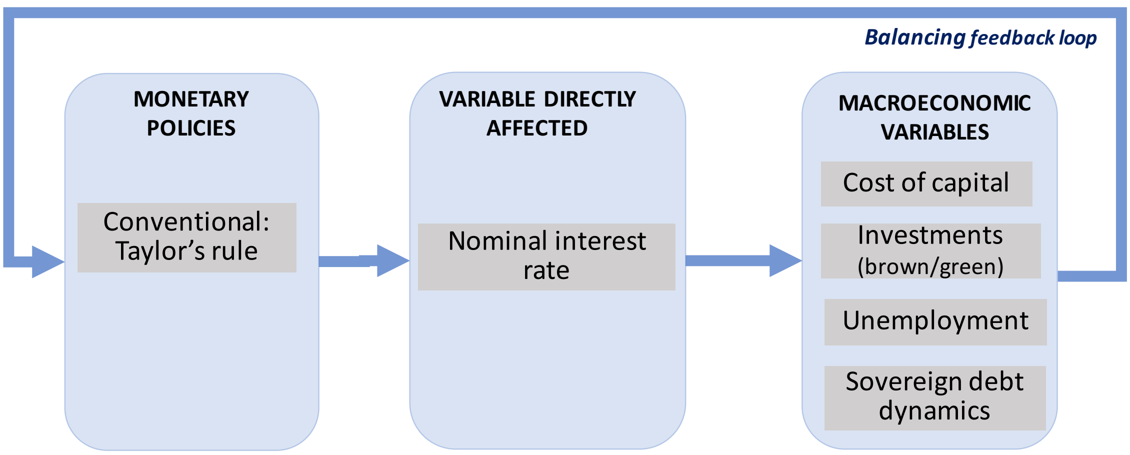

Figure 5 CMP transmission channels

In contrast, Figure 6 displays the unconventional monetary policies (i.e. QE)'s transmission channels. The QE works through the channel of inflation of capital goods via asset purchase (bonds) and affects their prices and yields; the cost of capital for green investments and the CAPEX for companies investing in brown capital goods and energy; the macroeconomic variables - including renewable energy capacity and sovereign debt. In the case of GQE, the only channel is green bonds, which represent the only eligible assets accepted by the CB.

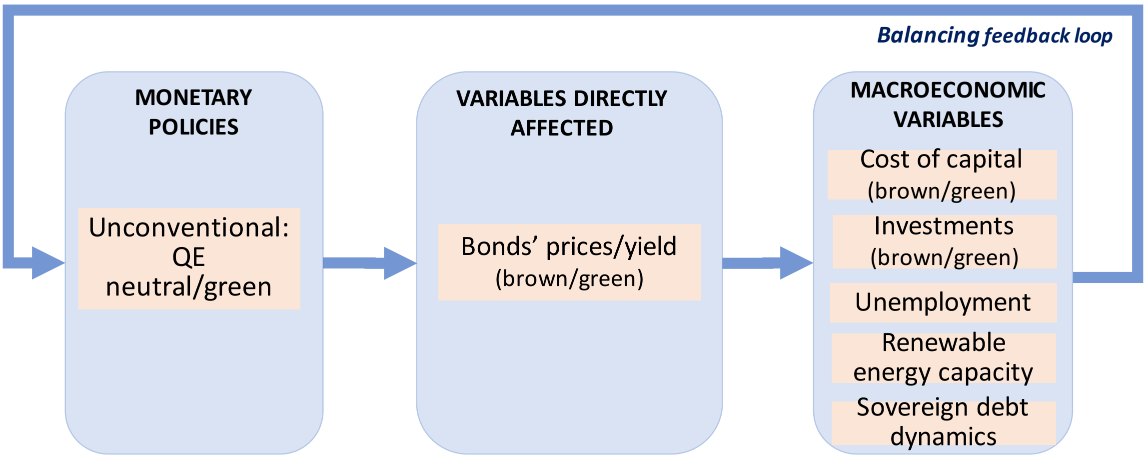

Figure 6 UQE and GQE transmission channels

Table 3 shows the values of the key model parameters used in the three scenarios.

Symbol	Scope	Value
ε_{sp}	amount of energy produced per solar panel	0.01 e.u.
ε_{o}	amount of energy produced per unit of oil	10 e.u.
μ_{e}	mark-up on energy unit costs	10 %
μ_{o}	growth rate of oil price	0.0 %
γ_{sp}	percentage of subsidized solar panel price	15 %
α_{GU}	maximum allowed leverage for the green utility	1
c_{bond}	(brown/green) bond coupon	0.01 c.u.
δ_{Hk}	risk spread on bonds by capitalists	1 %
δ_{BA}	risk spread on bonds by the bank	1 %
σ_{ε}	standard deviation of random shock to portfolio weights	1e-5
γ_{G}	share of the workforce employed in the public sector	20%
γ_{UQE}	share of outstanding (brown/green) bonds purchased by the CB at each time step under the UQE policy	1 %
γ_{GQE}	share of outstanding green bonds purchased by the CB at each time step under the GQE policy	15 %

Table 3 Model's parameters. The table shows the value of the new parameters introduced in this updated version of EIRIN, where e.u. stands for energy units, and c.u. stands for currency units. For the remaining model's parameters, see Monasterolo and Raberto (2018).

