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Balance-Sheet Based and Unconventional Policies in an Agent-Based Model

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Abstract

In this paper we shed more light about the interactions between accounting policies and unconventional monetary policies. By employing a modified version of the Schumpeter meeting Keynes Agent-Based model (KS model) we study the effects that Mark-to-Market (MtM) accounting standards might have in terms of financial stability, economic growth and sustainability of public finances. We also study the effects of Quantitative Easing (QE), modeled as the intervention of the central bank for the clearing of bad-debts accumulated by the financial institutions. Our results suggest that the Mark-to-Market standard might generate instability in the credit side of the economy because of its pro-cyclical nature; the QE instead, being counter-cyclical might counteract the negative effects. However, a QE policy alone, does not outperform a baseline scenario with historical accounting standards and without unconventional monetary policies, suggesting that QE might be useful to counteract peculiar crisis events but shall not become a conventional instrument to be employed at any occasion.

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1 Introduction

Accounting standards are important policy choices that might have real macroeconomic implications. As a matter of fact, in the past, large financial and economic crises brought to a reconsideration of these policy choices. At the two poles of such a choice stand two opposite alternatives: the historical value accounting principle vis-à-vis the mark-to-market accounting principle (also known as fair value principle).

While before the *Great Depression* and until 1934, firms and banks had great flexibility about reporting the asset valuations they held in their portfolios, by the early 1940s the historical value accounting had become the standard.[1] Also as a result of regulation, in the 1970s however, the introduction of derivative contracts and other financial instruments induced the SEC to reconsider the usage of historical value accounting and to allow banks adopting the mark-to-market principle for the evaluation of futures and other foreign exchange contracts. During the 1980s, the fair value accounting principle was extended also to debt and equity contracts for the banking sector and by the 1990s, the mark-to-market accounting became the standard since the FASB required "all entities to disclose the fair value of financial instruments, both assets and liabilities recognized and not recognized in the statement of financial position, for which it is practicable to estimate fair value" (see FASB, 1991).

In the recent years however, economists have been raising concerns about the fact that mark-to-market accounting principles might have played an important role in the fast amplification of the financial crisis. The fall in the values of a large fraction of securities which were strongly correlated with house prices, led to large and almost immediate devaluations of the asset side of the banking sector, due to the adoption of the fair value accounting standard, and have strongly influenced the ability of the banking industry to continue to perform its basic lending activity. This of course have had important real effects as also documented by Heaton et al. (2010); Bhat et al. (2011); Kolasinski (2011) and might have played a role in lowering the liquidity of the market. All in all therefore, questions concerning the macroeconomic effects of the mark-to-market accounting principle, are important matters that naturally correlates with other questions about market liquidity, Brunnermeier and Pedersen (2009), credit cycles (see Kiyotaki and Moore, 1997), macroprudential regulation Galati and Moessner (2013) and unconventional monetary policy Rodnyansky and Darmouni (2017).

In the last decade indeed the introduction of unconventional monetary policies by several Central Banks have been of fundamental role to keep the value of long-term yields to low levels (Krishnamurthy and Vissing-Jorgensen, 2011; Duca, 2013), to counteract the low credit supply (Rodnyansky and Darmouni, 2017), and to dampen the downward phase of the credit cycle (Bhattarai and Neely, 2016).[2] The common wisdom of monetary policy showed its greatest limitation when the short-term interest rates hit the zero lower bound (ZLB). To react to the liquidity trap, central banks from all over the world have been forced to design new policy instruments and to experiment new transmission mechanisms for monetary policy to be effective: the Quantitative Easing policy is the most evident form of this.

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[1] After the Securities and Exchange Commission (SEC) forbade revaluation of assets in the balance sheets in 1934. For a complete historical narrative of the accounting principles used in the US see SEC (2008).

[2] See also Guerini et al. (2018) for a discussion about how the QE might have had different effects in US and EU also due to the combination with two different approaches with respect to fiscal policies.

Nowadays there are therefore two ways of implementing monetary policies (see Borio and Zabai, 2016). The first comprehends *interest rates policies*, the second points to *balance sheet policies*. The first set includes the conventional Taylor rule (whose effects have been extensively discussed by means of empirical models Angrist et al. (2013), neoclassical models Galí (2015) and evolutionary models Dosi et al. (2015)), the new forward guidance principles (which have mostly drawn the attention of empirical and experimental economic research (see respectively Swanson, 2017; Ahrens et al., 2017)) and the maturity transformation programmes (see Ehlers, 2012); these policies aim at controlling and fixing some reference short-term interest rate, to which the yield curve is linked, and to affect in turn macroeconomic fundamentals. The second policy set includes instead the large asset purchase agreements, the non-standard supplies of funds as well as the newly introduced reserves policies – which are also macro-regulatory policies. These last tools have been only recently introduced and their effects are far from been fully investigated and understood.[3]

In this paper we try to shed more light about the interactions between accounting policies and unconventional monetary policies. By implementing policy experiments in a new version of the Schumpeter meeting Keynes Agent-Based model (K+S model, see Dosi et al., 2010, 2013, 2015; Lamperti et al., 2017) we indeed analyze the transmission mechanisms of different policies – such as mark-to-market accounting for banks assets and quantitative easing policies – and the aggregate macroeconomic effects that they generate. This paper is organized as follows: section 2 reviews the events of the last decade and the policies implemented by the four work major central banks (FED, ECB, BoE, BoJ); section 4 presents some specific equations of the model and discusses the new parts of the model that have been introduced with the aim of evaluating the above mentioned policies; in section 5 we perform the policy evaluation exercise and presents the result. Section 6 concludes. A final appendix A is dedicated to the presentation of the full model, which emerges from the merge of two versions of the K+S agent-based model (see Dosi et al., 2015; Lamperti et al., 2017).

2 Conventional and Unconventional Monetary Policies at the Four Major Central Banks

Let us start by discussing how unconventional monetary policies were implemented at 4 different central banks in the last decade. In figures 1 and 2 it is possible to see that notwithstanding the attempt of collecting the available central bank policies under common features and objectives, the balance sheets compositions (as well as their size) are still quite heterogeneous for each economic area. This is due to the fact that the different central banks carried out different policy combinations and had to overcome different situations.[4]

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[3] Among the balance sheet policies, Borio and Zabai (2016) recognize also the possibility of an intervention of the Central Bank onto foreign exchange markets to affect the exchange rate, but this tool is not discussed here.

[4] For example, in EU and UK the central bank aims at a pure inflation targeting while in US and in Japan also a output is, more or less explicitly, targeted. Also, when the crisis hit, the respective levels of public debts to GDP in US and UK were not as high as in many EU economies or as in Japan.

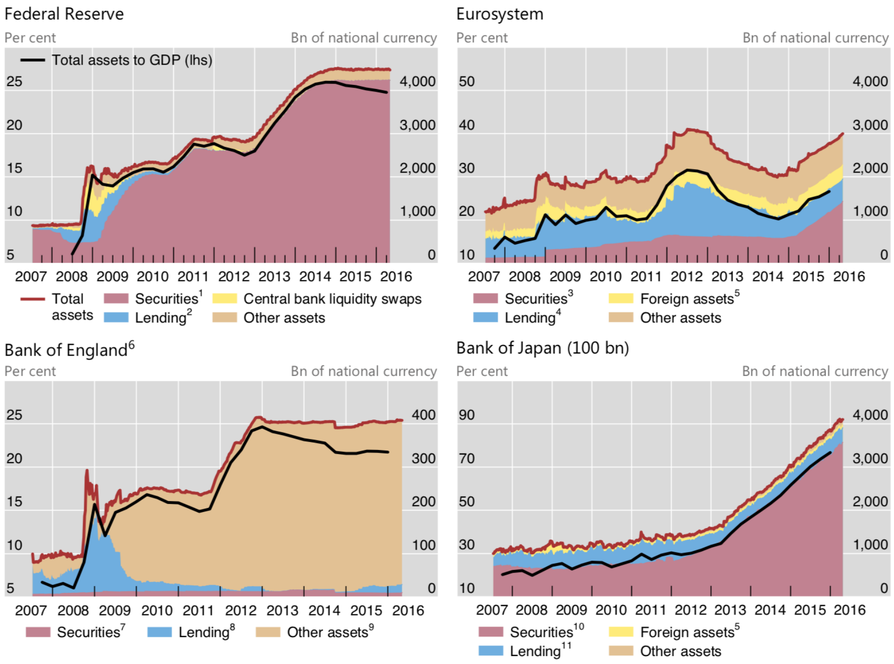

Figure 1: *Assets of the four major central banks.*

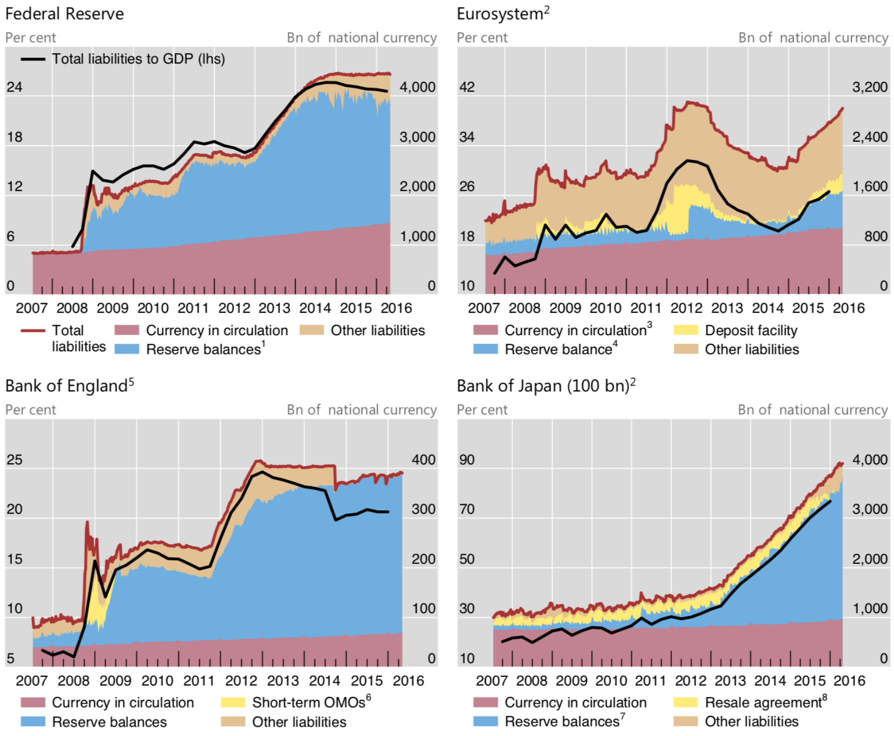

Figure 2: *Liabilities of the four major central banks.*

2.1 FED Policy Tools

Since the advent of the crisis, the way of doing policy at the Federal Reserve has undergone major transformations.[5] Nowadays, we can classify the tools employed by the Federal Reserve under four main categories: the first two are *interest rate policies* while the third and fourth instruments are *balance-sheet policies*. Some of these measures have been switched off as the 2008 crisis was fading away, but they might be restored in case of a new crisis event.

Open Market Operations (OMO) This is the standard (pre-crisis) method of doing monetary policy via acquisitions and sales of securities to control interest rates and in turn to affect investment and consumption. These operations can be either permanent or transitory: the first accommodate the longer-term factors driving the expansion of the Federal Reserve's balance sheet – mainly currency before the crisis and reserves during the crisis; the second aim at addressing reserve needs that are deemed to be transitory in nature and that can easily be fixed by means of REPOs and Reverse REPOs contracts.

Maturity Extension Programme (MEP) These are measures that, by prolonging the maturity of the portfolio of assets held by the central bank, dampens the upward pressure on the long-run interest rates. In particular, the FED during the crisis – by means of two interventions in 2011 and 2012 – sold a total of 667 Billions USD short-term Treasury securities with maturity lower than 3 years and in exchange, used the same amount of money to buy Treasury securities with maturity between 6 and 30 years.

Crisis Response Operations (CRO) When the liquidity trap was reached and the target nominal rate hit the ZLB during the crisis, standard OMO were ineffective for the control of investment and consumption. New methods for the liquidity provisions have therefore been designed by the FED. Among them we can distinguish between liquidity provision to banks and other financial institutions and liquidity provision to borrowers and investors in key credit markets. In the first set of tools there are the Term Auction Facility (TAF), the Term Securities Lending Facility (TSLF) and the Primary Dealer Credit Facility (PDCF), all of which are aimed at increasing short term liquidity in exchange of high-quality collaterals. In the second set there are the Commercial Papers Funding Facility (CPFF), the Money Market Investor Funding Facility (MMIFF) and other instrument aimed at providing funds to professional investors and special purpose vehicles in exchange of eligible collaterals.

Asset Purchase Agreements (APA)[6]. These operations expand the standard OMOs and consist in straight acquisition of assets by means of the central bank. From 2008 onward, the FED had intervened with four large scale asset purchase agreements, beginning to acquire 175 Billion USD of obligations and other 1.25 Trillion USD of guaranteed Mortgage Backed Securities from Freddie Mae and Freddie Mac in the 2008-2010 period. In 2009 it also extended the QE to long-term Treasury securities, buying 300 Billion USD and it increased the acquisition to 600 Billion USD in the 2010-2011 period. Furthermore, starting from the end of 2012 (with the near end of the Maturity Exchange

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[5] This section draws from scattered information available at `https://www.federalreserve.gov`.

[6] This practice has also been more commonly dubbed Quantitative Easing (QE). Here we will use the two terms as perfect substitute.

Programme) the FED started to buy MBS and Treasury securities at a monthly rate of 85 Billion USD each month, until the end of 2014 when all the purchases of new securities have been stopped.[7]

2.2 ECB Policy Tools

Also in the European Union the available monetary policy measures have been largely expanded as a reaction to the prolonged crisis: long-term refining operations as well as asset purchases programmes have indeed been carried out also in the EU. However in the first attempts to respond to the crisis (2009-2012 period) only few resources have been dedicated to unconventional monetary programmes; after 2014 the amount of resources has instead been increased substantially.[8] The first two measures below can be thought as *interest rates policies* while the last one falls into the *balance sheet policies* category.

Open Market Operations (OMO) This is the bulk of the EuroArea monetary policy instruments and consists in buying and selling securities in exchange of weekly (Main Refinancing Operations) or three-months (Longer Term Refinancing Operations) liquidity. Also, institutions can deposit or obtain overnight liquidity at a respectively lower and higher interest rates (Deposit Facility and Marginal Lending Facility). Also, the ECB requires to banks and financial institutions to hold deposits on accounts with their national central bank which compose the minimum required reserves (MRR). All in all, these measures form the interest rate corridor system and allows the ECB to set the short-term interest rates in order to reach the 2% inflation target.

Long Term Refinancing Operations (LTRO) In June 2014 and January 2015, the ECB has introduced two new policy instruments that shall allow to manipulate also long-term interest rates. These two instruments are the *Targeted LTRO* and the *3-years LTRO*. The first has been a measure by which the ECB have guaranteed financing up to 4-years to the banks at particularly favourable conditions and where the amount that banks could have borrowed, was linked to their outstanding loans to non-financial corporations and households. The second was instead an instrument by which the ECB provided a 3-year lending to the financial institutions accepting in exchange also lower-quality collaterals and by by allowing reduced reserves ratios. These measured have allowed the ECB to keep relatively low interest rates during the period from mid-2014 to mid-2016.

Asset Purchase Programmes (APP) Also the ECB have introduced some forms of QE, even if during the very first implementations, the resources dedicated to it have been clearly insufficient for the scope of cleaning the financial institution balance sheets.[9] After March 2015 the ECB have begun a substantial QE plan instead, by which every month acquires on average around 60 Billions Euro of sovereign bonds (in the largest amount), corporate securities, asset backed securities and covered bonds. Figure 3 depicts the evolution of the QE measures implemented by the ECB in the last 2 years and its likely development.

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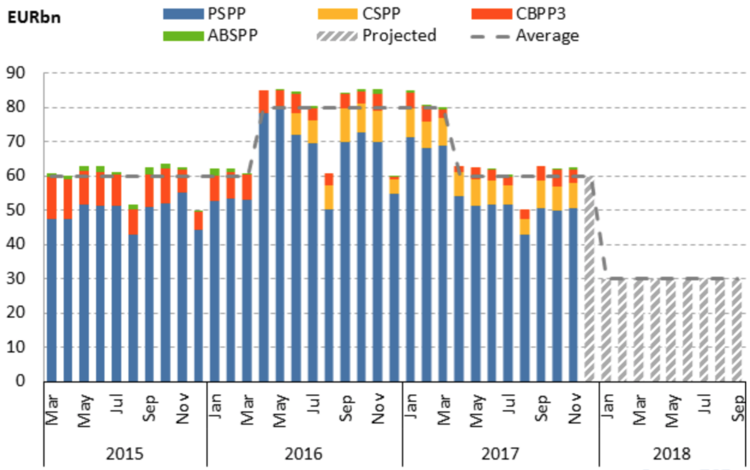
[7] The amount purchased each month have been modestly reduced since the end of 2013.

[8] This section draws from material available at `http://www.ecb.europa.eu/mopo/html/index.en.html`.

[9] The first forms of QE implemented by the BCE have been the 1^{st} and 2^{nd} Covered Bonds Purchase Programmes (CBPP1 and CBPP2) which have been done during the 2009-2010 and the 2011-2012 periods and are not depicted in Figure 3.



Source: ECB.

Figure 3: *Asset Purchase Programme of the ECB.*

2.3 BoE Policy Tools

The bank of England tends to be less informative concerning the monetary policy description. On their official website they distinguish mostly between two types of monetary policy. The BoE classifies its policies the same way as Borio and Zabai (2016) do, distinguishing only between interest rate and balance sheet policies. In particular, from the information available on the website, it seems that the BoE did not perform LTRO or maturity transformation during the crisis.

Interest Rate (IR) This is the standard tool that has been used during the last 30 years to reach the 2% inflation target and consists in an operation performed by the Monetary Policy Committee that sets the Bank interest rate, which represents the reward given to commercial banks for holding deposits at the central bank. The BoE specifies that there is no upper bound, while there is a positive (but small) lower bound for this rate. This type of policy is comparable to the OMO performed by FED and ECB.

Quantitative Easing (QE) This is a tool of recent introduction that shall be used only when the lower bound for the IR policy is hit. QE is set 8 times per years by the Monetary Policy Committee and it aims at boost spending. This policy is comparable to the APA of the FED or the APP of ECB. QE does not require the printing of new money and instead is a digital creation of new money by the purchases of assets from the balance sheet of other agents. The BoE make these purchases from the private sector, for example from pension funds, high-street banks and non-financial firms. But most of these assets are government bonds: indeed the market for government bonds is quite large, meaning that the BoE can buy large quantities of bonds fairly quickly and speed up the intervention. At the moment, the BoE has purchased around 435 Billions of Sterling in government bonds and around 10 Billions of Sterling in corporate bonds.

2.4 BoJ Policy Tools

As it is also clear from Figure 1 the Bank of Japan experienced an increase in the asset size, similar to the one experienced by the FED. This reflect a similar evolution in the portfolio of monetary policy tools. Indeed, apart from the standard OMO, the BoJ incremented the purchases of long-term assets by means of the QQE (Quantitative and Qualitative Easing) that begun in 2013 with the so called "Abenomics" programme. QQE started as a purchase of around 60 Trillions of Yen per year (530 billions USD) but in 2014 the measure has been scaled-up and nowadays the purchase is of around 80 Trillions of Yen per year (700 billions USD).