Figures from 7 to 13 show the results of the simulations of the conventional (CMP) and unconventional (UQE and GQE) CB's monetary policies' scenarios for the bonds' market, the real economy, the credit sector, the CB and the government. The simulations show the policy differentiation that characterizes the three scenarios over the time. Each scenario is represented by a different color. The simulations are 120 steps long. Time steps are purely indicative and are not specified in real terms.

Bonds market. The green/brown bonds' markets are mostly affected in the unconventional monetary policy scenarios (UQE and GQE) as a result of the CB's assets purchase, as shown in Figure 7, 8, 9, while the CMP scenario has minor effects on the change in the number of bonds outstanding and their prices.

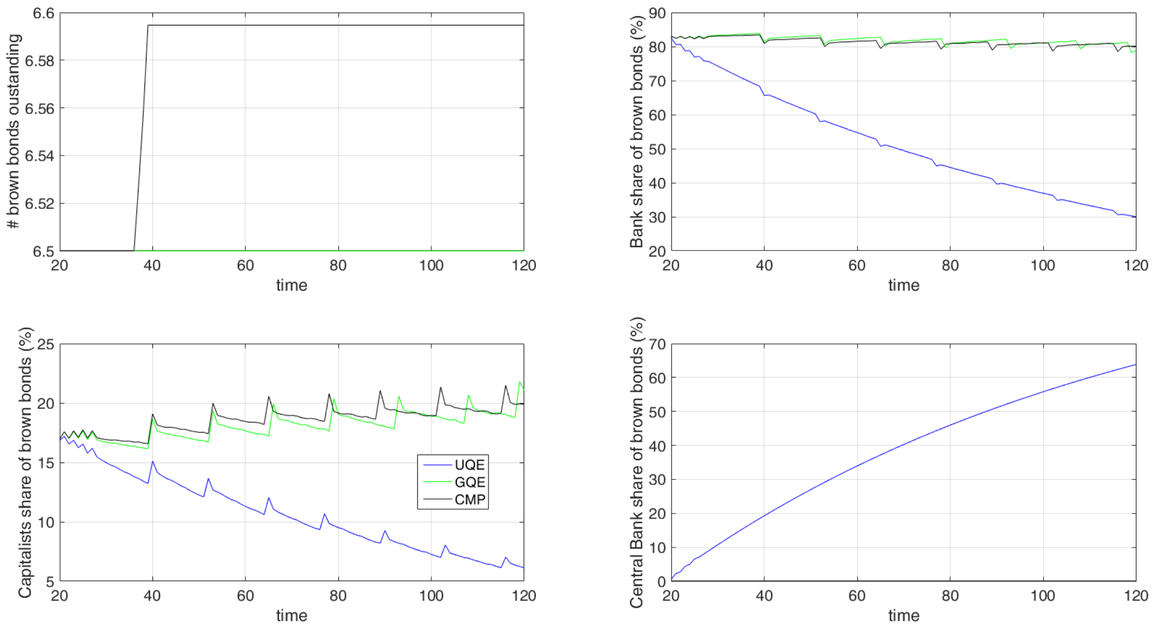

Figure 7 Brown bonds market. The top left corner shows the dynamics of brown sovereign bond outstanding, i.e. the cumulative issuance by the government. Brown bonds are held in Hk, BA and CB's portfolios according to the share displayed in the bottom left, top right and bottom right panels, respectively. In the scenarios characterized by unconventional monetary policies, the brown bonds' share on CB's portfolio increases only in the case of UQE (blue scenario) as a result of the conditionality on assets' eligibility introduced by the CB in the GQE scenario (green scenario).

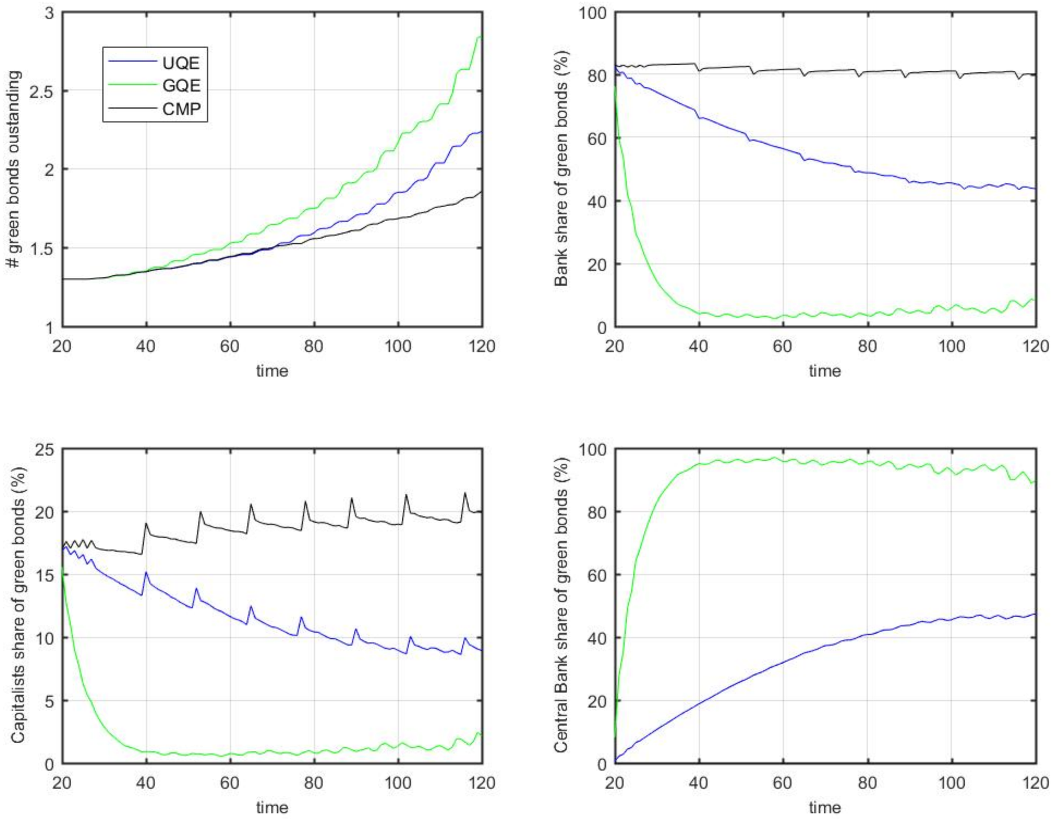

Figure 8 Green bonds market. The introduction of unconventional monetary policies, in particular in the case of the GQE, has a positive effect on the green bonds issued by the government and thus on green bonds outstanding (top left panel). In GQE, the share of green bonds owned by Hk and BA (respectively bottom left and top right panels) decreases as a consequence of the CB's purchase (bottom right panel), which in turn increases its green bonds' holdings, thus contributing to decarbonize its portfolio. In contrast, green bonds outstanding is the lowest in the CMP scenario. Here, Hk and BA's shares of green bonds reach the highest levels because in absence of CB's assets' purchase, the CB doesn't expand its bonds' holdings.