3 Literature Review

In this section we present the recent empirical and theoretical evidence concerning the effects of the accounting and unconventional monetary policies. Concerning accouning policies most of the studies have been of qualitative or empirical nature. For what concerns the quantitative easing instead, the literature focused either on case studies or on general equilibrium models.

3.1 Accounting Policies

The adoption of different accounting principles have been slowly evolving during the last century moving from a purely historical cost-based approach toward a more financial flows fair-value approach. Indeed, it is only since the 1970s that the mark-to-market accounting practice has become more commonly adopted by banks and financial institutions and only since the 1990s that has become predominant (FASB, 1991).

The motivations that supported such a transition can be found in the economic theory and in particular, in the efficient market hypothesis (EMH) by Fama (1970). According to the EMH indeed, the market price is the best measure of the fundamental economic value of any asset because it correctly aggregates all the private information. Hence, if the EMH holds true, there is a strong justification for a regulator imposing banks and financial institution to report the mark-to-market value of all the assets they are holding in their portfolios.[10] This will provide a more precise economic evaluation of the controlled institution, which can in turn be better regulated (see Heaton et al., 2010).

However, the fair value also has its drawbacks – as reported by Landsman (2006) – which mainly are derived from the empirical literature or from case studies. First of all, it is difficult to estimate the fair value for all the securities whose markets are illiquid and for which traded volumes are relatively low. Second, if the market price is a bad proxy of the underlying fundamental economic value – i.e. in all these occasions where the EMH does not hold true, which are nowadays believed to be more and more frequent – the regulators might take biased regulatory decisions. Third, the mark-to-market suffers some implementation issues, including larger accounting discretion and ability of manipulation than the historical cost-based practice (see Landsman, 2006). Finally, the real effects of the mark-to-market usage might also be heterogeneous due to different regulatory and institutional arrangements (see La Porta et al., 1998).

The empirical literature has also partly investigated whether the fair value might provide some useful information to investors. Barth (1994) finds that the correlation between the reported fair value and the share price has increased over time implying that – under the assumption that price reflects

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[10] However the EMH has been largely been contrasted by theoretical as well as empirical arguments. For a review see Shiller (2003); Lo (2004, 2017).

fundamental – the fair value measurement error has been decreasing. Barth et al. (1995) confirm the previous evidence but find additionally that that fair value evaluation are much more volatile than historical cost-based measures and that the incremental volatility is not reflected in the share price volatility. In general there is therefore evidence for the fair value to have improved its performance as an accurate measure of economic fundamentals over time. But most of the studies confirming such an hypothesis have investigated upon the 1980-1990 period, in which the markets have been fairly liquid and no large financial crisis has been observed. In a more recent work, Bhat et al. (2011) shows that mark-to-market might be uninformative when markets are illiquid and when there are periods of distress.

From the European side instead, a critique to the fair value accounting standard is reported by Bignon et al. (2009) who claim that mark-to-market based accounting generates fundamental problems because (i) the complementarity of assets which possibly generate increasing returns, force the internal accountants to select a specific valuation models with the aim of determining the assets value, however different valuation models might generate large differences in the final price of the assets (reliability problem); (ii) the existence of excessive financial market volatility (i.e. the failure of the EMH), creates additional valuation risks and all in all it possibly reduces the capacity of investments (financial volatility problem). Finally, Boyer (2007) confirms that, by mixing present profit with unrealized capital gains and losses, the mark-to-market accounting generates discrepancies between the creation value and the liquidation value of assets. All in all, according to Boyer (2007) the fair value introduces an accounting accelerator on top of the already present and typical financial accelerator (see Bernanke et al., 1994).

3.2 Unconventional Monetary Policies

To identify causal relations for unconventional monetary policies by means of the commonly available time series approaches it is an extremely difficult task: as a matter of fact most of these "policy shocks" occured in the same period and they typically have been endogenous replies to the global financial crisis more than exogenous marginal changes. It might therefore appear a surprise that, notwithstanding this inner difficulty, most of the research investigating upon the effects of unconventional monetary measures has been carried out via empirical exercises (see Bhattarai and Neely, 2016). However, to cope with the intrinsic difficulties, researches and central bankers working in this domain have been mostly interested into event studies. Most of these works have been focusing on a specific central bank announcement – or intervention – and they have typically employed short-term and high frequency datasets with the aim of evaluating the effects of the policy under investigation on the domestic short- and long-term yields. Using this approach, Krishnamurthy and Vissing-Jorgensen (2011), Gagnon et al. (2011), Christensen and Rudebusch (2012) and Duca (2013) provide a somehow converging evidence, validating the hypothesis that large asset purchases programmes have reduced long-term interest rates, preventing high liquidity premiums from depressing financial institutions and financial markets. Swanson (2017) instead, compares the effects brought about by forward guidance and large-scale asset purchases in the ZLB period (2009-2015) claiming that while the former is more effective in the short-run, the latter is a preferable instrument for the control of medium/long-term yields and for reducing interest rates uncertainty. In a different fashion is instead the work by Altavilla and Giannone (2017), who have instead employed a survey of individual professional forecasters, to evaluate the effects of QE announcements on the expectations of domestic returns, finding that the declarations of accommodative policies affected the expectations of bond yields to drop significantly for at least 1 year. Different in spirit is also the work by Gorodnichenko and Ray (2017), which focuses on the identification of the transmission mechanisms, finding that the main channel trough which the QE operates is market segmentation and that QE is an effective policy tool to modify the interest rate structure during crisis periods, but is likely to be less powerful in normal times.[11] All in all there is quite a support for the evidence that most of the unconventional policies that have been proposed, had a positive effect on financial stability, by reducing both short- and long-term yields as well by increasing the liquidity of the financial system.[12]

What has instead to be better grasped, is whether the unconventional monetary policies had a positive effect also on the real economy. In general, the empirical evidence seem to support the fact that the adopted measures have generated also positive returns for the real economy (see Bhattarai and Neely, 2016). In fact, even if there is yet a lot of uncertainty concerning the size, the empirical consensus on the positive direction of the effects of UMP on output and inflation is more or less established: Kapetanios et al. (2012), Baumeister and Benati (2013) and Gambacorta et al. (2014) employ panel and/or threshold vector autoregressive models to find that a positive increase in inflation (estimates are between 0.5% and 2%) as well as in output (between 0.9% to 3.6%) are generated by the introduction of the unconventional monetary policies adopted. However, possibly due to the difficulty of establishing clean transmission mechanisms, many prominent economists are still doubtful on the claims that this stream of research provides. Borio and Zabai (2016) suggest indeed that there might be a leak in the transmission of the unconventional monetary policy measures from the financial sector to the real sector and that these short-term positive effects might as well vanish in the long-run, when the cost-benefit of the measures deteriorates. Rogoff (2017) claims instead that “many economists are rightly concerned that unconventional monetary policy tools are poor substitutes for conventional interest rate policy and might well have more side-effects”, and implies that there is the possibility that these new tools are only imperfectly capable of managing private demand and in turn inflation and output.[13]

However, the debate concerning the effects of UMP on output and inflation is also reinforced by the presence of theoretical analysis, carried out by means of general equilibrium or agent-based models.

Let us here begin with the results stemming from the large-scale DSGE model that has been formally used at the Federal Reserve for assessing the impact of UMP.[14] Using this model, Chung et al. (2011) have evaluated that the asset purchase program contributed mostly to the reduction of the 10-

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[11] As Gorodnichenko and Ray (2017) put it, with some oversimplifications: “purchases of assets in a particular segment move prices more strongly in that segment”. This is also in line with the findings of Krishnamurthy and Vissing-Jorgensen (2011).

[12] For a critical review of the literature see also Martin and Milas (2012), who claim that only the very first wave of QE succeeded in decreasing the interest rates and that the effects on the real economy are instead in general very mild.

[13] The claim by Rogoff (2017) is however in contrast with the results by Peersman (2011) who finds that the transmission channels of balance sheet policies are similar to those of the standard interest rates policies.

[14] For more information on the baseline FRB/US model see `https://www.federalreserve.gov/econres/us-models-about.htm`.

years treasury yield, to the increase in the core inflation as well as to the decrease in unemployment. Oddly enough, using the same model, Engen et al. (2015) have established that the QE programmes had no effects on output, inflation and unemployment in the initial post-crisis years (i.e. between the 2009 and 2010 period) but have sped up the pace of recovery from 2011 onward; furthermore according to the latter paper (that confirms the results of Altavilla and Giannone (2017)) the most important channel of transmission has been the update in expectations of the private sector that "understood that monetary policy was going to remain more accommodative over a longer period of time". Results similar to those of Engen et al. (2015) have been also obtained in Chen et al. (2012) by means of a medium-scale DSGE model estimated with Bayesian techniques on the US data. The findings confirm that there have been only modest effects of QE on GDP growth and inflation in the short-run, but that output might be mildly be positive affected in the long-run. More recently, Farmer and Zabczyk (2016) have investigated the effects of what they call *Qualitative Easing* – which basically consists in a Maturity Extension Programme – in a general equilibrium model with limited asset market participation. Their findings suggest that such a policy is Pareto-improving as it stabilizes non-fundamental fluctuations in the stock market. Finally, after 10 years of adoption all around the world, a recent paper by Quint and Rabanal (2017) have instead used a DSGE model to investigate on the possibility of using unconventional monetary policy tools also during more tranquil periods and not only during large recessions that hit the ZLB – transforming them *de facto* into "conventional" tools. They find that these instruments can be useful also in normal times only if the economy is affected by shocks with financial origins; they are instead ineffective if in normal times the economy shall only respond to demand or supply shocks.

To our knowledge instead the unique ACE model directly investigating the transmission mechanisms and the effects of QE is the one by Cincotti et al. (2010) that finds that a quantity easing monetary policy coupled with a counter-cyclical fiscal policy provide better macroeconomic performance vis-à-vis a tight fiscal policy and no central bank intervention in the bond market; however they also find that QE might generate higher inflation and might be responsible for a higher variability of output in the long-run. More recently the ABM literature has been focusing on topics close to QE, but without fully investigating on the effects of such a policy. Assenza et al. (2017) for example, have introduced a stylized unconventional monetary policy exercise in their ABM by means of a cash-in-hand policy: this is closer to a "helicopter money" and it has the form of a quasi fiscal policy – the cash provided by the CB immediately increase the asset side of the consumers – rather than to a fully-fledged QE exercise – which instead affects the asset side of the banking industry. Their findings suggest however that the cash-in-hands policy is dominated by a standard Taylor rule interest rate rule. Popoyan et al. (2017) have instead included a comprehensive and detailed macroprudential framework into a larger scale model and have combined the regulatory setups with different conventional monetary policy interest rate rules; findings suggest that a triple-mandate Taylor rule (targeting output-gap, inflation and credit growth) co-ordinated with a Basel III prudential regulation is the best policy mix to improve the stability of the banking sector and smooth output fluctuations but that also a much simpler regulatory framework – composed by minimum capital requirements and counter-cyclical capital buffers – allow to achieve macroeconomic outcomes similar to the first-best. However, van der Hoog and Dawid (2017) find that more stringent capital requirements (which are naturally pro-cyclical) induce larger output fluctuations and lead to deeper and more fragile recessions; in their model, a more stringent liquidity regulation proves to be the best policy for dampening output fluctuations and for preventing severe downturns. van der Hoog (2017) finds also that the introduction of regulatory limits to credit growth by means of a non-risk-weighted capital ratio has only mild effects, while the adoption of strict loan eligibility criteria (such as cutting off funding to all financially unsound firms) has a larger impact and it is better aimed at fostering macro-financial stability. Finally, Schasfoort et al. (2017) have been focusing on the transmission mechanisms of different forms of monetary policy, finding that the interest rates policy might be a blunt tool for the control of inflation.

4 The model

As already anticipated, we build upon the tradition of the "KS agent-based model". In particular with this work we unify the two branches of the model that both departed from the Dosi et al. (2013) version. As a matter of fact in the following versions a bifurcation occurred (see figure 4). On one side Dosi et al. (2015) have embedded into the model a banking sector composed by heterogeneous banks and have employed the model to study the effects of austerity fiscal policies and of interest rate monetary policies; on the other side, Lamperti et al. (2017) appended an energy sector and a climate box to the model in order to study the effects of climate shocks onto the economic system as well as to investigate upon the feedbacks between environment and economy.[15] Here, we unify these two research strands and we introduce new policies exercises. In particular we focus on the effects of balance sheet unconventional monetary policies – Quantitative Easing – and of accounting policies – Mark-to-Market evaluation of banks assets. We do this with three objectives in mind: first, to study and investigate whether the policy prescriptions of Dosi et al. (2015) are still valid when an energy sector and a feedback mechanism between the economic system and the environment are present; second, to introduce new unconventional policies that directly affect the balance sheets of the banking sector (e.g. QE) and to study their relative performances vis-à-vis other policies that bypass the banking system and provide direct monetary incentives for firms to invest and household to consume (e.g. Helicopter Money); third, to draw and test new policy instruments that might improve the environmental resilience (e.g. green-QE), minimizing the probability of climate shocks to negatively affect the economy (this will come about in a follow-up paper).

For the sake of brevity, in what follows we do not describe the full model, which is however included into appendix A, but we focus only on the newly introduced policies and on the modifications of the original version of model that have been necessary to cope with the new policies. In particular, the environmental section, the climate box, the energy sector, the technical change, the investment behaviour of the firms and the consumption behaviour of the households are unchanged. Variations to the credit market, to the balance sheets of the banking sector, to the government behaviour and to the central bank behaviour have instead been necessary and constitute, together with the newly

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[15] Also other two branchings took place, but moving from the Dosi et al. (2010) version of the model. The first involved the study of labour market institutions and labour market policies (see Dosi et al., 2017a); the second involved the enlargement of the model in a multinational dimension, allowing to investigate trade and catching up processes (see Dosi et al., 2017b).

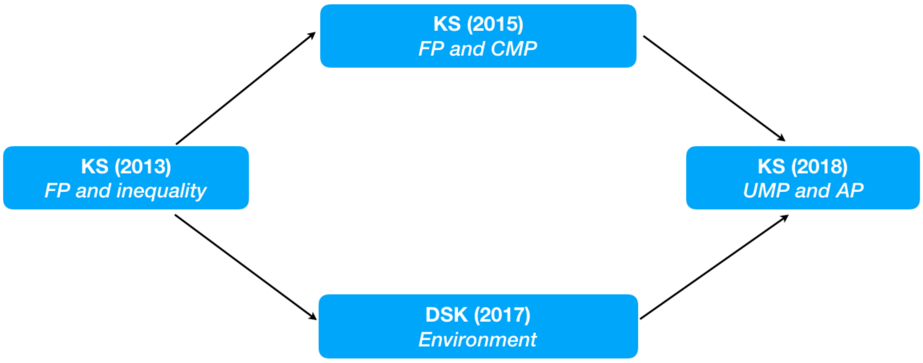

Figure 4: *Evolution of the KS model, for the versions that affect the model here presented.*

implemented policies the contribution of this paper.

4.1 Mark-to-Market accounting

As already mentioned in the introductory section, fair value accounting and historical value accounting are opposite extremes. Indeed, while the former looks at variations in the market value balance sheet to indicate changes in the financial conditions of a bank, the latter looks at the realizations of cash flows to measure changes the financial condition of the financial institution.

Since the FASB (1991) directives, the companies operating in the financial sector, are required to report the fair value of the debt and equity securities that they hold in the asset sides of their balance sheets. However, the usage of the mark-to-market principle implies that banks might be forced to adjust the value of their assets account as soon as some of their direct borrowers default on their loans during the year and even if these borrowers simply become more financially unstable. This is true also for financial institutions holding government debt. If government bonds becomes riskier, so that they cannot be considered as "risk-free assets" – a situation that has occurred during the financial crisis and in the decade that followed it (see Caballero et al., 2017) – and if the mark-to-market accounting principle is operating, the banks shall take the higher likelihood of default of the government into account and accordingly, they shall adjust their asset by depreciating the government bonds they have in their portfolio of assets.

In the previous versions of the model, this evaluation mechanism was absent and the unique mechanism by which the value of the banking sector asset side could have declined, was generated by the bankruptcy of some consumption good firms, then unable to repay their outstanding debt to some specific bank. This new accounting policy is instead an important mechanism for the model, indeed it unleashes a positive feedbacks between the government and the banking sectors: if the government accumulates debt – which we assume is the metric for risk – then the government bonds are revalued downward, because there is an higher chance that the government might go bankrupt. This in turn, decreases the assets side of the banking system, reducing the availability of credit which, might have a negative impact on the ability of producing new private investments. Also the opposite holds true and if the public debt decreases (due to surpluses), bonds are revalued upward and this allows banking industry to produce a larger amount of credit to the consumption good firms.

In particular we here model the mark to market accounting principle as an evaluation standard that the banks adopt when filling and reporting their balance sheets. Such a standard requires that the banks evaluation of the bonds in their portfolio is performed at their current price (market value) rather than at their nominal historical value.

Let's begin from the definition of the bonds market in the model. The variation in the bonds supply is determined by the deficit. Whenever the government spending is larger than government revenues, the government shall issue an amount of bonds equal to the amount of deficit. Quite naturally, as time passes by, the total outstanding amount of bonds is equivalent to the government debt. Hence, for every period we have that:

$$B_t^S = min\left\{G_t - T_t, 0\right\}$$
$$B_t^{Out} = Debt_t$$

The demand for bonds instead derive from the liquidity situation of the banks. In particular, we assume that the banks buy a quota of the total newly issued bonds (i.e. a quota of the deficit) proportionally to their market share. This implies that:

$$B_{h,t}^D = f_{h,t} * B_t^S$$

where $f_{h,t}$ represents the market share bought by the bank h in period t.

Liquidity of the banks is however important and plays a role. To demand such an amount of government bonds indeed, the bank shall be sufficiently liquid and shall hold an equivalent amount of cash to pay for the desired amount of newly issued bonds. Some banks might indeed from time to time be illiquid and will not be able to buy the whole amount of government debt they desire. In this case, a second mechanism that we introduce in this version of the model comes about: the lender of last resort central bank. Here we indeed assume that the the Central Bank intervenes in the primary market for bonds and directly buys the quota of newly issued bonds that is leftover due to the insufficient liquidity of the banking system. Ideally this can be considered as a very mild form of central bank unconventional monetary policy, even if the central bank in such occasions does not affect the balance sheets of the financial institutions.

When the bonds market is closed and the quotas of newly issued bonds have been assigned, government bonds are stored by the banks in the asset side of the balance sheet. From the following period onward, they will be evaluated at their fair value which is determined as follows: we assume that the discount factor by which the assets are reevaluated is a function of the government debt to GDP – the implicit measure of the government solvency – and of the quota of total outstanding bonds hold by the Central Bank – an implicit measure of the illiquidity of the credit market. In formula we then have that. In particular, moving from a fixed baseline interest rate paid on government bonds $r^{bonds} = \bar{r}$, the discount factor will evolve according to:

$$r_t^{mtm} = r^{bonds} + \varpi_1 \frac{Debt}{GDP} + \varpi_2 * \frac{B_{cb}^{out}}{B_t^{out}};$$

where r^{mtm} represents the variable part of the mark-to-market discount factor and, as already anticipated, positively depends on the likelihood of government insolvency and on the illiquidity of the credit market.