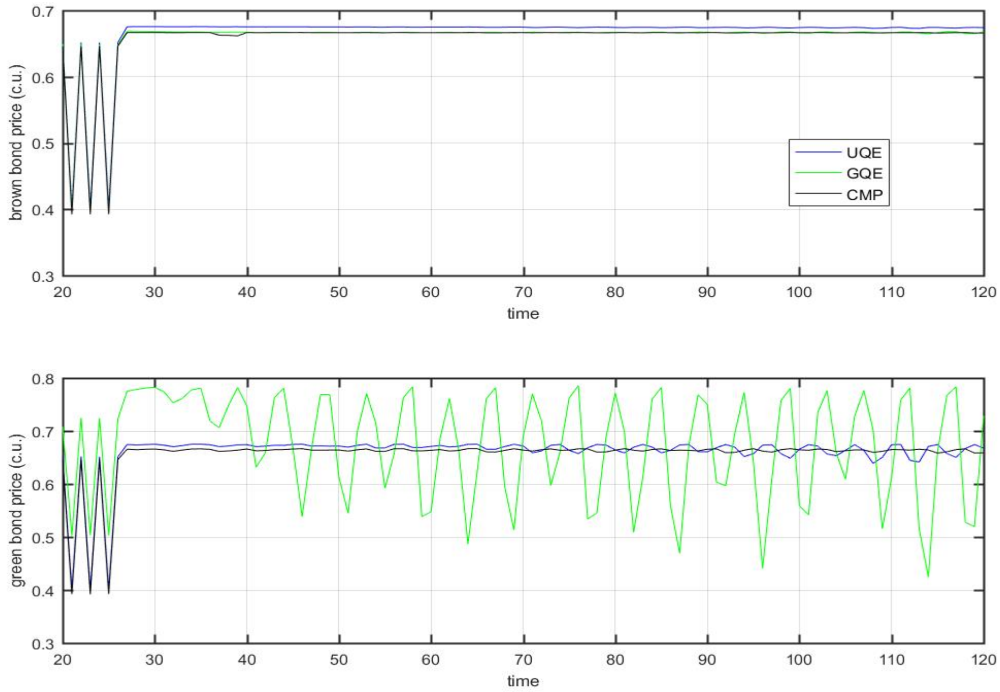

Figure 9 Green/brown bonds' prices. Brown bonds' prices increase the most in the case of UQE (blue scenario) and remains still in the case of green QE (green scenario). The initial large fluctuations of brown bonds' prices are linked to the market and agents' portfolios' reallocation related to the change in interest rate applied by the CB in the case of both conventional and unconventional monetary policies. In contrast, green bonds' prices increase the most in the first stages of the green QE, and then display high oscillations. We observe larger fluctuations in the value of green bonds in comparison with brown bonds due the initial smaller volume of the former, which is thus more influenced by the BA and Hk's portfolios' reallocation induced by both conventional and unconventional monetary policies. The increase in green bonds issuance displays a similar trend to that of green capital endowment - i.e. new solar panels (Figure 10) because green bonds are issued by the government to cover the desired public support to capital investments in renewable energy. Thus, the issuance of green bonds comes with a clear conditionality. It is worth noting that in the case of GQE (green scenario), the increase in the number of green bonds outstanding as a consequence of government's issuance, and their purchase by the CB (bottom right panel), is much faster than in the case of UQE (blue scenario).

This result has two important implications on the timing and magnitude of the low-carbon transition. The first is on the pace of new green investments, which occur earlier and at higher amounts in GQE scenario in comparison to the UQE and CMP scenarios, thus contributing to narrow the green investments gap. The second is related to the development of the green bonds' market, which is closely linked to the new green investments in the real economy. Under these conditions, the GQE scenario emerges as a clear opportunity for the development of the green economy, which grows faster than in the other scenarios. New green investments foster the increase in new green jobs and lead to a faster decrease in unemployment and supporting demand, thus contributing to accomplish the unconventional monetary policies' mission as stated by several central banks' governors in the last couple of years. In addition, they support the sound development of the green bonds market, thus avoiding the risk of a green bubble.