Thus at the end of the period, when compiling the balance sheet, the fair value of the government bonds is:

$$B_{h,t}^{mtm} = \frac{B_{h,t}}{1 + r_t^{mtm}}.$$

In section 5 we will report outcomes stemming from the comparison between scenarios in which the mark-to-market accounting principle is used, against scenarios in which historical value is used. In the second case, we will simply set $r_t^{mtm} = 0, \ \forall \ t \in [1, T]$ and hence all the banks will always evaluate bonds at their nominal value $B_{h,t}$ discounted only at the baseline, risk-free, rate r^{bonds}.

4.2 Quantitative Easing

Closely following the description of the implementation of QE by the 4 major central banks (see section 2), in the model we introduce a new policy instrument by which the central bank can directly intervenes on the balance sheets of the financial institutions to dampen the effects of an illiquid credit market.

In the K+S model, the first activity of the banking sector is that of providing credit to the consumption good firms, whose internal financial resources are insufficient for investing into the new (more efficient) machineries provided by the capital good firms as well as for covering production costs. The credit activity endogenously generates a financial cycle (see Dosi et al., 2015). Some firms – due to unsuccessful innovations and competitive losses – might become insolvent and go bankrupt. When this happen, a direct negative effect on the bank with outstanding credit occurs: the loan indeed used to enter into the bank balance sheet as an asset, but when the borrower defaults, this asset loses all its value – and it becomes a bad debt – causing a net loss for the bank, and in turn it negatively affects the ability of the bank to inject new liquidity into the real sector, lowering the bank's credit supply.

While in the previous version of the model the bad debts generated an immediate net loss for the bank, we assume that the QE dampens this situation as the cost is now shared between the bank itself and the Central Bank, which intervenes by injecting cash into the banks balance sheet, and partially contributing to the loss. In particular, we assume that Quantitative Easing takes a very simple linear form:

$$QE_{h,t} = \alpha_{qe} BadDebt_{h,t}$$

where $QE_{h,t}$ is the amount of resources that the central bank injects into the banks h balance sheet to buy a fraction fraction $\alpha_{qe} \in [0, 1]$ of the bank h bad debts. Very intuitively, the parameter α_{qe} represents a fine tuning parameter measuring the QE aggressiveness: the higher α_{qe}, the larger the intervention of the central bank and the lower the effect that a possible bankruptcy might have on the bank h credit supply. In practice, the Central Banks exogenously generates new liquidity, and partially bears the cost of the banks loss. This mechanism might be of particular importance to dampen the credit cycle and to avoid a shortage of credit supply. Indeed, in the K+S model, the credit supply for each bank is positively related to its equity and is instead inversely dependent on the amount of bad debt:

$$TC_{h,t} = \frac{NW_{h,t-1}}{\tau^b(1+\beta BadDebt_{h,t-1})}$$

meaning that a QE intervention, aimed at reducing $BadDebt$ shall support the total credit supply toward the real sector of the economic system.

5 Results

The analysis of the model is performed by means of agent-based MonteCarlo simulations: we run a set of independent simulations to wash away across-simulation variability and to evaluate the statistical significance of our policy claims.[16]

Before moving to the policy exercise, we verify that in the baseline case, the new version of the model is able to replicate all the stylized facts already presented in the previous versions of the model, to which we build upon. In particular, we replicate the full list of stylized facts presented in Dosi et al. (2015); Lamperti et al. (2017). While in table 1 we present some summary statistics under the baseline scenario, the first validation test – i.e. replication of stylized fact – is presented in the appendix B.[17] After having observed the ability of the model of replicating a large list of stylized fact, we proceed with the policy exercises.

The final aim of this paper is that of evaluating different mix of policies. Thanks to the flexibility of the agent-based simulation framework we can compare the model under different policy scenarios. In particular, as anticipated, we are interested into the evaluation of the effects of the Mark-to-Market accounting policy as well as of the Quantitative Easing on the real sector of our simulated economic system. Tables 2 and 3 summarize the results of the policy comparisons, reporting respectively averages and standard deviations – i.e. measuring respectively growth and volatility. The values in the table report, for each variable, the ratio between the average value of a variable in the first scenario (as specified in the "id" column) and the average value of that same variable in the second scenario. We also report the t-statistics and the p-values aiming at statistically test whether the ratio between

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[16] All the results presented below refer to averages across 50 MonteCarlo runs. Since most of the variables under investigation are ergodic (see Guerini and Moneta, 2017), 50 MonteCarlo runs, each composed by 500 time periods (and leading to 25000 observations for each variable) is sufficient to obtain reliable statistics. Between the different scenarios, the unique source of variation is given by the Pseudo Random Number Generator.

[17] We show that the model produces at the macro-level: (i) a self-sustained long-run endogenous growth with (ii) short run business cycles, (iii) fat-tailed GDP growth rates distribution (iv) coherent volatility of GDP, consumption and investment, (v) coherent dynamic auto- and cross-correlations between GDP, consumption and investment, (vi) coherent dynamic cross-correlations of private debt and total deposits with GDP, (vii) coherent dynamic auto- and cross-correlations between private debt and amount of bad debt, (viii) coherent dynamic cross-correlations of GDP and energy demand. At the micro level: (i) right-skewed fat-tailed distribution of firms size in both sectors, (ii) Pareto distribution of large firms in both sectors, (iii) Laplace distribution of the growth rates of firms in both sectors, (iv) non-persistent productivity growth rates of firms in both the sectors.

	variable	MC average	MC std. dev.
1	GDP growth	0.0307	0.0006
2	GDP volatility	0.0378	0.0036
3	Crisis likelihood	0.0438	0.0129
4	Consumption growth	0.0307	0.0006
5	Consumption volatility	0.0236	0.0032
6	Investment growth	0.0303	0.0015
7	Investment volatility	0.4507	0.0535
8	Unemployment level	0.0325	0.0281
9	Full employment likelihood	0.0685	0.0936
10	Private debt growth	0.3384	0.0759
11	Private debt volatility	0.0017	0.0062
12	Energy demand growth	0.0265	0.0020
13	Emissions growth	0.0004	0.0003
14	Emissions in 2100	2.3827	0.1174
15	Temperature anomaly in 2100	3.1615	0.1694

Table 1: *Summary statistics of selected variables in the baseline scenario.*

the two considered scenarios, is significantly different from 1 (the null hypothesis according to which the two compared scenario provide the same results).

5.1 Standalone policies

We begin by comparing the Mark-to-market (MtM) scenario with the baseline (Base) case (ID = 1 in tables 2 and 3). The unique difference in the design of the model between these two scenarios is given by the accounting policy, which impacts only on the balance sheets of the banks, affecting in turn the aggregate credit supply and hence, the real sector. We observe that when the Mark-to-Market is adopted, the growth rates of GDP and consumption are significantly lower and this in turn also generates a higher levels of unemployment, which (via the subsidies that the government shall pay) strongly impact on the public finances, generating much larger deficits and increasing Debt-to-GDP.[18] Similar results are also obtained when the MtM and the Baseline cases are compared under a dual-mandate monetary policy (ID = 6 in the two tables). In such a situation indeed, also the investment growth rate is significantly lower in the MtM scenario vis-à-vis the baseline one. Also concerning the volatility of the system, presented in table 3, we observe that for most of the considered variables the standard deviation is higher in the MTM scenario with respect to the baseline one (see ID = 6 for example). All in all therefore, we conclude that the standalone Mark-to-market accounting policy, is worse off with respect to the historical value accounting practice. Furthermore, the MtM does not even generate a trade-off between growth and volatility: in both the comparisons, the historical value seems to be better-off.

The second standalone comparison that we perform concerns the exploratory evaluation of the proposal of transforming the QE (an unconventional monetary policy tool) into a conventional in-

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[18] The negative sign in front of the Debt-to-GDP value in Row 1 of table 2 (i.e. the -8.45) has to be interpreted as a shift from the government surplus (present on average in the baseline scenario) to a position of government debt (present on average in the Mark-to-Market scenario).

strument for the Central bank to use in its standard operations also in more tranquil periods (see Quint and Rabanal, 2017). The outcomes of our simulation exercise (ID = 2 and ID = 7, respectively for the comparisons in a pure inflation targeting scenario or in a dual mandate scenario) suggest that the QE, adopted into the baseline scenario (in which the government is in surplus and inflation and output growth are relatively stable) makes no harm, but also does not make any better for the system. Average growth rates are statistically indistinguishable as well as volatilities.[19] This absence of statistical difference might be due to the fact that in the baseline scenario the economy does not experience prolonged and severe crises, therefore also the periods of high government deficit are rare and low are the volume of bad debts; as a consequence, both the intervention of the Central Bank in the bonds market as a lender of last resort and the amount of bad debt acquired by the Central banks trough QE operations are relatively weak and scarce, explaining the low impact of the QE policy. Hence, we conclude that there is no need of burdening a central bank with another discretional tool for monetary policy: in tranquil periods, with historical cost accounting, the interest rate monetary policy rules, accompanied by a countercyclical fiscal policy, are sufficient to avoid the generation of large and prolonged crises.

5.2 Composition of policies

The second step for policy analysis is that of evaluating policy combinations. In particular we aim at evaluating the performances of a scenario in which the QE monetary policy is employed together with the MtM accounting policy. We observe that the role for the QE, when accompanied with counter-cyclical fiscal policies, might be substantial. As a matter of fact, we can see (ID = 3 and ID = 8) that when we compare a policy mix embedding the QE policy with the MtM accounting framework with the Baseline one, the differences are small and mostly non statistically significant (only the surplus deteriorates vis-à-vis the baseline case). This implies that the QE is able to offset the negative effects brought about by the MtM accounting policy. The positive effect of the QE, can also be observed (ID = 4, ID = 9) by comparing a policy scenario which includes both QE and MtM against a scenario where there is MtM without unconventional monetary policy. We observe indeed that the growth rates of GDP, consumption and investment are higher that the unity.

The keys to understand and interpret the transmission mechanism that are below this set of results are in the existence of a positive feedback between GDP, private debt and bad debt which are positively correlated at several lags and leads – we document the dynamic cross correlations between these variables in appendix B, in figures 8 and 9. The fair value accounting policy further increases this positive correlation structure indeed: in periods of expansion, the higher GDP and the surplus created by the government decrease the riskiness of government bonds. This in turn increases the value of the bonds which are held as assets in the banks balance sheets, greasing the wheel of credit that flows to the real sector. But a too large availability of credit, also implies that an higher fraction of the loans will become bad-debts because of the failure of some consumption good firms that will then be unable to repay the debt. Without the QE, this in turn reduces the availability of credit and generate recessions. A boom and bust dynamic is endogenously generated by such a transmission

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[19] Only the volatility of inflation slightly improves.

AVERAGES

	ID	GDP growth	Cons. growth	Inv. growth	Unemp.	Inflation	Debt-to-GDP	Large Crises
1	MTM / Base (ratio)	0.93	0.93	0.99	4.32	0.96	-8.45	1.11
1	MTM / Base (t-stat)	-3.31	-3.28	-0.44	2.88	-1.42	-2.34	1.62
1	MTM / Base (p-value)	0.00	0.00	0.67	0.01	0.16	0.02	0.11
2	QE / Base (ratio)	1.00	1.00	1.01	1.17	0.99	0.79	0.98
2	QE / Base (t-stat)	-0.72	-0.89	0.97	2.30	-0.69	-1.52	-0.25
2	QE / Base (p-value)	0.48	0.38	0.34	0.03	0.49	0.13	0.81
3	QE + MTM / Base (ratio)	1.00	0.99	1.00	1.14	0.99	0.64	1.10
3	QE + MTM / Base (t-stat)	-1.41	-1.46	0.07	1.50	-0.30	-2.54	1.25
3	QE + MTM / Base (p-value)	0.16	0.15	0.94	0.14	0.76	0.01	0.22
4	QE + MTM / MTM (ratio)	1.10	1.10	1.01	0.97	1.06	0.76	1.04
4	QE + MTM / MTM (t-stat)	2.89	2.87	0.55	-0.31	1.96	-3.18	0.71
4	QE + MTM / MTM (p-value)	0.01	0.01	0.58	0.76	0.06	0.00	0.48
5	QE + MTM / QE (ratio)	1.00	1.00	0.99	1.04	1.01	1.10	1.26
5	QE + MTM / QE (t-stat)	-0.49	-0.37	-0.90	0.57	0.71	0.70	3.18
5	QE + MTM / QE (p-value)	0.63	0.71	0.37	0.57	0.48	0.49	0.00
6	MTM + DM / Base + DM (ratio)	0.98	0.98	0.98	1.51	1.00	0.50	1.09
6	MTM + DM / Base + DM (t-stat)	-1.87	-1.89	-2.21	1.51	-0.12	-1.15	1.06
6	MTM + DM / Base + DM (p-value)	0.07	0.07	0.03	0.14	0.90	0.25	0.30
7	QE + DM / Base + DM (ratio)	1.00	1.00	0.99	1.06	1.00	0.86	1.10
7	QE + DM / Base + DM (t-stat)	-0.11	-0.09	-0.92	1.16	-0.16	-0.55	1.10
7	QE + DM / Base + DM (p-value)	0.91	0.93	0.36	0.25	0.87	0.59	0.28
8	QE + MTMT + DM / Base + DM (ratio)	1.00	1.00	1.00	1.10	0.99	0.90	1.14
8	QE + MTMT + DM / Base + DM (t-stat)	0.58	0.59	0.32	1.77	-0.66	-0.37	1.35
8	QE + MTMT + DM / Base + DM (p-value)	0.57	0.56	0.75	0.08	0.51	0.72	0.18
9	QE + MTMT + DM / MTM + DM (ratio)	1.02	1.02	1.02	1.04	1.00	1.10	1.13
9	QE + MTMT + DM / MTM + DM (t-stat)	1.97	2.00	2.35	0.74	-0.19	0.87	1.52
9	QE + MTMT + DM / MTM + DM (p-value)	0.05	0.05	0.02	0.46	0.85	0.39	0.13
10	QE + MTMT + DM / QE + DM (ratio)	1.00	1.00	1.02	1.07	0.99	1.18	1.14
10	QE + MTMT + DM / QE + DM (t-stat)	0.86	0.82	1.73	1.60	-0.40	1.46	1.58
10	QE + MTMT + DM / QE + DM (p-value)	0.39	0.41	0.09	0.12	0.69	0.15	0.12

Table 2: *Comparison of different policies. Averages across MonteCarlo. Ratios between the policies named in the "id" column. Base = Baseline (with countercyclical fiscal policy and single mandate monetary policy). MTM = Mark-to-Market accounting policy. QE = Quantitative Easing monetary policy. DM = Dual mandate monetary policy.*

STANDARD DEVIATIONS

	ID	GDP growth	Cons. growth	Inv. growth	Unemp.	Inflation	Debt-to-GDP
1	MTM / Base (ratio)	1.04	1.11	1.02	2.42	1.06	20.60
1	MTM / Base (t-stat)	1.79	2.40	0.81	2.83	2.06	2.88
1	MTM / Base (p-value)	0.38	1.46	1.47	1.30	1.86	2.56
2	QE / Base (ratio)	0.98	1.01	1.00	1.05	0.99	1.20
2	QE / Base (t-stat)	0.08	0.02	0.42	0.01	0.05	0.01
2	QE / Base (p-value)	0.70	0.15	0.15	0.20	0.07	0.01
3	QE + MTM / Base (ratio)	1.00	1.02	1.01	1.05	1.01	1.37
3	QE + MTM / Base (t-stat)	-1.04	0.31	-0.16	1.01	-0.62	1.58
3	QE + MTM / Base (p-value)	1.22	1.53	1.14	0.91	1.90	2.29
4	QE + MTM / MTM (ratio)	0.98	0.96	1.01	0.93	0.97	1.05
4	QE + MTM / Base (t-stat)	0.30	0.76	0.87	0.32	0.54	0.12
4	QE + MTM / Base (p-value)	0.23	0.13	0.26	0.37	0.06	0.03
5	QE + MTM / QE (ratio)	1.03	1.02	1.03	1.02	1.03	1.27
5	QE + MTM / QE (t-stat)	0.22	0.59	0.61	0.67	0.49	1.49
5	QE + MTM / QE (p-value)	0.92	1.89	0.94	2.07	1.70	2.27
6	MTM + DM / Base + DM (ratio)	0.99	1.02	1.01	1.42	1.01	2.52
6	MTM + DM / Base + DM (t-stat)	0.83	0.56	0.54	0.51	0.63	0.14
6	MTM + DM / Base + DM (p-value)	0.36	0.06	0.35	0.04	0.10	0.03
7	QE + DM / Base + DM (ratio)	1.00	1.01	1.02	1.00	1.02	1.16
7	QE + DM / Base + DM (t-stat)	-1.39	-1.31	0.37	-0.98	-1.15	0.36
7	QE + DM / Base + DM (p-value)	-3.40	0.67	-2.98	0.08	-2.97	6.91
8	QE + MTMT + DM / Base + DM (ratio)	1.01	1.04	1.04	1.06	1.05	1.24
8	QE + MTMT + DM / Base + DM (t-stat)	0.17	0.19	0.71	0.33	0.25	0.72
8	QE + MTMT + DM / Base + DM (p-value)	0.00	0.51	0.00	0.94	0.00	0.00
9	QE + MTMT + DM / MTM + DM (ratio)	1.02	1.03	1.03	1.04	1.05	1.25
9	QE + MTMT + DM / MTM + DM (t-stat)	2.01	0.89	1.38	0.29	1.70	1.66
9	QE + MTMT + DM / MTM + DM (p-value)	-6.09	-1.02	-3.99	0.89	-4.71	2.13
10	QE + MTMT + DM / QE + DM (ratio)	1.01	1.04	1.02	1.07	1.04	1.22
10	QE + MTMT + DM / QE + DM (t-stat)	0.05	0.38	0.17	0.77	0.10	0.10
10	QE + MTMT + DM / QE + DM (p-value)	0.00	0.31	0.00	0.38	0.00	0.04

Table 3: *Comparison of different policies. Standard deviations across MonteCarlo. Ratios between the policies named in the "id" column. Base = Baseline (with countercyclical fiscal policy and single mandate monetary policy). MTM = Mark-to-Market accounting policy. QE = Quantitative Easing monetary policy. DM = Dual mandate monetary policy.*

mechanism. The QE instead is an asymmetric measure that introduces a negative feedback between the dynamic cross-correlation between debt and bad-debt: by cleaning the banks balance sheet and removing bad-debts the QE avoids large falls in the credit supply even in recession periods, supporting investments. The QE basically, works as a reflecting barrier that pushes the economic system far from the recessions in a relatively short term.

6 Conclusions

Accounting policies have been largely neglected by the economic literature during the last decades, notwithstanding the important macroeconomic and financial implications that they might have. However, as also happened in the past, large financial and economic crises led to a reconsideration of accounting policies. As a matter of fact, after the advent of the great financial crisis, some economists such as Bignon et al. (2009); Kolasinski (2011) have begun to criticize the status quo of the accounting standards: the fair value or mark-to-market principle. In this paper we carry on such a debate, and we add to the empirical research by investigating by means of a new version of the large scale KS agent-based model (following the lines of Dosi et al., 2010, 2013, 2015; Lamperti et al., 2017) the effects of the mark-to-market policy. Furthermore, since the reply of most central banks to the turmoils of the 2008 crisis have been unconventional, we link the adoption of such accounting standards with the introduction of innovative forms of monetary policies such as the Quantitative Easing.