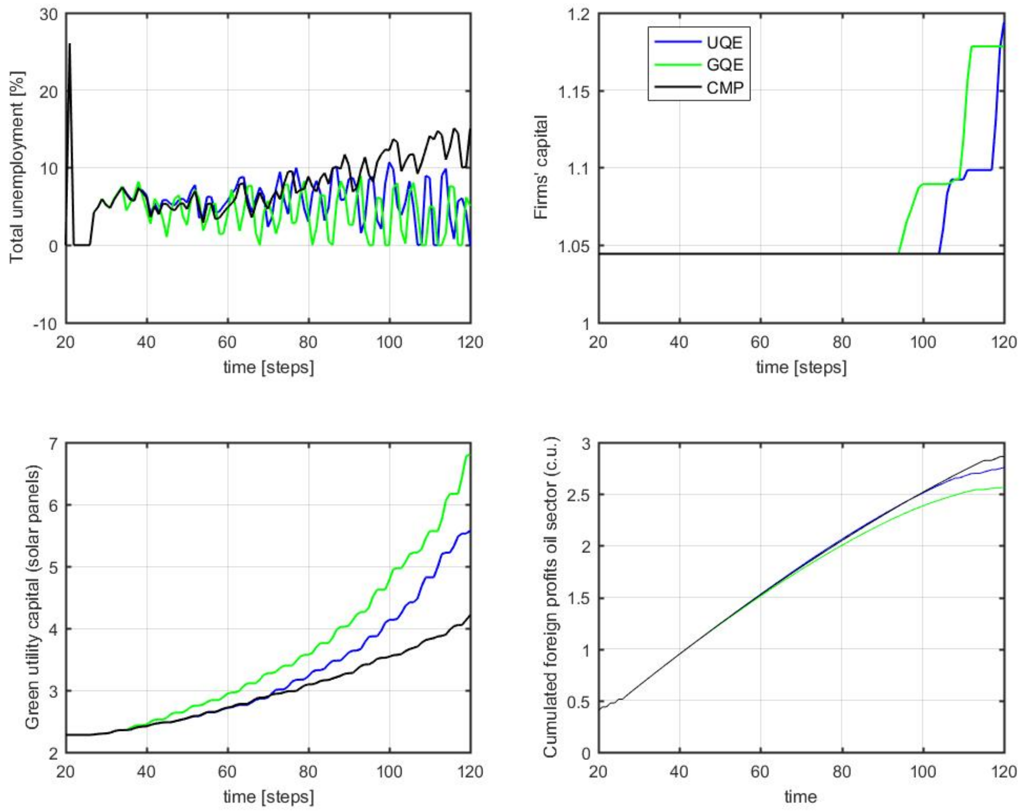

Figure 10 Real economy. The figure displays the trend of total unemployment rate (in %), firms' capital endowment (in units of capital goods), green utility capital (in number of solar panels) and the cumulated profits of the oil company (owned by a foreign agent) in the EIRIN economy. The currency unit is indicated with *c.u.* and it is used in relation to the monetary variables, in order to distinguish these values from the a-dimensional numbers that are used, for instance, in the case of capital endowments. Total unemployment decreases the most in the case of GQE due to the higher demand for investments in the economy, in particular for green investments (i.e. firm capital and solar panels, respectively top right and bottom left panel). In contrast, the profits of the foreign sector, which are linked to the profits of the oil company, are the lowest in the case of GQE as a consequence of the higher installment of green solar panels, and thus to the production and consumption of renewable energy. Consistently, the number of new solar panels is lower in CMP and UQE in comparison to the GQE scenario. In contrast, the CMP scenario records the least performing results in terms of investments (which are only sufficient to meet the capital depreciation) and, as a consequence, of unemployment (top left panel).

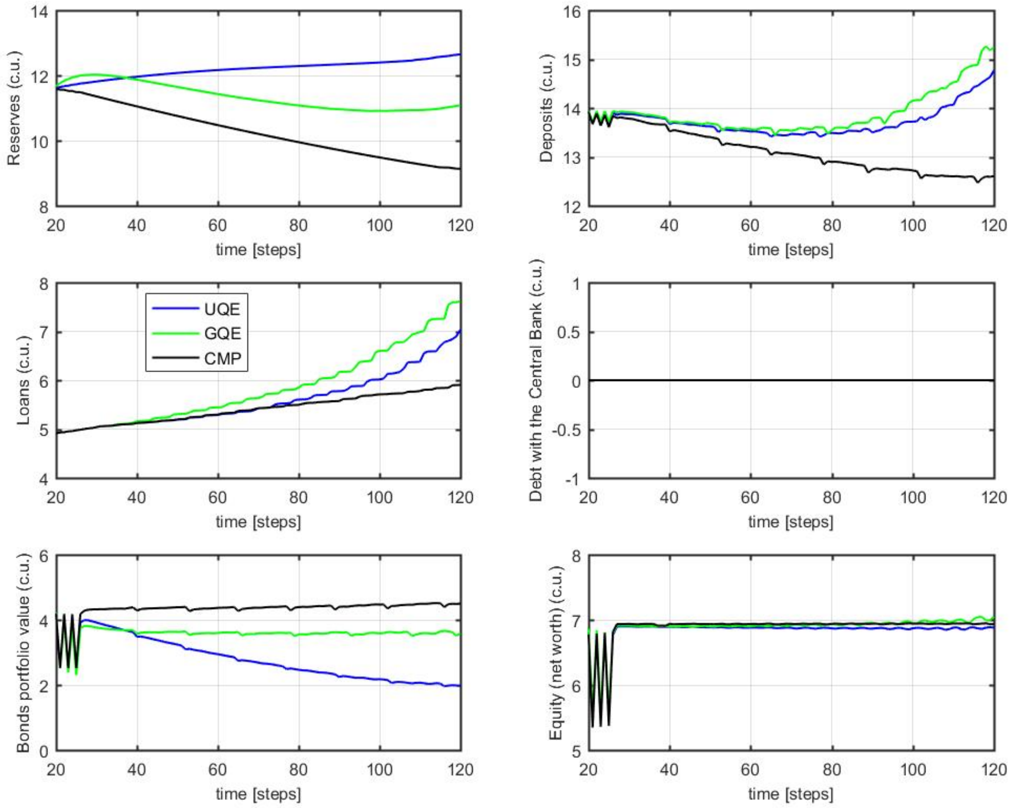

Figure 11 Credit market. Bank's credit to the real economy and thus endogenous money creation (i.e. new loans and deposits) is the highest in the case of GQE due to the increase in investments in renewable energy (i.e. new solar panels), which also drive unemployment down (see Figure 10). The sustained rate of increase in new loans drives bank's profits up. These, in turn, drive Hk's profits up (through the dividend channel), leading to a stronger demand for consumption goods by Hk (in comparison to Hw), eventually increasing inequality among households. In addition, wealth concentration in the credit market increases in the case of unconventional monetary policies (UQE and GQE scenarios), being the BA the only intermediary for the CB assets' purchase programs. In contrast, investments in the real economy decrease the most in the case of CMP, thus driving endogenous money creation down. Finally, the BA bonds' portfolio value (bottom left panel) increases the most in the case of UQE because BA purchases both brown and green bonds, being both eligible for the CB's assets purchase program. Consistently, in the UQE scenario BA's reserves increase the most.