Fair value accounting is introduced by means of a periodic revision of the evaluation of the balance sheets of the banking industry, which is updated according to the risk of the balance sheet itself. In particular, we introduce a negative correlation between government solvency and liquidity risks and bonds value. Quantitative easing is instead introduced according to a close description of the policies employed by the four major central banks. The central bank in our model indeed acquires low valued assets and non-performing loans from the balance sheets of the banks, cleaning them up and solving at the same time both liquidity and solvency of the banking industry, in turn supporting the credit activity and the degrees of investments. All in all therefore, with this paper we study the macroeconomic and financial outcomes that emerge from the interactions between accounting policies and unconventional monetary policies.

The policy results are in line with the intuitions by Bignon et al. (2009); Heaton et al. (2010) and suggest that the fair value is possibly harmful, largely at odds with the objectives of long-run sustainable growth: by increasing the relationship between loans (hence private debt), GDP and non-performing loans, the mark-to-market accounting practice leads to an higher likelihood of recessions and to lower growth regimes. The QE policy, can counterbalance these negative effects and can restore long-term economic growth: hence it is welcome in a context where the fair-value is the rule. However, QE alone does not perform better-off than a standard interest rate monetary policy, accompanied by counter-cyclical fiscal policy, aimed at supporting the consumption levels of unemployed workers.

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References

Frank Ackerman, Elizabeth A. Stanton, and Ramón Bueno. Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE. *Ecological Economics*, 69(8):1657 – 1665, 2010. ISSN 0921-8009. doi: http://dx.doi.org/10.1016/j.ecolecon.2010.03.013. URL `http://www.sciencedirect.com/science/article/pii/S0921800910001096`.

Tobias Adrian and Hyun Song Shin. Liquidity and leverage. *Journal of Financial Intermediation*, 19(3):418–437, 2010. URL `https://EconPapers.repec.org/RePEc:eee:jfinin:v:19:y:2010:i:3:p:418-437`.

Steffen Ahrens, Joep Lustenhouwer, and Michele Tettamanzi. The stabilizing role of forward guidance: A macro experiment. Annual conference 2017 (vienna): Alternative structures for money and banking, Verein für Socialpolitik / German Economic Association, 2017. URL `https://EconPapers.repec.org/RePEc:zbw:vfsc17:168063`.

Leon Hartwell Allen and Jeffrey S. Amthor. Plant physiological responses to elevated CO2, temperature, air pollution, and UV-B radiation. In G M Woodwell and F T Mackenzie, editors, *Biotic Feedbacks in the Global Climatic System*, pages 51–84. Oxford University Press, New York, 1995.

LH Allen. Plant responses to rising carbon dioxide and potential interactions with air pollutants. *Journal of Environmental Quality*, 19(1):15–34, 1990.

Carlo Altavilla and Domenico Giannone. The effectiveness of non-standard monetary policy measures: Evidence from survey data. *Journal of Applied Econometrics*, 32(5):952–964, 2017. URL `https://EconPapers.repec.org/RePEc:wly:japmet:v:32:y:2017:i:5:p:952-964`.

Joshua Angrist, Oscar Jorda, and Guido Kuersteiner. Semiparametric estimates of monetary policy effects: String theory revisited. Working Paper Series 2013-24, Federal Reserve Bank of San Francisco, 2013. URL `https://EconPapers.repec.org/RePEc:fip:fedfwp:2013-24`.

Quamrul Ashraf, Boris Gershman, and Peter Howitt. How inflation affects macroeconomic performance: An agent-based computational investigation. *Macroeconomic Dynamics*, 20(2):558–581, 2016. doi: 10.1017/S1365100514000303.

Tiziana Assenza, Alberto Cardaci, Domenico Delli Gatti, and Jakob Grazzini. Policy experiments in an agent-based model with credit networks. *Economics - The Open-Access, Open-Assessment E-Journal*, 66, 2017. URL `http://www.economics-ejournal.org/economics/discussionpapers/2017-66`.

Mary Barth. Fair value accounting: Evidence from investment securities and the market valuation of banks. *Accounting Review*, pages 1–25, 1994.

Mary E. Barth, Wayne R. Landsman, and James M. Wahlen. Fair value accounting: Effects on banks' earnings volatility, regulatory capital, and value of contractual cash flows. *Journal of Banking and Finance*, 19(3-4):577–605, 1995.

Christiane Baumeister and Luca Benati. Unconventional monetary policy and the great recession: Estimating the macroeconomic effects of a spread compression at the zero lower bound. *International Journal of Central Banking*, 9(2):165–212, 2013. URL `https://EconPapers.repec.org/RePEc:ijc:ijcjou:y:2013:q:2:a:9`.

Loïc Berger, Johannes Emmerling, and Massimo Tavoni. Managing catastrophic climate risks under model uncertainty aversion. *Management Science*, 2016. doi: 10.1287/mnsc.2015.2365. URL `http://dx.doi.org/10.1287/mnsc.2015.2365`.

Ben Bernanke, Mark Gertler, and Simon Gilchrist. The financial accelerator and the flight to quality. Technical report, National Bureau of Economic Research, 1994.

Gauri Bhat, Richard Frankel, and Xiumin Martin. Panacea, pandora's box, or placebo: Feedback in bank mortgage-backed security holdings and fair value accounting. *Journal of Accounting and Economics*, 52(2):153 – 173, 2011. ISSN 0165-4101. doi: https://doi.org/10.1016/j.jacceco.2011.06.002. URL `http://www.sciencedirect.com/science/article/pii/S0165410111000498`.

Saroj Bhattarai and Christopher Neely. A survey of the empirical literature on U.S. unconventional monetary policy. Working Papers 2016-21, Federal Reserve Bank of St. Louis, 2016. URL `https://EconPapers.repec.org/RePEc:fip:fedlwp:2016-021`.

Vincent Bignon, Yuri Biondi, and Xavier Ragot. An economic analysis of fair value: Accounting as a vector of crisis. *Available on SSRN*, 2009.

Alessandra Boca, Marzio Galeotti, Charles P Himmelberg, and Paola Rota. Investment and time to plan and build: A comparison of structures vs. equipment in a panel of Italian firms. *Journal of the European Economic Association*, 6(4): 864–889, 2008.

Claudio Borio and Anna Zabai. Unconventional monetary policies: a re-appraisal. BIS Working Papers 570, Bank for International Settlements, 2016. URL `https://EconPapers.repec.org/RePEc:bis:biswps:570`.

Robert Boyer. Assessing the impact of fair value upon financial crises. *Socio-economic review*, 5(4):779–807, 2007.

Markus K. Brunnermeier and Lasse Heje Pedersen. Market liquidity and funding liquidity. *The Review of Financial Studies*, 22(6):2201–2238, 2009. doi: 10.1093/rfs/hhn098. URL `http://dx.doi.org/10.1093/rfs/hhn098`.

Ricardo Caballero, Emmanuel Farhi, and Pierre-Olivier Gourinchas. The safe assets shortage conundrum. *Journal of Economic Perspectives*, 31(3):29–46, 2017. URL `https://EconPapers.repec.org/RePEc:aea:jecper:v:31:y:2017:i:3:p:29-46`.

Massimiliano Caporin and Fulvio Fontini. The long-run oil–natural gas price relationship and the shale gas revolution. *Energy Economics*, forthcoming, 2016. ISSN 0140-9883. doi: http://dx.doi.org/10.1016/j.eneco.2016.07.024. URL `http://www.sciencedirect.com/science/article/pii/S0140988316301967`.

Tamma A Carleton and Solomon M Hsiang. Social and economic impacts of climate. *Science*, 353(6304):aad9837, 2016.

Richard E Caves. Industrial organization and new findings on the turnover and mobility of firms. *Journal of economic literature*, 36(4):1947–1982, 1998.

Han Chen, Vasco Cúrdia, and Andrea Ferrero. The macroeconomic effects of large-scale asset purchase programmes. *Economic Journal*, 122(564):F289–F315, 2012. URL `https://EconPapers.repec.org/RePEc:ecj:econjl:v:122:y:2012:i:564:p:f289-f315`.

Jyh-Min Chiang, Louts R. Iverson, Anantha Prasad, and Kim J. Brown. Effects of climate change and shifts in forest composition on forest net primary production. *Journal of Integrative Plant Biology*, 50(11):1426–1439, 2008. ISSN 1744-7909. doi: 10.1111/j.1744-7909.2008.00749.x. URL `http://dx.doi.org/10.1111/j.1744-7909.2008.00749.x`.

Jens Christensen and Glenn Rudebusch. The response of interest rates to us and uk quantitative easing. *Economic Journal*, 122(564):F385–F414, 2012. URL `https://EconPapers.repec.org/RePEc:ecj:econjl:v:122:y:2012:i:564:p:f385-f414`.

Hess Chung, Jean-Philippe Laforte, David L. Reifschneider, and John Williams. Estimating the macroeconomic effects of the fed's asset purchases. *FRBSF Economic Letter*, (jan31):03, 2011. URL `https://EconPapers.repec.org/RePEc:fip:fedfel:y:2011:i:jan31:n:2011-03`.

Silvano Cincotti, Marco Raberto, and Andrea Teglio. Credit money and macroeconomic instability in the agent-based model and simulator Eurace. *Economics - The Open-Access, Open-Assessment E-Journal*, 4:1–32, 2010. URL `https://EconPapers.repec.org/RePEc:zbw:ifweej:201026`.

Juan-Carlos Ciscar, Ana Iglesias, Luc Feyen, László Szabó, Denise Van Regemorter, Bas Amelung, Robert Nicholls, Paul Watkiss, Ole B. Christensen, Rutger Dankers, Luis Garrote, Clare M. Goodess, Alistair Hunt, Alvaro Moreno, Julie Richards, and Antonio Soria. Physical and economic consequences of climate change in europe. *Proceedings of the National Academy of Sciences*, 108(7):2678–2683, 2011. doi: 10.1073/pnas.1011612108. URL `http://www.pnas.org/content/108/7/2678.abstract`.

Juan-Carlos Ciscar, Bert Saveyn, and D. Van Regemorter. Economic modelling of climate impacts: a partial review. *Review of Business and Economic Literature*, 57(2):144–157, 2012. URL `http://EconPapers.repec.org/RePEc:sen:rebelj:v:57:i:2:y:2012:p:144-157`.

Peter M. Cox, Richard A. Betts, Chris D. Jones, Steven A. Spall, and Ian J. Totterdell. *Nature*.

Melissa Dell, Benjamin F Jones, and Benjamin A Olken. What do we learn from the weather? the new climate–economy literature. *Journal of Economic Literature*, 52(3):740–798, 2014.

G. Dosi, M.C. Pereira, A. Roventini, and M.E. Virgillito. When more flexibility yields more fragility: The microfoundations of Keynesian aggregate unemployment. *Journal of Economic Dynamics and Control*, 81(C):162–186, 2017a. URL `https://ideas.repec.org/a/eee/dyncon/v81y2017icp162-186.html`.

Giovanni Dosi. Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, 26(3):1120–1171, 1988. ISSN 00220515. URL `http://www.jstor.org/stable/2726526`.

Giovanni Dosi, Giorgio Fagiolo, and Andrea Roventini. Schumpeter meeting keynes: A policy-friendly model of endogenous growth and business cycles. *Journal of Economic Dynamics and Control*, 34:1748 – 1767, 2010. ISSN 0165-1889. doi: https://doi.org/10.1016/j.jedc.2010.06.018.

Giovanni Dosi, Giorgio Fagiolo, Mauro Napoletano, and Andrea Roventini. Income distribution, credit and fiscal policies in an agent-based keynesian model. *Journal of Economic Dynamics and Control*, 37:1598 – 1625, 2013. ISSN 0165-1889. doi: https://doi.org/10.1016/j.jedc.2012.11.008.

Giovanni Dosi, Giorgio Fagiolo, Mauro Napoletano, Andrea Roventini, and Tania Treibich. Fiscal and monetary policies in complex evolving economies. *Journal of Economic Dynamics and Control*, 52:166 – 189, 2015. ISSN 0165-1889. doi: https://doi.org/10.1016/j.jedc.2014.11.014.

Giovanni Dosi, Andrea Roventini, and Emanuele Russo. Endogenous growth and global divergence in a multi-country agent-based model. LEM Papers Series 2017/32, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy, 2017b. URL `https://ideas.repec.org/p/ssa/lemwps/2017-32.html`.

John Duca. Did the commercial paper funding facility prevent a great depression style money market meltdown? *Journal of Financial Stability*, 9(4):747–758, 2013. URL `https://EconPapers.repec.org/RePEc:eee:finsta:v:9:y:2013:i:4:p:747-758`.

Torsten Ehlers. The effectiveness of the federal reserve's maturity extension program - operation twist 2: the portfolio rebalancing channel and public debt management. In Bank for International Settlements, editor, *Threat of fiscal dominance?*, volume 65, pages 245–255. Bank for International Settlements, 2012. URL `https://EconPapers.repec.org/RePEc:bis:bisbpc:65-14`.

Robert Eisner. Components of capital expenditures: Replacement and modernization versus expansion. *The Review of Economics and Statistics*, pages 297–305, 1972.

Eric M. Engen, Thomas Laubach, and David L. Reifschneider. The macroeconomic effects of the federal reserve's unconventional monetary policies. Finance and Economics Discussion Series 2015-5, Board of Governors of the Federal Reserve System (U.S.), 2015. URL `https://EconPapers.repec.org/RePEc:fip:fedgfe:2015-05`.

Natalia Fabra and Juan Toro. Price wars and collusion in the spanish electricity market. *International Journal of Industrial Organization*, 23(3–4):155 – 181, 2005. ISSN 0167-7187. doi: http://dx.doi.org/10.1016/j.ijindorg.2005.01.004. URL `http://www.sciencedirect.com/science/article/pii/S0167718705000123`.

Eugene F Fama. Efficient capital markets: A review of theory and empirical work. *The journal of Finance*, 25(2):383–417, 1970.

Roger Farmer and Pawel Zabczyk. The theory of unconventional monetary policy. CEPR Discussion Papers 11196, C.E.P.R. Discussion Papers, 2016. URL https://EconPapers.repec.org/RePEc:cpr:ceprdp:11196.

FASB. Disclosures about fair value of financial instruments, statement of financial accounting standards no. 107. Technical report, Financial Accounting Standards Board, Norwalk, Connecticut., 1991.

Martin S Feldstein and David K Foot. The other half of gross investment: Replacement and modernization expenditures. *The Review of Economics Statistic*, pages 49–58, 1971.

Inez Fung. Models of oceanic and terrestrial sinks of anthropogenic CO2: A review of the contemporary carbon cycle. In RonaldS. Oremland, editor, *Biogeochemistry of Global Change*, pages 166–189. Springer US, 1993. ISBN 978-1-4613-6215-9. doi: 10.1007/978-1-4615-2812-8-9. URL http://dx.doi.org/10.1007/978-1-4615-2812-8-9.

Joseph Gagnon, Matthew Raskin, Julie Remache, and Brian P. Sack. Large-scale asset purchases by the federal reserve: did they work? *Economic Policy Review*, (May):41–59, 2011. URL https://EconPapers.repec.org/RePEc:fip:fednep:y:2011:i:may:p:41-59:n:v.17no.1.

Gabriele Galati and Richhild Moessner. Macroprudential policy – a literature review. *Journal of Economic Surveys*, 27(5): 846–878, 2013. doi: 10.1111/j.1467-6419.2012.00729.x.

Jordi Galí. *Monetary policy, inflation, and the business cycle: an introduction to the new Keynesian framework and its applications*. Princeton University Press, 2015.

Leonardo Gambacorta, Boris Hofmann, and Gert Peersman. The effectiveness of unconventional monetary policy at the zero lower bound: A cross-country analysis. *Journal of Money, Credit and Banking*, 46(4):615–642, 2014. URL https://EconPapers.repec.org/RePEc:wly:jmoncb:v:46:y:2014:i:4:p:615-642.

Domenico Delli Gatti, Mauro Gallegati, Bruce Greenwald, Alberto Russo, and Joseph E. Stiglitz. The financial accelerator in an evolving credit network. *Journal of Economic Dynamics and Control*, 34(9):1627 – 1650, 2010. ISSN 0165-1889. doi: https://doi.org/10.1016/j.jedc.2010.06.019. URL http://www.sciencedirect.com/science/article/pii/S0165188910001491. Computational perspectives in economics and finance: Methods,dynamic analysis and policy modeling.

Michael D. Gerst, Richard B. Howarth, and Mark E. Borsuk. Accounting for the risk of extreme outcomes in an integrated assessment of climate change. *Energy Policy*, 38(8):4540 – 4548, 2010. ISSN 0301-4215. doi: http://dx.doi.org/10.1016/j.enpol.2010.04.008. URL http://www.sciencedirect.com/science/article/pii/S0301421510002818.

Lavoie M. Godley W. *Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth*. Palgrave McMillan, 2007. ISBN 0-230-50055-2,0-230-50055-2,978-0-230-50055-6.

Austan Goolsbee. The business cycle, financial performance, and the retirement of capital goods. *Review of Economic Dynamics*, 1(2):474–496, 1998.

Yuriy Gorodnichenko and Walker Ray. The effects of quantitative easing: Taking a cue from treasury auctions. NBER Working Papers 24122, National Bureau of Economic Research, Inc, 2017. URL https://EconPapers.repec.org/RePEc:nbr:nberwo:24122.

J. Goudriaan and P. Ketner. A simulation study for the global carbon cycle, including man's impact on the biosphere. *Climatic Change*, 6(2):167–192, 1984. ISSN 0165-0009. doi: 10.1007/BF00144611. URL http://dx.doi.org/10.1007/BF00144611.

Bruce C. Greenwald and Joseph E. Stiglitz. Financial market imperfections and business cycles. *The Quarterly Journal of Economics*, 108(1):77–114, 1993. ISSN 00335533, 15314650. URL http://www.jstor.org/stable/2118496.

Mattia Guerini and Alessio Moneta. A method for agent-based models validation. *Journal of Economic Dynamics and Control*, 82(C):125–141, 2017. ISSN 0165-1889. doi: https://doi.org/10.1016/j.jedc.2017.06.001. URL http://www.sciencedirect.com/science/article/pii/S0165188917301367.

Mattia Guerini, Francesco Lamperti, and Andrea Mazzocchetti. Unconventional monetary policy: Between the past and future of monetary economics. *European Journal of Economics and Economic Policy: Intervention*, 2018.

Stéphane Hallegatte and Michael Ghil. Endogenous Business Cycles and the Economic Response to Exogenous Shocks. Working Papers 2007.20, Fondazione Eni Enrico Mattei, 2007. URL `https://ideas.repec.org/p/fem/femwpa/2007.20.html`.

D Harvey, J Gregory, M Hoffert, A Jain, M Lal, R Leemans, S Raper, T Wigley, and J De Wolde. An introduction to simple climate models used in the IPCC Second Assessment Report, 1997.

John C. Heaton, Deborah Lucas, and Robert L. McDonald. Is mark-to-market accounting destabilizing? analysis and implications for policy. *Journal of Monetary Economics*, 57(1):64 – 75, 2010. doi: https://doi.org/10.1016/j.jmoneco.2009.11.005.

Solomon Hsiang, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, DJ Rasmussen, Robert Muir-Wood, Paul Wilson, Michael Oppenheimer, et al. Estimating economic damage from climate change in the united states. *Science*, 356(6345):1362–1369, 2017.

IPCC. *Climate change 2001: the scientific basis*. Cambridge University Press, Cambridge (UK), 2001.

IPCC. *Climate change 2007-the physical science basis: Working Group I contribution to the Fourth Assessment Report of the IPCC*, volume 4. Cambridge University Press, Cambridge (UK) and New York (US), 2007a.

IPCC. Climate change 2007: synthesis report. In R.K. Pachauri and A. Reisinger, editors, *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva (Switzerland), 2007b.

IPCC. *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*. Cambridge University Press, New York (US), 2012.

George Kapetanios, Haroon Mumtaz, Ibrahim Stevens, and Konstantinos Theodoridis. Assessing the economy-wide effects of quantitative easing. *Economic Journal*, 122(564):F316–F347, 2012. URL `https://EconPapers.repec.org/RePEc:ecj:econjl:v:122:y:2012:i:564:p:f316-f347`.

Richard W. Katz and Barbara G. Brown. Extreme events in a changing climate: Variability is more important than averages. *Climatic Change*, 21(3):289–302, 1992. ISSN 0165-0009. doi: 10.1007/BF00139728. URL `http://dx.doi.org/10.1007/BF00139728`.

Nobuhiro Kiyotaki and John Moore. Credit cycles. *Journal of Political Economy*, 105(2):211–248, 1997.

Adam C. Kolasinski. Mark-to-market regulatory accounting when securities markets are stressed: Lessons from the financial crisis of 2007–2009. *Journal of Accounting and Economics*, 52(2):174 – 177, 2011. ISSN 0165-4101. doi: https://doi.org/10.1016/j.jacceco.2011.07.002. URL `http://www.sciencedirect.com/science/article/pii/S0165410111000565`.

Arvind Krishnamurthy and Annette Vissing-Jorgensen. The effects of quantitative easing on interest rates: Channels and implications for policy. *Brookings Papers on Economic Activity*, 42(2 (Fall)):215–287, 2011. URL `https://EconPapers.repec.org/RePEc:bin:bpeajo:v:42:y:2011:i:2011-02:p:215-287`.

Rafael La Porta, Florencio Lopez-de-Silanes, Andrei Shleifer, and Robert Vishny. Law and finance. *Journal of Political Economy*, 106(6):1113–1155, 1998. ISSN 00223808, 1537534X.

Francesco Lamperti, Giovanni Dosi, Mauro Napoletano, Andrea Roventini, and Alessandro Sapio. Faraway, so close: Coupled climate and economic dynamics in an agent-based integrated assessment model. Technical Report 12, LEM Working Paper Series, 2017.

Wayne Landsman. Fair value accounting for financial instruments: some implications for bank regulation. *BIS Proceedings*, 2006.

Andrew W Lo. The adaptive markets hypothesis: Market efficiency from an evolutionary perspective. 2004.

Andrew W Lo. *Adaptive markets: Financial evolution at the speed of thought*. Princeton University Press, 2017.

Christopher Martin and Costas Milas. Quantitative easing: a sceptical survey. *Oxford Review of Economic Policy*, 28(4): 750–764, 2012. URL `https://EconPapers.repec.org/RePEc:oup:oxford:v:28:y:2012:i:4:p:750-764`.

H Damon Matthews. Implications of CO2 fertilization for future climate change in a coupled climate–carbon model. *Global Change Biology*, 13(5):1068–1078, 2007.

W. D. Nordhaus. An optimal transition path for controlling greenhouse gases. *Science*, 258(5086):1315–1319, 1992. doi: 10.1126/science.258.5086.1315. URL `http://www.sciencemag.org/content/258/5086/1315.abstract`.

William D Nordhaus. *A question of balance: economic modeling of global warming*. Yale University Press New Haven, 2008.

Hans Oeschger, Ulrich Siegenthaler, Ulrich Schotterer, and A Gugelmann. A box diffusion model to study the carbon dioxide exchange in nature. *Tellus*, 27(2):168–192, 1975.

Gert Peersman. Macroeconomic effects of unconventional monetary policy in the euro area. CESifo Working Paper Series 3589, CESifo Group Munich, 2011. URL `https://EconPapers.repec.org/RePEc:ces:ceswps:_3589`.

Edmund S Phelps and Sidney G Winter. Optimal price policy under atomistic competition. In *Microeconomic foundations of employment and inflation theory*, pages 309–337. New York: WW Norton, 1970.

Robert S. Pindyck. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management*, 63(3):289 – 303, 2012. ISSN 0095-0696. doi: http://dx.doi.org/10.1016/j.jeem.2011.12.001. URL `http://www.sciencedirect.com/science/article/pii/S0095069611001598`.

Robert S. Pindyck. Climate change policy: What do the models tell us? *Journal of Economic Literature*, 51(3):860–72, September 2013. URL `http://ideas.repec.org/a/aea/jeclit/v51y2013i3p860-72.html`.

Lilit Popoyan, Mauro Napoletano, and Andrea Roventini. Taming macroeconomic instability: Monetary and macro-prudential policy interactions in an agent-based model. *Journal of Economic Behavior & Organization*, 134(C):117–140, 2017. doi: 10.1016/j.jebo.2016.12.01.

Dominic Quint and Pau Rabanal. Should unconventional monetary policies become conventional? Discussion Papers 28/2017, Deutsche Bundesbank, 2017. URL `https://EconPapers.repec.org/RePEc:zbw:bubdps:282017`.

MICHAEL Renton, NANCY Shackelford, and RACHEL J. Standish. How will climate variability interact with long-term climate change to affect the persistence of plant species in fragmented landscapes? *Environmental Conservation*, 41: 110–121, 6 2014. ISSN 1469-4387. doi: 10.1017/S0376892913000490.

ROGER Revelle and HANS E. Suess. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO2 during the past decades. *Tellus*, 9(1):18–27, 1957. ISSN 2153-3490. doi: 10.1111/j.2153-3490.1957.tb01849.x. URL `http://dx.doi.org/10.1111/j.2153-3490.1957.tb01849.x`.

Richard L Revesz, Peter H Howard, Kenneth Arrow, Lawrence H Goulder, Robert E Kopp, Michael A Livermore, Michael Oppenheimer, and Thomas Sterner. Global warming: Improve economic models of climate change. *Nature*, 508(7495): 173–175, 2014.

Alexander Rodnyansky and Olivier M. Darmouni. The effects of quantitative easing on bank lending behavior. *The Review of Financial Studies*, 30(11):3858–3887, 2017. doi: 10.1093/rfs/hhx063.

Kenneth Rogoff. Dealing with monetary paralysis at the zero bound. *Journal of Economic Perspectives*, 31(3):47–66, 2017. URL `https://EconPapers.repec.org/RePEc:aea:jecper:v:31:y:2017:i:3:p:47-66`.

Julio J Rotemberg. Behavioral aspects of price setting, and their policy implications. Technical report, National Bureau of Economic Research, 2008.

Jan Rotmans. *IMAGE: An Integrated Model to Assess the Greenhouse Effect*, volume 1. Springer Science & Business Media, 1990.

Jorge L. Sarmiento, Tertia M. C. Hughes, Ronald J. Stouffer, and Syukuro Manabe. *Nature*.

Joeri Schasfoort, Antoine Godin, Dirk Bezemer, Alessandro Caiani, and Stephen Kinsella. Monetary policy transmission in a macroeconomic agent-based model. *Advances in Complex Systems (ACS)*, 20(08):1–35, 2017.

Stephen H Schneider and Starley L Thompson. Atmospheric CO2 and climate: importance of the transient response. *Journal of Geophysical Research: Oceans (1978–2012)*, 86(C4):3135–3147, 1981.

SEC. Report and recommendations pursuant to section 133 of the emergency economic stabilization act of 2008: study on mark-to-market accounting. Technical report, United States Securities and Exchange Commission, 2008.

Gaius R. Shaver, Josep Canadell, F. S. Chapin, Jessica Gurevitch, John Harte, Greg Henry, Phil Ineson, Sven Jonasson, Jerry Melillo, Louis Pitelka, and Lindsey Rustad. Global warming and terrestrial ecosystems: A conceptual framework for analysis. *BioScience*, 50(10):871–882, 2000. doi: 10.1641/0006-3568(2000)050[0871:GWATEA]2.0.CO;2. URL `http://bioscience.oxfordjournals.org/content/50/10/871.short`.

Robert J Shiller. From efficient markets theory to behavioral finance. *Journal of economic perspectives*, 17(1):83–104, 2003.

John Sterman, Thomas Fiddaman, Travis Franck, Andrew Jones, Stephanie McCauley, Philip Rice, Elizabeth Sawin, and Lori Siegel. Climate interactive: the c-roads climate policy model. *System Dynamics Review*, 28(3):295–305, 2012.

John D Sterman, Thomas Fiddaman, Travis Franck, Andrew Jones, Stephanie McCauley, Philip Rice, Elizabeth Sawin, and Lori Siegel. Management flight simulators to support climate negotiations. *Environmental Modelling & Software*, 44: 122–135, 2013.

Joseph E. Stiglitz and Andrew Weiss. Credit rationing in markets with imperfect information. *The American Economic Review*, 71(3):393–410, 1981. ISSN 00028282. URL `http://www.jstor.org/stable/1802787`.

Eric Swanson. Measuring the effects of federal reserve forward guidance and asset purchases on financial markets. NBER Working Papers 23311, National Bureau of Economic Research, Inc, 2017. URL `https://EconPapers.repec.org/RePEc:nbr:nberwo:23311`.

Frank Thomalla, Tom Downing, Erika Spanger-Siegfried, Guoyi Han, and Johan Rockström. Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. *Disasters*, 30(1):39–48, 2006.

Rick Tidball, Joel Bluestein, Nick Rodriguez, and Stu Knoke. Cost and performance assumptions for modeling electricity generation technologies. Technical report, ICF International, Fairfax, VA (United States), 2010.

Richard SJ Tol. Estimates of the damage costs of climate change, part ii. dynamic estimates. *Environmental and Resource Economics*, 21(2):135–160, 2002.

Sander van der Hoog and Herbert Dawid. Bubbles, crashes, and the financial cycle: The impact of banking regulation on deep recessions. *Macroeconomic Dynamics*, page 1–42, 2017. doi: 10.1017/S1365100517000219.

Detlef P van Vuuren, Jason Lowe, Elke Stehfest, Laila Gohar, Andries F Hof, Chris Hope, Rachel Warren, Malte Meinshausen, and Gian-Kasper Plattner. How well do integrated assessment models simulate climate change? *Climatic Change*, 104(2):255–285, 2011.

Sander van der Hoog. The limits to credit growth: Mitigation policies and macroprudential regulations to foster macrofinancial stability and sustainable debt. *Computational Economics*, Jun 2017. doi: 10.1007/s10614-017-9714-4.

Martin L. Weitzman. On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, 91(1):1–19, February 2009.

Martin L. Weitzman. Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy*, 5(2):275–292, 2011. doi: 10.1093/reep/rer006. URL `http://reep.oxfordjournals.org/content/5/2/275.abstract`.

Stan D. Wullschleger, W.M. Post, and A.W. King. On the potential for a CO2 fertilization effect in forests: Estimates of the biotic growth factor based on 58 controlled-exposure studies. *Biotic Feedbacks in the Global Climatic System (eds Woodwell, GM and Mackenzie, FT)*, pages 85–107, 1995.

Maosheng Zhao and Steven W. Running. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, 329(5994):940–943, 2010. doi: 10.1126/science.1192666. URL `http://www.sciencemag.org/content/329/5994/940.abstract`.

A Appendix - DSK model complete description

While in the core of the paper we have specified only the variations introduced in the paper, in this appendix we present the full formal structure of the model as originally developed by Dosi et al. (2010, 2013, 2015); Lamperti et al. (2017).[20]

We begin from the description of the search processes and the determination of production and prices in the *capital-good sector* and to the equations related to the determination of production, investment, prices and profits in the *consumption-good sector*. We then shift our attention toward the *banking sector* and to the determination of credit supply. Then we describe the functioning of the *energy sector* as well as the equations included in the *climate box*. Finally we shortly describe the *co-evolution* and the feedbacks between climate and economy.

A.1 The capital good sector

The economy comprises a capital-good and a consumption-good sector, which are vertically related by investment in machines.

Firms in the capital-good industry produce machine-tools using labour and energy. They innovate and imitate in order to increase both labour productivity and energy efficiency of their machines, as well as to reduce their own production costs. However, innovation and imitation are costly processes and firms need to invest in R&D a fraction of their past sales.

The technology of the machines of vintage τ is captured by their *labour productivity*, *energy efficiency* and *environmental friendliness* and it is represented by a set of six coefficients $(A^k_{i,\tau}, B^k_{i,\tau})$, with $k \in \{L, EE, EF\}$.

Let us start with labor productivity, L: $A^{LP}_{i,\tau}$ stands for the productivity of the capital-good in the consumption-good industry, while $B^{LP}_{i,\tau}$ is the productivity of the production technique needed to manufacture the machine.

The apex EE, instead, refers to energy efficiency: $A^{EE}_{i,\tau}$ represents the output per energy unit obtained by a consumption-good firm using the machine-tool, and $B^{EE}_{i,\tau}$ is the corresponding ratio characterizing the production of the capital-good manufacturer technique. Given the monetary wage, $w(t)$, and the cost of energy, $c^{en}(t)$, the unitary cost of production for capital-good firm i is given by:

$$c^{cap}_i(t) = \frac{w(t)}{B^{LP}_{i,\tau}} + \frac{c^{en}(t)}{B^{EE}_{i,\tau}}. \tag{1}$$

Similarly, the unitary production cost of a consumption-good firm j is:

$$c^{con}_j(t) = \frac{w(t)}{A^{LP}_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}}. \tag{2}$$

Finally, machines and techniques are characterized by their degree of environmental friendliness (identified by the apex EF), which corresponds to the amount of polluting substances they emit in each period for each unit of energy employed throughout the production process. Pollutants can be of different sources and affect the quality of air, water and ground.[21] In this model the dynamics of all GHG emissions are proxied by that of CO_2. This means that we assume that all non-CO_2 emissions can be converted into CO2 emissions at a constant conversion rate. Hence, $A^{EF}_{i,\tau}$ refers to the environmental friendliness of the machine-tool, while $A^{EF}_{i,\tau}$ to that of firm i's production technique.

Firms in the capital-good industry adaptively strive to increase market shares and profits trying to improve their technology via innovation and imitation. They are both costly processes: firms invest in R&D a fraction of their past sales in the attempt to discover new technology or to imitate more advanced competitors. As in Dosi et al. (2010), both innovation and imitation are modeled as two step processes. The first step captures the stochastic nature of technical change and determines whether a firm successfully innovates or imitates through a draw from a Bernoulli distribution, where the (real) amount invested in R&D, that is, ultimately, number of people devoted to search, affects the likelihood of success. The second step determines the size of the technological advance via additional stochastic processes:

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[20] This section strongly draws from the original papers unless significant modifications have been made in order to comply with the new equations presented in section 4.

[21] See the website of the US Environmental Protection Agency (EPA) for additional information about specific pollutants, `http://epa.gov`.

$$
\begin{aligned}
A^k_{i,\tau+1} &= A^k_{i,\tau}(1+\chi^k_{A,i}) \quad \text{for } k = LP, EE && (3)\\
B^k_{i,\tau+1} &= B^k_{i,\tau}(1+\chi^k_{B,i}) \quad \text{for } k = LP, EE, && (4)
\end{aligned}
$$

$$
\begin{aligned}
A^{EF}_{i,\tau+1} &= A^{EF}_{i,\tau}(1-\chi^{EF}_{A,i}) && (5)\\
B^{EF}_{i,\tau+1} &= B^{EF}_{i,\tau}(1-\chi^{EF}_{B,i}), && (6)
\end{aligned}
$$

where $\chi^k_{A,i}$ and $\chi^k_{B,i}$ are independent draws from $Beta(\alpha^k, \beta^k)$ distributions over the supports $[\underline{x}^k, \overline{x}^k]$, respectively for $k \in \{LP, EE, EF\}$. The support of each distribution defines the potential size of the technological opportunity (Dosi, 1988) along the corresponding dimension. Specifically, in case of successful innovation, the new vintage of capital-goods will be characterized by a novel combination of labour productivity, energy-efficiency and environmental friendliness (i.e. amount of pollutants per unit of energy used in the production process, see equations 5 and 6). Finally, successful imitators have the opportunity to copy the technology of the closest competitors in the technological space.[22]

A.2 The consumption good sector

Firms in the consumption-good industry produce a homogeneous good using their stock of machines, energy and labour under constant returns to scale. Their demand comes from the consumption expenditures of workers. The desired level of production Q^d_j depends upon adaptive expectations $D^e_j = f[D_j(t-1), D_j(t-2), ..., D_j(t-h)]$, desired inventories (N^d_j), and the actual stock of inventories (N_j):

$$
Q_j(t)^d = D^e_j(t) + N^d_j(t) - N_j(t), \tag{7}
$$

where $N_j(t) = \iota D^e_j(t),\ \iota \in [0,1]$.

Given the desired level of production firms evaluate their desired capital stock (K^d). Therefore, if the actual capital stock is not sufficient to produce the desired amount, firms invest in order to expand their production capacity.

$$
EI^d_j(t) = K^d_j(t) - K_j(t). \tag{8}
$$

Firms also invest to replace current machines with more technologically advanced ones. In particular, given $\Xi_i(t)$, the set of all vintages of machines owned by firm j at time t, the machine of vintage τ is replaced with a new one if

$$
\frac{p^{new}}{c^{con}_j(t) - c^{new}} = \frac{p^{new}}{\left[\frac{w(t)}{A^{LP}_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}}\right] - c^{new}_j} \leq b \tag{9}
$$

where p^{new} and c^{new} are the price and unitary cost of production associated to the new machine and b is a payback parameter determining firms' "patience" in obtaining net returns on their investments.[23] Gross investment of each firm is the sum of expansion and replacement investments. Aggregate investment just sums over the investments of all consumption good firms.

Labour productivities, energy consumption and emissions in the consumption-good industry evolve according to the technology embedded in the capital stock of each firm. Consumption-good firms choose their capital-good supplier comparing price, productivity, and energy efficiency of the currently manufactured machine tools they are aware of. Indeed, as the capital-good market is characterized by imperfect information, consumption-good firms can directly buy from a subset of machine-tool producers. Machine production is a time-consuming process: consumption-good firms receive the ordered machines at the end of the period. Pricing follows a variable mark up rule.[24]

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[22] The technological space is modeled as a 4-dimensional Euclidean space where ℓ^2 is chosen as the metric determining distance between couples of points. Each point represents a technology.

[23] This is in line with a large body of empirical analyses showing that replacement investment is typically not proportional to the capital stock (e.g. Feldstein and Foot, 1971; Eisner, 1972; Goolsbee, 1998).

[24] These assumptions finds all in line with large bodies of literature; see, e.g., Rotemberg (2008) for details on pricing,

Consumption-good firms must finance their investments as well as their production. In line with a large body of literature (Stiglitz and Weiss, 1981; Greenwald and Stiglitz, 1993) we assume imperfect credit markets. Firms first employ their cash stock, and if the latter does not fully cover total production and investment costs, they borrow external funds from a bank. More precisely, we assume that each firm deposits its net cash flows at the bank and, if it falls short of that, it can get access to an overdraft credit line. The bank sets the maximum amount of credit as a multiple of firms' deposits and it allocates them to borrowers on a pecking-order basis according to the ratio between net worth and sales (see Dosi et al., 2013). [25] Total credit demand by firms can be higher than the maximum supply of credit, in which case credit rationing arises.[26] More details on the relationship between firms and the financial system can be found in the Appendix A.

Firms sets the price of their final good applying a variable mark-up (μ_j) on their unit cost of production:

$$p_j^{con}(t) = c_j^{con}(t)[1 + \mu_j(t)]. \tag{10}$$

The mark-up change over time according to the evolution of firm's market share, f_j (in line with a lot of evolutionary literature and also with "customer market" models originally described by Phelps and Winter, 1970):

$$\mu_j(t) = \mu_j(t-1)\left[1 + v\frac{f_j(t-1) - f_j(t-2)}{f_j(t-2)}\right] \tag{11}$$

with $0 \leq v \leq 1$.