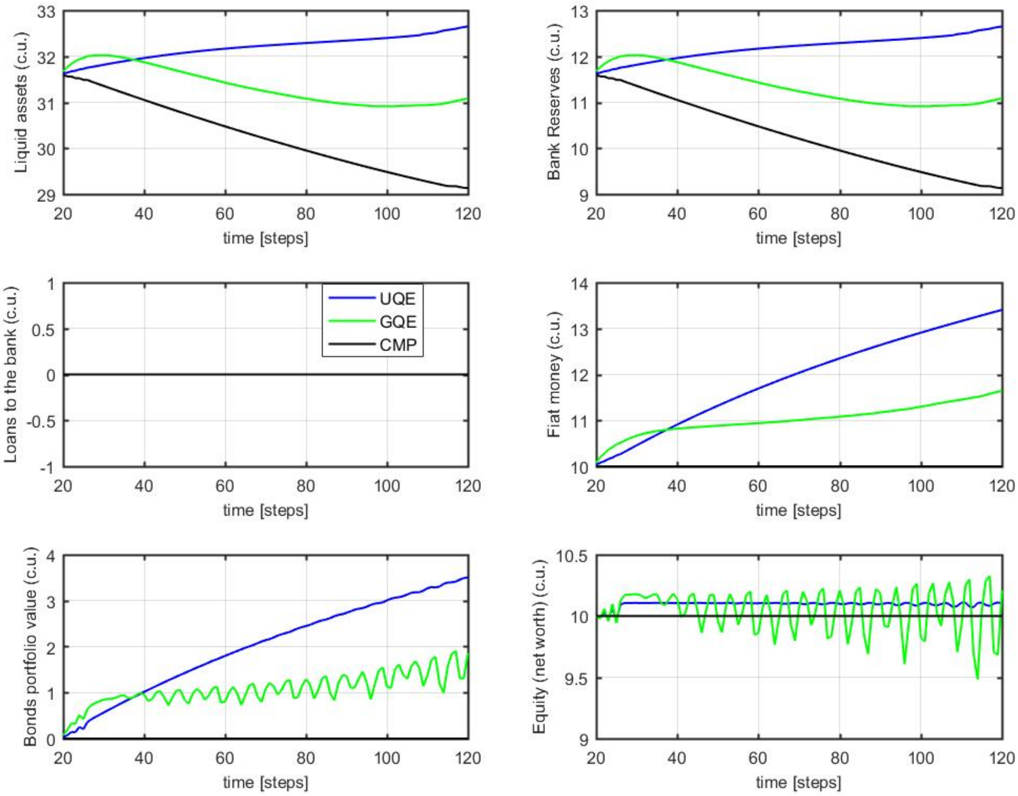

Figure 12 Central Bank's liquid assets, reserves, and fiat money. The effects of CB's unconventional monetary policies are more evident in the case of UQE where the CB accepts both green and brown bonds. Indeed, by construction, the CB assets' purchase is proportional to the number of outstanding bonds, which is higher in the case of brown bonds. The CB's fiat money shows the dynamics of the CB's newly generated money used to purchase bonds from BA under the unconventional monetary policies scenarios (UQE and GQE). The CB's liquid assets and reserves increase the most in the case of UQE because the CB purchases both green and brown bonds (while, by construction, the CB conditions its assets' purchase to green bonds in the case of GQE). In the CMP scenario, CB's fiat money remains constant and no additional purchase of bonds occurs. It is worth noting that in the three scenarios, the trend of CB's liquid assets mirrors that of CB's reserves. Indeed, CB's seigniorage profits due to the bonds' coupons payment by the government, which follows the CB's purchase of the bonds, are paid back to the government. This allows the government to keep the tax rate at lower levels in the case of UQE scenario, where the QE is stronger (see Figure 13). Under these conditions, a strong QE could help the government to foster the increase in green investments while meeting its budget balance, with negligible effects on increases in general taxation. In all the scenarios, BA doesn't need to borrow from the CB because its liquidity never turns negative.