Also the consumption-good market is characterized by imperfect information (see Rotemberg, 2008, for a survey on consumers' imperfect price knowledge). As a consequence, consumers cannot instantaneously switch to the most competitive producer even if the good is homogeneous. In turn, market shares evolve according to a "quasi replicator" dynamics: more competitive firms expand while firms with a relatively lower competitiveness level shrink. The competitiveness of firms depends on price as well as on unfilled demand.

At the end of every period, capital- and consumption-good firms compute their profits, pay taxes, and update their stock of liquid assets. A firm exits the market if its stock of liquid assets is negative or if its market share falls to zero. As the number of firms is fixed over time, each dead firm is replaced by a new entrant.[27]

A.3 The banking sector

In our model, money is endogenous as in Godley W. (2007); in fact, money supply depends on the lending activity of banks. Since we have assumed that firms in the capital-good sector are paid before starting the production of machines, credit is provided only to consumption-good firms. In the banking sector there are commercial banks that gather deposits and provide credit to firms. The number of banks is fixed and is related to the number of firms in the consumption-good sector: $B = F_2/a$ where the positive integer a can be taken as a proxy for the level of competition in the banking market and it is set according to the empirical literature on topologies of credit markets. Bank-firm couples are drawn initially and maintained fixed over time (the relationship holds both for deposits and credit), hence we assume that the firm-bank network is fixed over time. Banks are heterogeneous in their number of clients. Following the empirical evidence on the skewness of the bank size distribution the banks' number of clients is determined by a random draw NL_k from a Pareto distribution defined by the shape parameter $pareto_a$. Therefore, each bank k has a portfolio of clients Cl_k with clients listed as $cl = 1, \ldots, Clk$. In what follows, we first present how total available credit is determined by each bank, and how credit is allocated to each firm. Next, we move to describe the organisation of the credit flow in the economy and the liquidity account of the banks. Finally, we report the management of banking failures.

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imperfect information and behavioural attitudes of consumers and Boca et al. (2008) for presence of gestation lag effects in firms' investments.

[25] Notice that firms' deposits constitute the only "debt" of the bank in the model. Accordingly, the rule for the determination of maximum credit is equivalent to one where the bank sets credit supply in order not to violate a target on the debt-to-asset ratio. See Appendix A and Dosi et al. (2013, 2015) for further details.

[26] Finally, also the firms that are not credit rationed face limits in the utilization of their overdraft credit. The ratio between a firm's debt and its sales cannot exceed a maximum threshold that depends on the firm's past sales. In general we refer the interested reader to Dosi et al. (2013) for additional information on the role of the banking sector and credit supply in influencing model's dynamics.

[27] Furthermore, in line with the empirical literature on firm entry (Caves, 1998), we assume that entrants are on average smaller capital and stock of liquid assets than incumbents.

Banks are heterogeneous in terms of their fundamentals, their client portfolio, as well as their supply of credit, which is a function of their equity ($NW^b_{k,t}$). On the one hand, capital adequacy requirements inspired by Basel-framework rules (see e.g. Gatti et al. (2010); Cincotti et al. (2010); Ashraf et al. (2016)) constrain banks' credit supply. On the other hand, in line with the empirical evidence, banks maintain a buffer over the mandatory level of capital, whose magnitude is strategically altered over the business cycle according to their financial fragility. Following Adrian and Shin (2010), we proxy banks' fragility by the variable $Bda_{k,t}$, defined as the ratio between accumulated bad debt (i.e. loans in default) and bank assets (i.e. sum of the stocks of loans, sovereign bonds and reserves held by the bank). Therefore, given the parameter $\tau \in [0,1]$ (fixed by the regulatory authority) the higher the bad-debt-to-asset ratio, the lower the credit the bank provides to its clients:

$$TC_{k,t} = \frac{NW_{k,t-1}}{\tau^b(1+\beta BadDebt_{k,t-1})}$$

where $\beta > 0$ is a parameter which measures banks' sensitivity to their financial fragility. Credit supply is thus impacted by changes in the banks' balance sheet, which itself is affected by bank profits net of loan losses. This creates a negative feedback loop from loan losses to changes in banks' equity with a reduction in the amount of credit supplied by the lender in the next period. Then each consumption-good firm needing credit applies to its bank for a loan. The banks take their allocation decisions by ranking the applicants in terms of their creditworthiness, defined by the ratio between past net worth ($NW_{j,t-1}$) and past sales ($S_{j,t-1}$). Banks provide credit as long as their supply of credit ($TC_{k,t}$) is not fully distributed. A firm's ability to obtain credit depends therefore on its financial status which determines its ranking, but also on the financial fragility of its bank. It follows that in any period the stock of loans of the bank satisfies the following constraint: $\sum_{cl=1}^{Cl_k} Deb_{cl,k,t} = Loan_{k,t} \leq TC_{k,t}$.

The banks earn profits out of the loans they allocate as well as the sovereign bonds they own. As the firm-bank links are fixed, the interest rates on loans are not used by banks to compete between themselves, but rather to mirror the riskiness of their clients. The interest rate on loans (r_t^{deb}) is computed with a mark-up on the Central Bank interest rate (r_t^{cb}). The latter is fixed by the Central Bank according to a Taylor rule of the form:

$$r_t^{cb} = r^T + \gamma_\pi(\pi_t - \pi^T) + \gamma_U(U_t - U^T), \quad \gamma_\pi > 1, \quad \gamma_U \geq 0$$

where π_t represents current inflation, U_t current unemployment level and variables with apex T are target levels. γ_π and γ_U parameters, measure the aggressiveness of the central bank toward the two targets of low inflation-gap and/or low unemployment-gap. In the benchmark parametrisation, the Central Bank pursues inflation stabilisation only (hence $\gamma_U = 0$). Banks then fix the risk premium paid by their clients depending on their position in the credit ranking. In every period, four credit classes are created by the banks, corresponding to the quartiles in their ranking of clients. Given the base loan rate $r_t^{deb} = (1+\mu^{deb})r_t$, firm j in credit class $q = 1,2,3,4$ pays the interest rates: $r_{j,t}^{deb} = r_t^{deb}(1+(q-1)k_{const})$ where μ^{deb}, k_{const} are scaling parameters. Firms' deposits are rewarded at the rate r_t^D, banks' reserves at the Central Bank yield the reserves rate r^res_t, and sovereign bonds pay an interest rate $r^bonds_t = (1+\mu^{bonds})r_t$, with $\mu^{bonds} \in [-1,0]$. The different interest rates are set so that: $r_t^D \leq r^res_t \leq r^bonds_t \leq r \leq r^deb_t$.

Finally, the profits of the banks are computed as:

$$\Pi^b_{k,t} = \sum_{cl=1}^{Cl_k} r_t^{deb} + r_t^{res}Res_{k,t} + r_t^{bonds}Bonds_{k,t} - r^D Depo_{k,t} - BadDebet_{k,t}.$$

Banks experience a loan losses whenever one of their clients goes bankrupt and exits the market with a positive debt. Banks' profits net of taxes ($Net\Pi^b_{k,t} = (1-tr)\Pi^b_{k,t}$) are then added to their net worth ($NW^b_{k,t}$), which is equal to the difference between assets and liabilities. Banks' assets are composed of their reserves at the Central Bank ($Res_{k,t}$), their stock of sovereign bonds ($Bonds_{k,t}$) and their stock of loans ($Loans_{k,t}$), while firms' deposits ($Depo_{k,t}$) are the only liabilities. Accordingly the net worth of the bank reads: $NW^b_{k,t} = Loans_{k,t} + Res_{k,t} + Bonds_{k,t} - Depo_{k,t} + Net\Pi^b_{k,t}$. Loan losses represent a negative shock to bank profits, which may well become negative. If the net worth of the bank is not sufficient to cover such losses, the bank goes bankrupt. Whenever, a bank fails ($NW^b_{k,t} < 0$), the Government steps in and bails it out providing fresh capital. The cost of the public bail out ($G^{bailout}_{t,k}$) is the difference between the failed bank's equity before and after the public intervention. We assume that the bank's equity after the bailout is a fraction of the smallest incumbent's equity, provided it respects the capital adequacy ratio.

A.4 The public sector

The public sector levies taxes on firm profits and worker wages and pays to unemployed workers a subsidy, which corresponds to a fraction of the current market wage. In particular, we assume that the wage rate is determined by both institutional and market factors; wages are therefore indexed upon inflation gap, average productivity, and unemployment rate

$$\frac{\Delta w_t}{w_{t-1}} = \pi^T + \psi_1(\pi_{t-1} - \pi^T) + \psi_2 \frac{\Delta \bar{AB}_t}{\bar{AB}_{t-1}} - \psi_3 \frac{\Delta U_t}{U_{t-1}}, \tag{12}$$

where $\bar{AB}$ indicates the average productivity in the economy and $\psi_1, \psi_2, \psi_3 > 0$. Unemployed workers receive a public subsidy (w_t^u) which is a fraction of the current wage – i.e. $w_t^u = \varphi w_t$, with $\varphi \in [0, 1]$. The total amount of unemployment subsidies to be paid by the Government is therefore $G_t = w_t^u(L^S - L_t^D)$. We also assume that workers fully consume their income and accordingly, aggregate consumption depends on the income of both employed and unemployed workers: $C_t = w_t L_t^D + G_t$.

The taxes paid by firms and banks on their profits are gathered by the government at the fixed tax rate *tr*. Public expenditures are composed of the cost of the debt, the bank bailout cost and unemployment subsidies. Public deficit is then equal to $Def_t = Debt_t^{cost} + G_t^{bailout} + G_t - Tax_t$. If $Def_t > 0$, the Government has to issue new bonds, which are bought by banks according to their share in the total supply of credit.[28] If the demand for bonds from the Government is higher than what banks are able to buy, the Central Bank steps in and buys the remaining debt, behaving as a lender of last resort. If $Def_t < 0$, the Government uses the surplus to repay its debt. The debt-related expenditures at time *t* are therefore $Debt_t^{cost} = r_t^{bonds} Bonds_{t-1}^{stock}$.

The dynamics generated at the micro-level by decisions of a multiplicity of heterogeneous, adaptive agents and by their interaction mechanisms is the explicit microfoundation of the dynamics for all aggregate variables of interest (e.g. output, investment, and employment). The model satisfies the standard national account identities: the sum of value added of capital- and consumption goods firms equals their aggregate production (in our simplified economy there are no intermediate goods). That in turn coincides with the sum of aggregate consumption, investment and change in inventories (ΔN_t):

$$\sum_{i=1}^{F_1} Q_{i,t} + \sum_{j=1}^{F_2} Q_{j,t} = Y_t = C_t + I_t + \Delta N_t$$

In the benchmark scenario, the tax and unemployment subsidy rates are kept fixed throughout all the simulations. This implies that they act as automatic stabilisers and that the public deficit is free to fluctuate over time. Furthermore, as policy experiments we can study the effect of different fiscal rules, namely the 3%-deficit rule (mirroring the conditions in the European Stability and Growth Pact, SGP) and the debt-reduction rule (mirroring the Fiscal Compact) (see Dosi et al., 2015). With regards to monetary policy besides the benchmark Taylor rule adjusting only to the inflation gap, we implement a dual-mandate (DM) Taylor rule.

The 3%-deficit rule mimicks the SGP. Hence the government should reach a target public deficit equal to $Def_t \leq def_{rule} GDP_{t-1}$ where $def_{rule} = 0.03$ being the maximum value of the deficit to GDP ratio allowed. When the rule is binding, the Government has to reduce the amount of subsidies distributed in the period. In our experiments, we implement two versions of such a rule: the first one corresponds to the original version of the Stability and Growth Path (SGP), while the second one includes its 2005 revision allowing for more flexibility in bad times. More precisely, the fiscal rule is not binding if the output growth rate is negative. We will refer to this second case as the SGP supplemented with an "escape clause" (SGPec).

The debt-reduction rule is instead inspired by the Fiscal Compact (FC). In this case we add to the deficit over GDP ratio limit a debt-reduction rule: if the ratio of public debt on GDP is over the SGP target of 60%, it should be reduced by 1/20 th (5%) of the difference between the current and target levels in every year. If the debt-reduction rule is binding,

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[28] See also the model described in section 4.

the surplus necessary to satisfy it is $Def_t = -0.05(\frac{Debt_{t-1}}{GDP_{t-1}} - 0.6)$. In this case, both the excessive debt (60% of GDP) and excessive deficit (3% of GDP) conditions have to be met, which means that the maximum deficit allowed is the minimum between the one of the 3% rule and the one of the debt reduction rule. As the debt-reduction condition requires a surplus, it will always prevail over the deficit one. Also in this case, if the rule is binding, the amount of unemployment subsidies is reduced accordingly. In the experiments that follows we will consider a Fiscal Compact rule both with (FCec) and without (FC) an "escape clause".

A.5 The energy sector

Energy production is performed by a profit-seeking, vertically-integrated monopolist through power plants embodying *green* and *dirty* technologies.[29]

The energy monopolist produces on demand $D_e(t)$ units of electricity for firms in the capital-good and consumption-good industries (we exclude the possibility of energy blackouts). The profits of the energy producer are equal to:

$$\Pi_e(t) = p_e(t)D_e(t) - PC_e(t) - IC_e(t) - RD_e(t), \tag{13}$$

where $p_e(t)$ is energy price, $PC_e(t)$ is the total cost of generating an amount $D_e(t)$ of energy, $IC_e(t)$ denotes expansion and replacement investments, $RD_e(t)$ is the R&D expenditure. In the next sections, we explain in details the elements in equation 13.

A.5.1 Electricity producing technologies, costs and revenues

The energy firms produce electricity from a portfolio of power plants. The plants are heterogeneous in terms of cost structures, thermal efficiencies and environmental impacts. Green plants convert freely available, renewable sources of energy (such as wind, sunlight, water) into electrical power at a null unit production cost, i.e. $c_{ge}(t) = 0$, and produce no greenhouse gas emissions.[30] We shall assume for simplicity that green plants work at full capacity, hence the quantity of electricity that can be produced through the green technology, $Q_{ge}(t)$, is equal to its capacity $K_{ge}(t)$. Dirty plants burn fossil fuels (e.g. natural gas, coal, oil) through a process characterized by thermal efficiency A^{τ}_{de}, where τ denotes the technology vintage. Hence, the average production cost for a dirty plant of vintage τ is given by

$$c_{de}(\tau, t) = \frac{p_f(t)}{A^{\tau}_{de}} \tag{14}$$

where $p_f(t)$ is the price of fossil fuels, exogenously determined on international markets.[31] The dirty technology leaves a carbon footprint, in that burning fossil fuels yields em^{τ}_{de} emissions per energy unit.

As the electricity production is a highly capital-intensive process, which mainly requires power generation assets and resources, we assume away labour from electricity production. The total production cost depends on which plants are used. As the marginal cost of electricity production of green plants is zero, the monopolist will employ them first and it will switch on the dirty plants only if the green capacity is insufficient to satisfy demand. Even in that case, the cheapest dirty plants will be used first.[32]

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[29] The assumption of monopolistic production may sound questionable in light of the liberalization process at work in the energy markets, but it is worth noting that oligopolistic liberalized electricity markets are prone to tacit collusion rooted in repeated interaction, tall entry barriers, and a relatively high degree of transparency in supply offers (see e.g. Fabra and Toro, 2005).

[30] Naturally, the unit cost of production of green plants and their emissions are higher than zero. However, our simulation results do not substantially change if the unit cost of production and emissions of renewable energy plants are lower than those of fossil-fuel plants.

[31] The markets for fossil fuels are globally integrated and the prices of different fuels are linked, as also shown by the evidence of co-integration of their time series. Recently, the shale gas revolution has blurred this relationship (Caporin and Fontini, 2016). However, in presence of institutional factors, such as prices indexed on baskets of energy goods, we can consider fossil fuels as homogeneous in their impacts on electricity production costs.

[32] Such a merit order rule is based on the actual functioning of the electricity industry. Even before liberalization, the traditional goal of energy systems management was the minimization of system-wide electricity production, transmission, and distribution costs.

Let IM be the set of infra-marginal power plants, whose total production equals demand. If $D_e(t) \leq K_{ge}(t)$, IM only includes green plants and the total production cost is zero. If $D_e(t) > K_{ge}(t)$, the total energy production cost (PC_e) is positive as dirty power plants are activated:

$$PC_e(t) = \sum_{\tau \in IM} g_{de}(\tau, t) c_{de}(\tau, t) A^{\tau}_{de}, \tag{15}$$

where $g_{de}(\tau, t)$ is the absolute frequency of vintage τ plants.

The energy producer adds a fixed markup $\mu_e \geq 0$ on the average cost of the most expensive infra-marginal plant. Hence the selling price reads:

$$p_e(t) = \begin{cases} \mu_e & \text{if } D_e(t) \leq K_{ge}(t) \\ \bar{c}_{de}(\tau, t) + \mu_e & \text{if } D_e(t) > K_{ge}(t) \end{cases}, \tag{16}$$

where $\bar{c}_{de}(\tau, t) = \max_{\tau \in IM} c_{de}(\tau, t)$. Note that according to equation 16, the energy producer gains a positive net revenue on all infra-marginal plants.[33]

A.5.2 Energy plant investment

The energy producing firm needs to replace obsolete plants, as well as to perform expansion investments whenever the current capacity is insufficient to cover demand. New plants are built in house, but the costs of building new green and dirty plants differ. More specifically, we normalize to zero the costs of building new dirty plants, whereas a cost of IC^{τ}_{ge} must be sustained in order to install a new green plant.

The capacity stock $K_e(t)$ is defined as the sum of the capacities of all power plants across technologies (green, dirty) and vintages. As the capacities of individual plants are normalized to one, the capacity stock reads:

$$K_e(t) = \sum_{\tau} g_{de}(\tau, t) + \sum_{\tau} g_{ge}(\tau, t), \tag{17}$$

where $g_{de}(\tau, t)$ denotes the absolute frequency of vintage-τ dirty plants, and $g_{ge}(\tau, t)$ is the same for green plants. Given that green power plants produce at full capacity and dirty plants are characterized by thermal efficiencies A^{τ}_{de}, the maximum production level that can be obtained with the available capacity stock is

$$\overline{Q}_e(t) = \sum_{\tau} g_{de}(\tau, t) A^{\tau}_{de} + \sum_{\tau} g_{ge}(\tau, t). \tag{18}$$

Whenever the maximum electricity production level $\overline{Q}_e(t)$ falls short of the electricity demand $D_e(t)$, the monopolist invests (EI^d_e) to expand the capital stock:

$$EI^d_e(t) = \begin{cases} K^d_e(t) - K_e(t) & \text{if } \overline{Q}_e(t) < D_e(t) \\ 0 & \text{if } \overline{Q}_e(t) \geq D_e(t) \end{cases}. \tag{19}$$

The energy producers employ a payback period routine to choose the technology of its expansion investment. More specifically, the expansion investment involves only new green capacity, whenever the fixed cost of building the cheapest vintage of green plants ($\underline{IC}_{ge}$) is below the discounted production cost of the cheapest dirty plant ($\underline{c}_{de}$):

$$\underline{IC}_{ge} \leq b_e \underline{c}_{de}$$

where b_e is a discount factor, $\underline{IC}_{ge} = \min_{\tau} IC^{\tau}_{ge}$, and $\underline{c}_{de} = \min_{\tau} c^{\tau}_{de}$. If so, the producer builds $EI^d_e(t)$ units of new green capacity and the expansion investment cost amounts to

$$EC_e(t) = \underline{IC}_{ge} EI^d_e(t) \tag{20}$$

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[33] Other empirically observed ways of exploiting market power include withholding relatively cheap plants and causing network congestion. We think that modeling market power through markups captures all these practices. Note also that a monopolistic producer could arbitrarily increase the price beyond any limit, but this usually does not occur as producers fear regulatory intervention, wish to discourage entry, or there is a price cap set by the regulatory agency.

If instead the payback rule is not met, the entire expansion investment consists of the cheapest dirty plants and is undertaken at no cost ($EC_e(t) = 0$). Total costs are obtained from the sum of variable production costs and fixed investment costs. In the baseline configuration of the model, dirty plants are initialized with a 20% cost-advantage with respect to green energy plants, which is broadly consistent with the modelling assumptions suggested in Tidball et al. (2010).

A.5.3 R&D expenditures and outcomes

The energy producer tries to innovate in order to discover new green and dirty technologies. The R&D investment is a fraction $v_e \in (0,1)$ of previous period sales:

$$RD_e(t) = v_e S_e(t-1) \tag{21}$$

The R&D budget is split among green (IN_{ge}) and dirty (IN_{de}) technologies according to the following rule:

$$IN_{ge}(t) = \xi_e RD_e(t) \qquad IN_{de}(t) = (1-\xi_e) RD_e(t),$$

with $\xi_e \in (0,1)$. Given the R&D investment, the innovative search in the green and dirty technological trajectories is successful with probabilities $\theta_{ge}(t)$ and $\theta_{de}(t)$:

$$\theta_{ge}(t) = 1 - e^{-\eta_{ge} IN_{ge}(t)} \qquad \theta_{de}(t) = 1 - e^{-\eta_{de} IN_{de}(t)} \tag{22}$$

with $\eta_{ge} \in (0,1)$, $\eta_{de} \in (0,1)$.

Successful innovation in the green technology reduces the fixed costs, thus encouraging the installment of green plants.[34] Formally, we keep our modeling strategy consistent with the innovation process in the industrial side of the model (section A.1). Installment cost of a new vintage of green plants, IC^{τ}_{ge}, is lowered by a factor $x_{ge} \in (0,1)$ (a random draw from a Beta distribution) with respect to the previous vintage:

$$IC^{\tau}_{ge} = IC^{\tau-1}_{ge} x_{ge} \tag{23}$$

A successful innovation in the dirty technology, instead, works through a better thermal efficiency and the abatement of greenhouse gas emissions. The efficiency and emissions of a new dirty technology (vintage τ) are represented as a pair $(A^{\tau}_{de}, em^{\tau}_{de})$, related to the existing values as follows:

$$A^{\tau}_{de} = A^{\tau-1}_{de}(1 + x^{A}_{de}) \qquad em^{\tau}_{de} = em^{\tau-1}_{de}(1 - x^{em}_{de}) \tag{24}$$

where x^{A}_{de} and x^{em}_{de} are independent random draws from a Beta distribution. Note that the new dirty technology could be, in principle, characterized by higher thermal efficiency but also higher levels of emissions. This is to capture the fact that what we refer as an energy technology in the model corresponds, in the real world, to a complex set of procedures and routines allowing to move from energy resources (e.g. coal) to, basically, electricity. Advances in one aspect (e.g. energy intensity of coal washing), may not come together with advances in the others (e.g. generation of emissions in burning coals).

A.6 The climate box

The climate box links CO_2 emissions with atmospheric carbon concentration and the dynamics of Earth's mean surface temperature. Such relationships are modeled through a core carbon cycle as in Sterman et al. (2012, 2013). The climate box captures the major features of the physical and chemical relations governing climate change, paying particular attention to the feedbacks that might give rise to non-linear dynamics, while avoiding a complex and detailed description of the climatic process. The introduction of such feedbacks, whose importance in accelerating global warming has been largely investigated (Cox et al.), is not a novelty in integrated assessment. however, it constitutes one of the fields where improvements are more advocated to increase the reliability of models. This is why we believe it is important to include them, at

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[34] In real world, the thermal efficiencies of green technologies is far below 100% and there can be efficiency-improving innovations. As higher thermal efficiency allows a faster amortization of the fixed construction cost, we think that our modeling choice yields the same effects (lower fixed construction costs reduce the break-even point) in a more parsimonious setting.

least in a stylized manner (van Vuuren et al., 2011).[35]

A.6.1 The carbon cycle

Our carbon cycle is modelled as a one-dimensional compartment box based on Goudriaan and Ketner (1984) and Oeschger et al. (1975). On the one hand, atmospheric CO_2 is determined in each period by the interplay of anthropogenic emissions, exchanges with the oceans, and natural emissions from the biosphere. On the other hand, CO_2 is removed from the atmosphere as it is dissolved in the oceans and taken up by biomass through net primary production. To simplify, we model the biosphere as an aggregate stock of biomass endowed with a first order kinetics.

Net primary production (NPP), modeled here as the flux of carbon from the atmosphere to biomass, grows logarithmically with the CO_2 stock (Wullschleger et al., 1995) and it is negatively affected by temperature's increase:

$$NPP(t) = NPP(0)\left(1 + \beta_C \log\frac{C_a(t)}{C_a(0)}\right)(1 - \beta_{T_1} T_m(t-1)), \tag{25}$$

where $C_a(t)$ represents the stock of carbon in the atmosphere at time t, T_m is the increase in mean surface temperature from the pre-industrial level (corresponding to $t = 0$), β_C is the strength of the CO_2 fertilization feedback,[36] while β_{T_1} captures the magnitude of the temperature effect on NPP. A negative relationship between NPP and surface temperature is included to account for such an important climate-carbon feedback. Note that in line with recent findings (Zhao and Running, 2010), the second term of equation 25 captures the negative impact of global warming on the biosphere uptake, which gives rise to positive climate-carbon cycle feedbacks (Sterman et al., 2012).[37]

The concentration of carbon in the atmosphere depends also on the structure of exchanges with the oceans. The latter are represented by a two-layer eddy diffusion box which simplifies Oeschger et al. (1975).[38] In particular, it is composed by a 100 meters mixed layer (which constitutes upper oceans) and a deep layer of 3700 meters for an average total depth of 3800 meters. The equilibrium concentration of carbon in the mixed layer (C_m) depends on the atmospheric concentration and the buffering effect in the oceans created by carbonate chemistry:

$$C_m(t) = C_m^*(t)\left[\frac{C_a(t)}{C_a(0)}\right]^{1/\xi(t)} \tag{26}$$

where C_m^* is the reference carbon concentration in the mixed layer, $C_a(t)$ and $C_a(0)$ are respectiviely the concentration of atmospheric carbon at time t and at the initial point of the simulation, and ξ is the buffer (or Revelle) factor.[39]

The Revelle factor is not constant and rises with atmospheric CO_2 (Goudriaan and Ketner, 1984; Rotmans, 1990) implying that the oceans' marginal capacity to uptake carbon diminishes as its concentration in the atmosphere increases:

$$\xi(t) = \xi_0 + \delta \log\left[\frac{C_a(t-1)}{C_a(0)}\right] \tag{27}$$

where ξ_0 is the initial value of the Revelle factor, and $\delta > 0$ expresses the sensitivity of ξ to the relative atmospheric concentration of carbon.

The reference carbon concentration in the mixed layer (C_m^*) is affected by the negative effect of global warming on the seawater solubility of CO_2 (Fung, 1993; Sarmiento et al.), which, in turn accelerates climate change (Cox et al.). As in the

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[35] Our modelling effort give rise to a structure akin to the so-called Simple Climate Models (Harvey et al., 1997, for a review).

[36] The fertilization feedback refers to the phenomenon of increasing biosphere's carbon uptake due to the stimulus that CO_2 atmospheric concentration exerts on vegetation productivity (Allen, 1990; Allen and Amthor, 1995; Matthews, 2007).

[37] The role of warming on the biosphere uptake of carbon is still debated and strongly depends on local conditions (Shaver et al., 2000; Chiang et al., 2008; IPCC, 2001, ch. 3). However, the IPCC (2007a) reports evidences of stronger positive climate-carbon cycle feedbacks than previously thought, which would increase future estimates of CO_2 concentration in the atmosphere.

[38] Our representation of the oceans resembles that in Nordhaus (1992). The eddy diffusion refers to any diffusion process by which substances are mixed in a fluid as a result of a turbulent flow. A simplifying example consists in the diffusion of a dissolved sugar molecule across a coffee cup due to the eddies generated by the movements of the spoon.

[39] The Revelle factor (Revelle and Suess, 1957) expresses the absorption resistance of atmospheric carbon dioxide by the ocean surface layer. The capacity of the ocean waters to take up surplus CO_2 is inversely proportional to its value.

previous case, we approximate this feedback to a first order term:

$$C_m^*(t) = C_m(0)[1 - \beta_{T_2} T_m(t-1)] \tag{28}$$

where $C_m(0)$ is the initial concentration of carbon in the mixed layer of the oceans, and β_{T_2} models the sensitivity to temperature changes of the equilibrium carbon concentration in seawater .

Net flux of carbon through the oceans is determined by the relative concentration of carbon in the two layers. In particular, the net flux from the mixed to the deep layer (ΔC_{md}), is defined by:

$$\Delta C_{md}(t) = k_{eddy} \frac{\left[\frac{C_m(t-1)}{d_m} - \frac{C_d(t-1)}{d_d}\right]}{\bar{d}_{md}} \tag{29}$$

where d_d and d_m are respectively the thickness of deep and mixed layers, $\bar{d}_{md}$ is the mean thickness of the mixed and deep oceans, and k_{eddy} is the eddy diffusion parameter. The flux of carbon through the atmosphere, biosphere and oceans affects the heat transfer across the system and, hence, the dynamics of Earth's surface mean temperature.

A.6.2 Global warming

Once carbon exchanges among the atmosphere, the oceans and the biomass reach a new equilibrium, the updated concentration of carbon affect global warming mainly via radiative forcing. In particular, the global mean surface temperature is determined by the heat content of the surface and mixed layer of the oceans, which are aggregated into a single compartment. We model the behavior of temperatures in the different layers building on Schneider and Thompson (1981) and Nordhaus (1992). The heat content of the different layers is modulated by their reciprocal exchanges and, with respect to the upper compartment (atmosphere and surface oceans), by the CO_2 radiative forcing (F_{CO_2}).[40] Therefore, the dynamics of the temperature in the mixed (T_m) and deep (T_d) layers can be modelled as follows:

$$T_m(t) = T_m(t-1) + c_1 \{F_{CO_2}(t) - \lambda T_m(t-1) - c_3[T_m(t-1) - T_d(t-1)]\} \tag{30}$$

$$T_d(t) = T_d(t-1) + c_4 \{\sigma_{md}[T_m(t-1) - T_d(t-1)]\} \tag{31}$$

where temperature (T) is expressed as to pre-industrial levels, R_m and R_d are the thermal inertias in the two layers, λ is a climate feedback parameter, F_{CO_2} represents the radiative forcing in the atmosphere from GHG (relative to pre-industrial levels) and σ_{md} is a transfer rate of water from the upper to lower oceans accounting also for the heat capacity of water. The main climate variable we are interested in is the temperature of the surface-upper oceans compartment, T_m.

Accumulation of GHG leads to global warming through increasing radiative forcing (F_{CO_2}) according to:

$$F_{CO_2}(t) = \gamma \log\left(\frac{C_a(t)}{C_a(0)}\right), \tag{32}$$

with $\gamma > 0$. The anthropogenic emissions contributes to increase carbon concentration in the atmosphere (see Section A.7), thus inducing climate change via the radiative forcing of GHGs. At the same time, global warming exerts two important feedbacks on the dynamics of carbon, affecting its exchanges with the biosphere (eq. 25) and the oceans (eq. 28).

A.6.3 The timeline of events in the climate box

In each period, we assume that events in the economy and the climate box happen sequentially with the surface temperature as the last variable to be determined:

1. total emissions produced in period t add to the current stock of atmospheric CO_2 concentration, thereby modifying the biophysical equilibrium;
2. the increased carbon concentration affects oceans' marginal capacity to uptake CO_2;

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[40] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and it is an index of the importance of the factor as a potential climate change mechanism (IPCC, 2007b). To simplify, we use CO_2 as a proxy for all greenhouse gases and we consider only its radiative forcing.

3. carbon exchanges between the atmosphere and both biosphere and oceans take place, with the possible feedbacks from global warming;
4. the new equilibrium concentration of carbon in the atmosphere, $C_a(t)$, is determined;
5. $C_a(t)$ affects the new radiative forcing of GHG;
6. the radiative forcing determines the entity of climate change, i.e. the increase in mean surface and upper oceans' temperature;
7. a set of stochastic shocks hitting the economy are drawn from a distribution whose density function is affected by the dynamics of surface temperature.

The last point provides the feedback between the climate evolution and the dynamics of the economy. We describe it in more details in the next Section.

A.7 Climate and economy co-evolution

The dynamics of the climate and the economy are intimately interlinked: on one side, emissions affect the equilibrium temperature in the atmosphere; on the other, climate change induces a variety of effects (damages) on economic agents.

To begin with, production of goods and energy entails CO_2 emissions in the atmosphere, thereby increasing its concentration. Total emissions (Em) are simply obtained by summing CO_2 emissions in the machine-tool industry (Em^{cap}), consumption-good sector (Em^{con}) and in energy production (Em^{en}):

$$Em(t) = \sum_{\tau} \left(\sum_{i} Em^{cap}_{i,\tau}(t) + \sum_{j} Em^{con}_{i,\tau}(t) + Em^{en}_{\tau}(t) \right), \tag{33}$$

where τ denote the vintage of machine or power plant. Emissions are obtained straightforwardly multiplying the coefficient of environmental friendliness of the machine (plant) at stake with the total amount of energy units (fuel units, in the case of the energy sector) used in period t.

At the same time, climate change impacts on the economic system via multiple, possibly catastrophic, events hitting labour productivity, firm energy efficiency, firm-level capital stocks and inventories, etc. Climate change originates from increasing radiative forcing due to higher and higher CO_2 concentration in the atmosphere. As it is well discussed in Pindyck (2013), the choice of how to represent global warming-induced damages is the most speculative element of the analysis. Notwithstanding the burgeoning econometric literature on the assessment of the economic effects of climate change (Dell et al., 2014; Carleton and Hsiang, 2016; Hsiang et al., 2017), selecting an appropriate functional form for the damages is still challenging.[41]

In many cases, IAMs simply assess the impact of climate-change on the economy via aggregate fractional GDP losses. The usual practice consists in specifying an ad-hoc functional form for the so-called *damage function*, which express the percentage output loss for any level of temperature anomaly.[42] The adoption of simple aggregate damage functions brings three issues. First, by considering only GDP losses, it is not possible to distinguish between different types of damage. Second, the adoption of continuous and "smooth" damage functions rules out the treatment of catastrophic, more or less rare, climate events and impose not to look at the fluctuations such events might create in the economic system Hallegatte and Ghil (2007). Finally, there is an absolute degree of certainty in the occurrence of the damage: whenever an increase in average surface temperature materializes, some output is deterministically destroyed.

In the attempt to overcome such problems, we employ a genuine bottom-up approach to climate impact modeling (Ciscar et al., 2011, 2012). More specifically, our stochastic *agent-based damage generating function* evolves over time according to the dynamics of the climate. At the end of each period, a draw from the distribution establishes the size of the shock affecting firms and workers. The impact of climate shocks are heterogeneous across agents (e.g. some firms can face disasters, while others mild events) and it can affect different variables (e.g. labor productivity, capital stock, etc.).

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[41] Recently new empirical works explore climate impacts (see e.g. Carleton and Hsiang, 2016). However, we are not aware of IAMs accounting for them.

[42] For example, Nordhaus (2008) uses an inverse quadratic loss function, Weitzman (2009) proposes a negative exponential functional specification emphasizing the catastrophic role of large climate changes, while Tol (2002) uses sector and area specific loss functions.

The *disaster generating function* takes the form of a Beta distribution over the support $[0, 1]$, whose density satisfies:

$$f(s; a, b) = \frac{1}{B(a, b)} s^{a-1}(1-s)^{b-1}, \tag{34}$$

where $B(\cdot)$ is the Beta function and a, b are respectively the location and scale parameters. Both parameters are assumed to evolve across time reflecting changes in climate variables:

$$a(t) = a_0[1 + \log T_m(t)] \tag{35}$$

$$b(t) = b_0 \frac{\sigma_{10y}(0)}{\sigma_{10y}(t)}, \tag{36}$$

where $\sigma_{10y}(t)$ captures the variability of surface temperatures across the previous decade and a_0, b_0 are positive integers.[43] Equations (35) and (36) shape the disaster generating function as a right-skewed, unimodal distribution, whose mass shifts rightward as temperature increases, thereby raising the likelihood of larger shocks.[44] Equation (36) determines the size of the right tail of the distribution and it allows one to account for the importance of climate variability on natural disasters (Katz and Brown, 1992; Renton et al., 2014), which has been increasingly recognized as a major driver of climate disasters (Thomalla et al., 2006; IPCC, 2012; Revesz et al., 2014), even if most of the models do not even mention it.[45]

In each period a sample of climate-change shocks are drawn from the Beta distribution, which evolves over time according to the dynamics of the climate. In particular, we extract as many shocks as the agents affected in the given scenario of analysis. Shocks and agents are randomly matched, and each agent suffers a loss in the targeted variable proportional to the size of the shock (e.g. in the case of labour productivity, $A_{i,\tau}^{LP}(t) = [1 - \text{shock}_i(t)]\bar{A}_{i,\tau}^{LP}(t)$, where $\bar{A}^{LP}$ indicates the value that i's labour productivity would have taken in absence of climate damages).

B Appendix - Replication of stylized facts

B.1 Macro Stylized Facts

Let us start by looking at how the model replicates the macro empirical regularities (much more details on these results in Dosi et al. (2010) and Dosi et al. (2013)). Also in this version, the model is able to generate endogenous self-sustained growth patterns characterized by the presence of persistent fluctuations (see figure 5) as well as fat-tailed growth rates distributions (see figure 6 and 7). Furthermore, the relative magnitudes of the volatilities of GDP, consumption and investment are respected: in table 1 we have instead report a list of important stylized facts that the model is able to reproduce.

We also observe in figure 8 that the dynamic auto- and cross-correlation of GDP with consumption and investment are respected: consumption in highly pro-cyclical and synchronized with GDP (possibly reflecting a long-run cointegration relation) and investment is pro-cyclical and lagging.

Figure 9 presents instead the dynamic cross-correlations of GDP and private debt and of GDP and the amount of deposits: both are pro-cyclical and slightly leading.

Finally, we present some additional evidence on the dynamic auto- and cross-correlation between credit variables. In particular, figure 10 presents private debt and bad debt. This dynamic correlations are of particular importance for interpreting the results that we will present in the next section concerning the QE unconventional monetary policy and the mark to market accounting policy. It is indeed possible to see that private debt and bad debt are dynamically positively correlated, hence they might possible be a source of positive feedback mechanisms in the model aggregate dynamics.

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[43] For modelling purposes we estimate the standard deviation of the previous ten recorded temperatures; however, a widely used measure of climate variability corresponds to the count of extreme temperatures (IPCC, 2012).