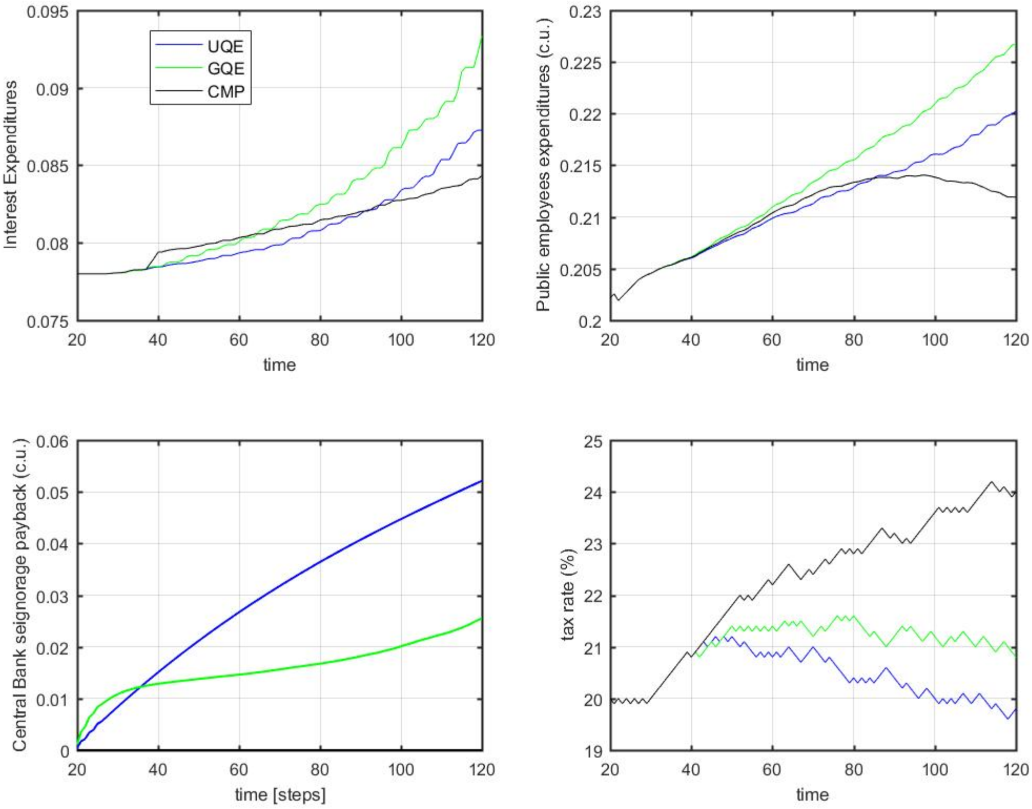

Figure 13 Government's interest expenditures, budget balance and taxation. The figure shows the positive effects of the seigniorage revenues on the dynamics of the government tax rates (bottom left panel). This happens despite higher government's expenses for debt service (top left panel), which are higher at the beginning of the simulations in the case of UQE but increase fast in the case of GQE as a consequence of the sustained green bonds' issuance. In addition, the top right panel shows public employment expenditures given by the dynamics of the nominal wage levels in the economy, which in turn depends on the unemployment level. Tighter labour market conditions imply a higher growth rate of the nominal wage (see Monasterolo and Raberto, 2018).

5. Conclusions

This paper presents three main novelties on the state of the art contributing to the discussion on how to fill in the green investment gap in the EU to achieve the Paris Agreement and the EU2030 climate and energy targets. First, by enriching the EIRIN SFC flow-of-funds behavioural model (Monasterolo and Raberto, 2018) with an energy sector and an energy market, and with a bond market, we can assess to what extent could conventional and unconventional monetary policies – i.e. an unconditioned QE and a green QE conditioned to the purchase of green sovereign bonds - affect the timing and magnitude of the low-carbon transition. Such policy options are receiving growing attention by academics and practitioners. However, an assessment of their impact on the (green) real economy and the credit market is still missing.

Second, we analyse under which conditions the implementation of such policies could lead to potential unintended effects in terms of credit market instability, income inequality and wealth concentration. It has been recently argued that the QE's introduction in the Euro-Area contributed to accrue inequality by benefitting the wealthiest households and sophisticated financial actors. Nevertheless, an assessment of the conditions leading to such outcomes has not been provided yet.

Third, with EIRIN we introduce structural and behavioural solutions that represent an advancement on DSGEs models for the analysis of unconventional monetary policies in an economy recalling the characteristics of the EU in the last decade (e.g. weak aggregate demand, low inflation, low/negative interest rates). In particular, with EIRIN we can:

- Model households and economic sectors that are heterogeneous in terms of consumption/investment/saving behaviors, and access to financial market. In addition, their expectations are influenced by the government's fiscal policies and subsidies, and by the CB's monetary policies. Furthermore, EIRIN features heterogeneous energy sources (renewable/fossil fuels), and green/brown capital and consumption goods, where green goods have lower resource intensity thus limiting the impact of the production system on the production of CO2 emissions. This level of heterogeneity allows us to display the monetary policies' drivers of sustainability, financial stability and their distributive effects, while keeping complexity at a manageable level. Thus, we can overcome a main limit of ABMs, such as the arbitrariness of behavioural rules, the difficulty to assess the causal chains leading to results, and the overcomplexity due to the number of agents and interactions.
- Provide a description of the stocks and flows through which the socio-economic and financial system interact. The adoption of Stock-Flows Consistency and of a balance sheet accounting approach (Lavoie, 2014) allows to track all transactions and to display change in agents' balance sheets as a result of endogenous dynamics, thus promoting model's transparency and results' accountability. In particular, we can represent how CB's balance sheet composition changes as a consequence of unconventional monetary policies, and the flows that it generates in the economy.
- Display emerging (and often unexpected) macroeconomic dynamics, determined by heterogeneous agents' interactions, cross-sectors feedback loops, amplification effects and time delays, and understand the shocks transmission channels from the credit market to the real economy as a result of policies' introduction. Understanding shocks transmission channels is fundamental to inform central bankers and regulators about the effects of their policies on markets and agents' investments and expectations, and thus allow them to decide the timing and magnitude of their policies.
- Compare conventional monetary policies implemented via bank lending with unconventional ones implemented via QE, and assess their effect on the stability of the credit sector and on the bond market, by distinguishing between credit, bond and capital market for funding green investments.
- Analyse the effects of each monetary policy scenario in terms of its contribution to sustainability (i.e. development of the green economy) and financial stability (i.e. the exposure to the risk of carbon stranded assets) by looking at the changes in level and composition (green/brown assets) of the agents' balance sheets, including the central bank's one. Then, we analyse the implications on wealth concentration and income inequality across households.

We find that a green QE conditioned to the CB's purchase of green sovereign bonds has relevant implications on the timing and magnitude of the low-carbon transition. Conditioned to the model's assumptions, the green QE contributes the most to scale-up investments in renewable energy, with positive spillover effects on the green economy in terms of firms' capital accumulation and unemployment. Indeed, in the GQE scenario, the economy experiences better borrowing conditions for renewable energy investments thus stimulating bank's endogenous money creation. In addition,

by construction the GQE supports the issuance of green sovereign bonds and thus the development of the green bonds market.
We provide the following interpretation of this result: the GQE is able to release the government's budget conditions by providing fast liquidity to support renewable energy investments, thus allowing to overcome governments' current budget constraints and to keep taxation at lower levels than in the case of conventional monetary policies. This, in turn, stimulates the economy leading to lower unemployment levels, higher investment rates and endogenous money creation.
Finally, by preferring green bonds (which are associated to green investments), the CB contributes to decarbonize its and the EIRIN's investors' portfolio, thus building resilience against the risk of stranded assets. Therefore, by implementing a green QE, CB could play a key role in the low-carbon transition by promoting sustainability and financial stability, this latter being at the core of CBs' mandates.
In addition, we find that the introduction of unconventional monetary policies contributes to improve the government's budget balance via direct (i.e. government funding rate) and indirect (i.e. seigniorage) channels. In the former, the government's funding rate decreases as a consequence of the CB's assets purchase, which in turn boosts sovereign bonds' prices. In the latter, the CB's pay-back of the stream government bonds' coupons leads to release a fraction of the government debt's service.
However, we find that CB's unconventional monetary policies have not negligible distributive effects in terms of income inequality and wealth concentration due to their influence on general taxation and on assets' prices, respectively. Such distributive effects develop via different channels. Both CB's unconventional monetary policies (and in particular the unconditioned ones) contribute to increase the value of both green and brown bonds, as well as to increase BA's reserves deposited at the CB. Hk and BA benefit the most from the unconventional monetary policies because they are the only agents who can purchase the green/brown bonds, whose value increase in both the UQE and GQE scenarios. This, in turn, leads to increase income inequality between the worker (Hw) and the capitalist (Hk) household by benefitting the latter, who increases its income. As explained in section 2, Hk's income gains don't trickle down proportionally on economic growth, being the capitalist's propensity to consume (on total income) lower than that of Hw, who disposes of lower income and wealth.
The BA increases its endogenous money creation as a result of a higher demand for investments (in particular, the green ones), as well as its reserves, being the only intermediary for the CB's assets' purchase. The accumulation of assets in the hands of BA contributes to increase wealth concentration in the credit sector and in the BA's shareholder (i.e. Hk), with effects on inequality between households. At this regard, it is worth noting that after the last financial crisis, several analyses showed that wealth concentration in credit and financial institutions did not contribute to economic growth. In contrast, it contributed to accrue inequality (see Monasterolo and Raberto, 2018 for an overview) and to increase the complexity of risk (Battiston et al., 2016). Finally, our results show that the characteristics of the country's fiscal system, i.e. how regressive the tax system is and the level of tax elusion, could either amplify or reduce the distributive effects of unconventional monetary policies.

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