[44] Naturally, any distribution would be feasible for sampling climate shocks. Our choice should be considered as a first attempt towards a micro-foundation of climate damages. The Beta distribution is flexible enough to explore a wide range of scenarios and to genuinely account for fat-tailed climate risks (Ackerman et al., 2010; Weitzman, 2011; Pindyck, 2012).

[45] The majority of studies accounting for climate catastrophes employ some variant of the DICE model (see also Gerst et al., 2010; Berger et al., 2016) where an arbitrary large output loss is identified as a catastrophe. To the contrary, our modeling effort should be seen as an attempt at providing evidence of how large shocks at the individual level might impact on aggregate dynamics, outside optimal growth paths.

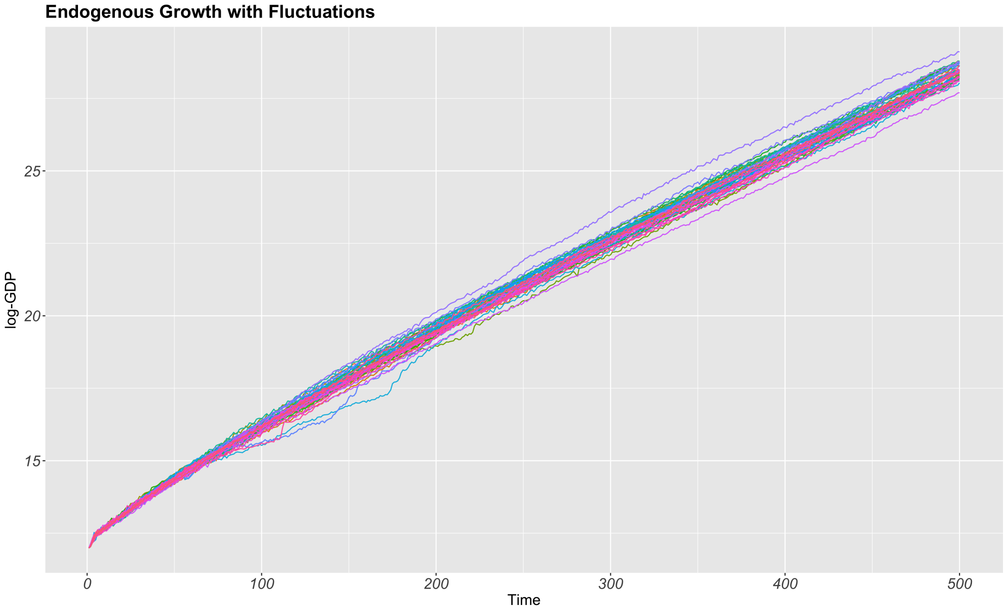

Figure 5: *Log-GDP time series for each MonteCarlo run displaying long-run linear growth trends with short-run business cycles.*

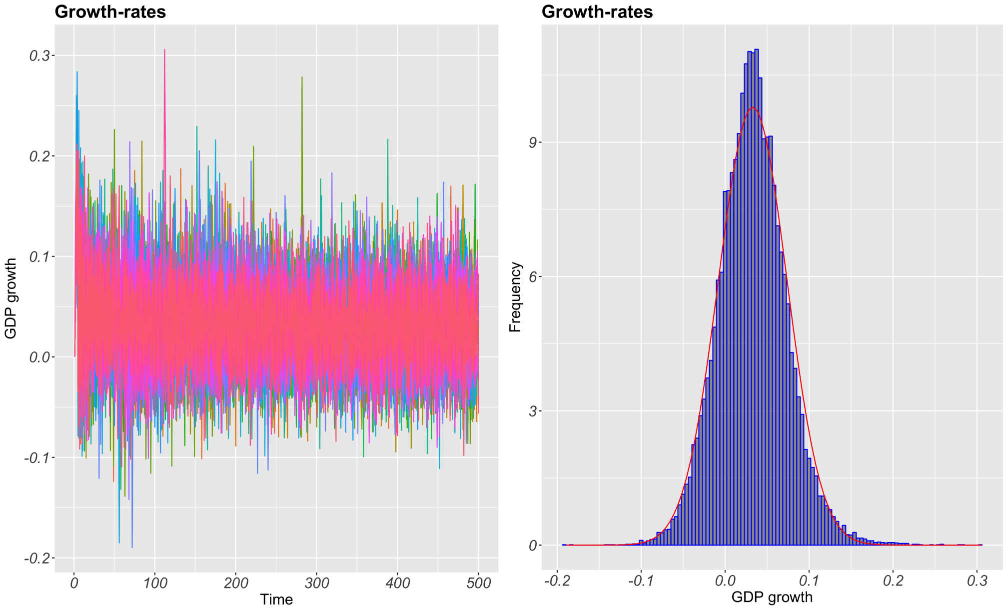

Figure 6: *Left panel: GDP growth rate time series for each MonteCarlo run. Right panel: MonteCarlo pooled growth rates distribution (histogram) versus a normal distribution with equivalent mean and standard deviation (red kernel density).*

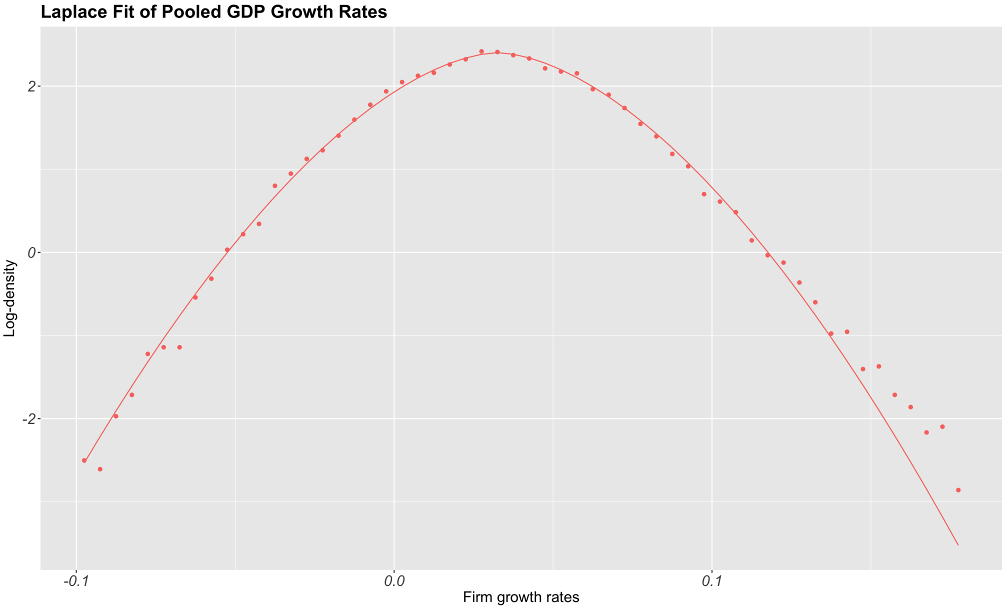

Figure 7: *MonteCarlo pooled growth rates distribution, laplace fit.*

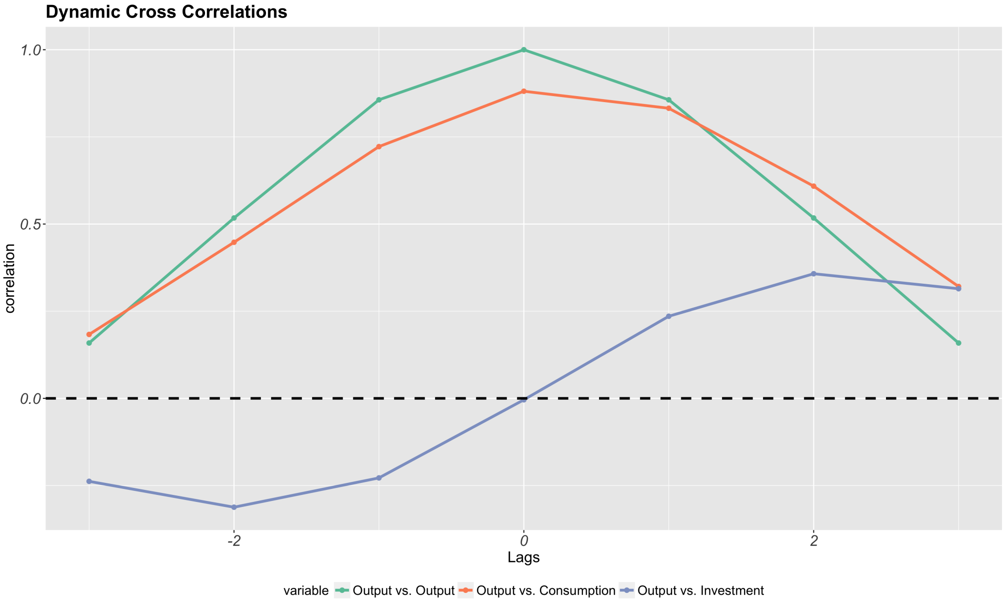

Figure 8: *Dynamic auto-correlation of GDP (green) and dynamic cross-correlations between BP filtered (6,32,12) GDP and consumption (red) and between GDP and investment (blue).*

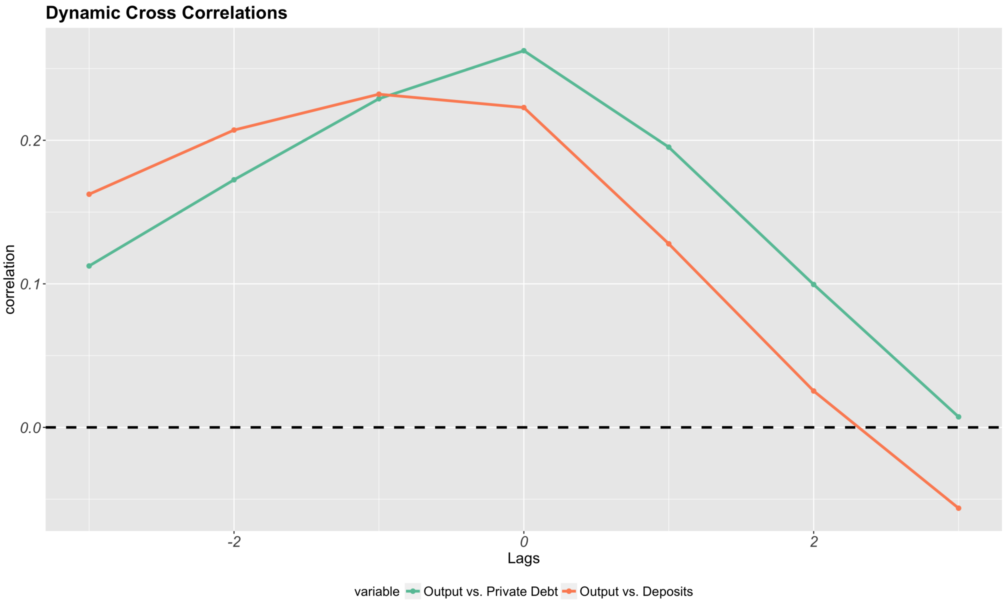

Figure 9: *Dynamic cross-correlation between BP filtered (6,32,12) GDP and private debt outstanding (green) and between GDP and total amount of deposits (red).*

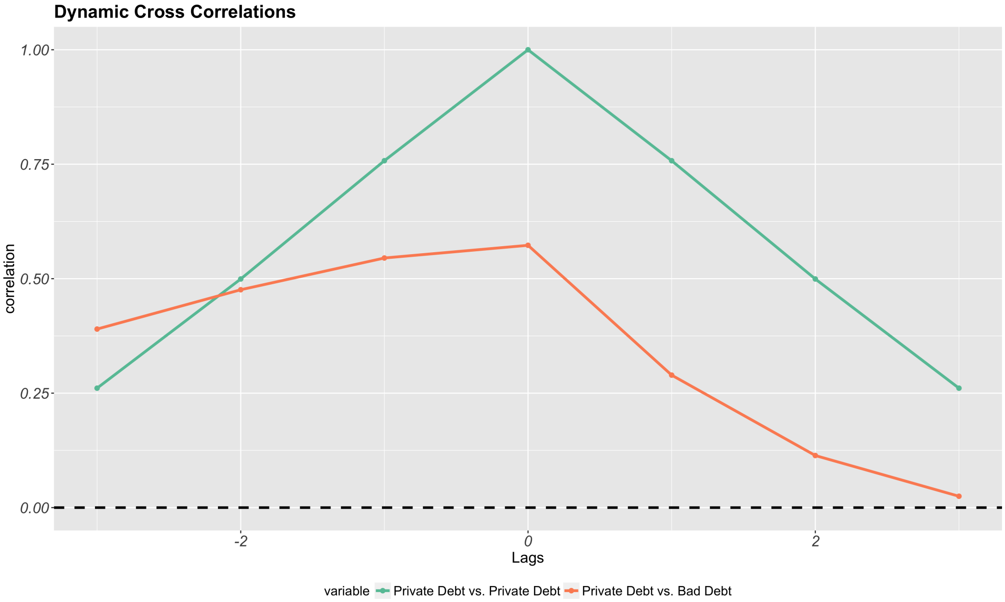

Figure 10: *Dynamic auto-correlation of BP filtered (6,32,12) total private debt outstanding and dynamic cross-correlation between private debt outstanding and the total amount of bad debt (red).*

We close the macro replication part with a stylized fact related to the energy sector presented in figure 11 As in the Lamperti et al. (2017) version of the model, we indeed find that the energy demand is pro-cyclical at lagging values.

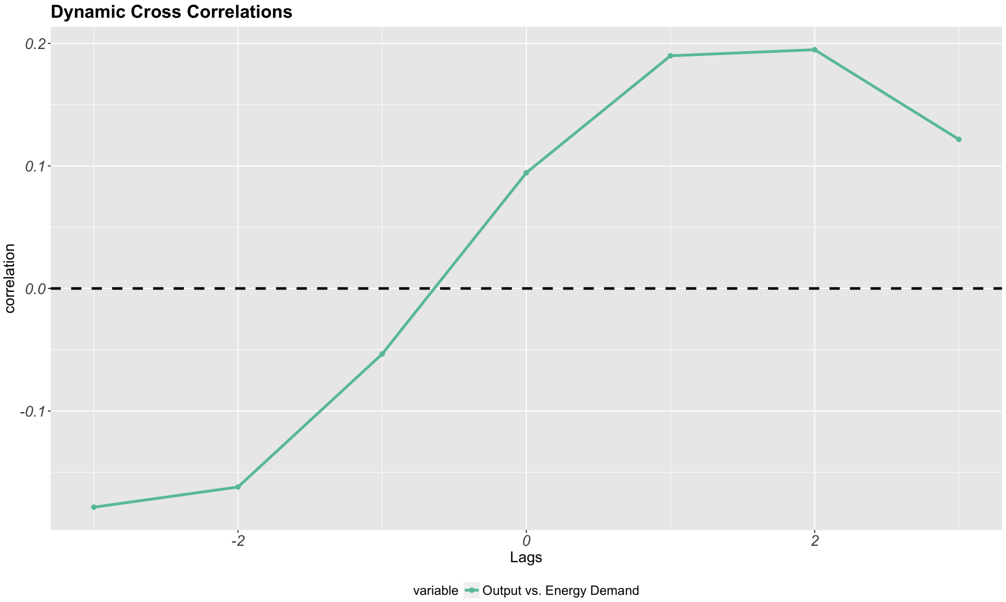

Figure 11: *Dynamic cross-correlation of BP filtered (6,32,12) GDP and energy demand.*

B.2 Micro Stylized Facts

Concerning the micro stylized facts, we here focus on the distributional properties of the firms. In particular we investigate the size distribution and the growth rates distribution (see figure 12), the productivity growth distribution (see figure 14) and the persistence in productivity (see figure 15).

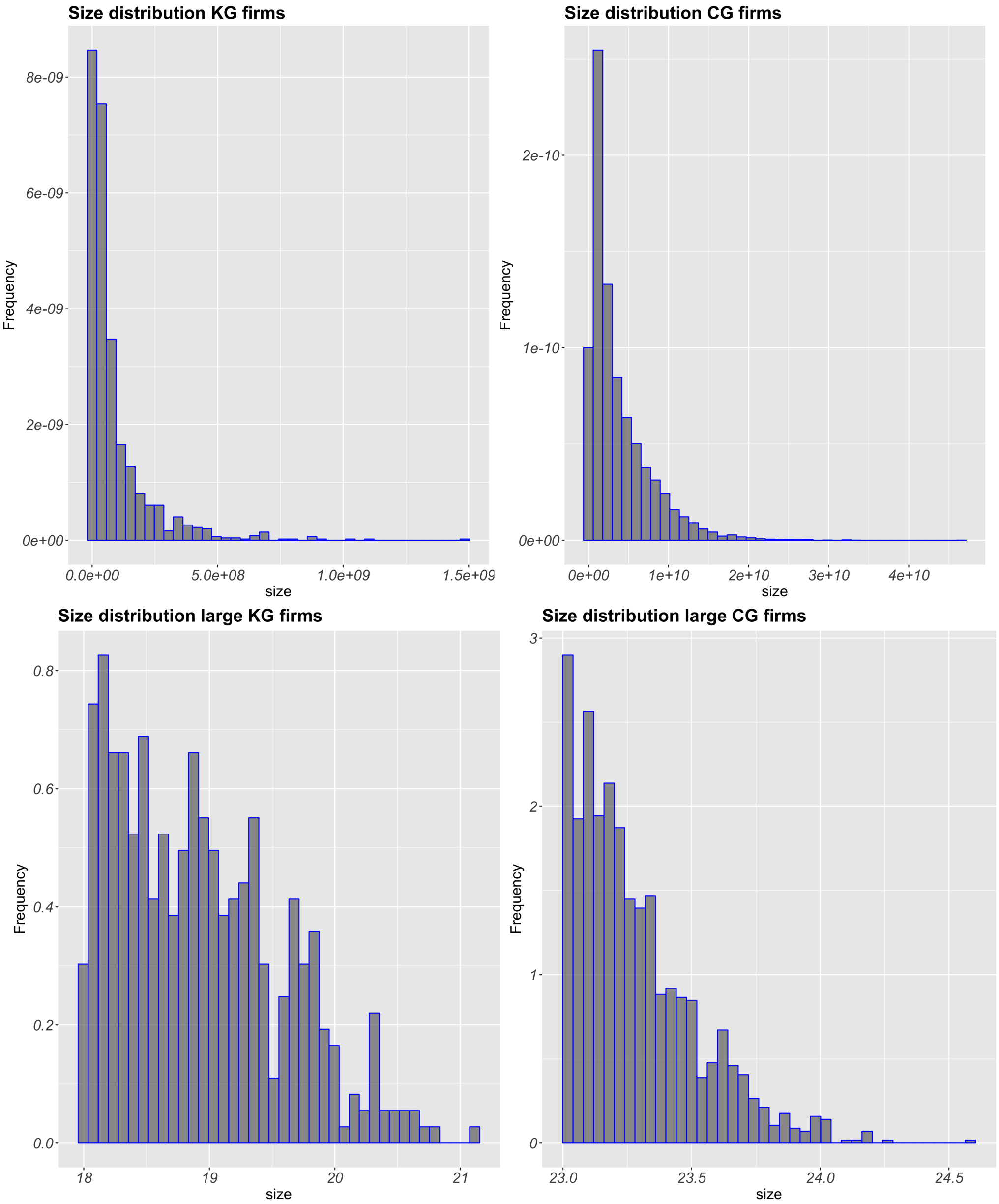

Figure 12: *Size distributions of all firms (upper panels) and log-size distribution of large firms (lower panels). Left: capital goods sector. Right: consumption good sector.*

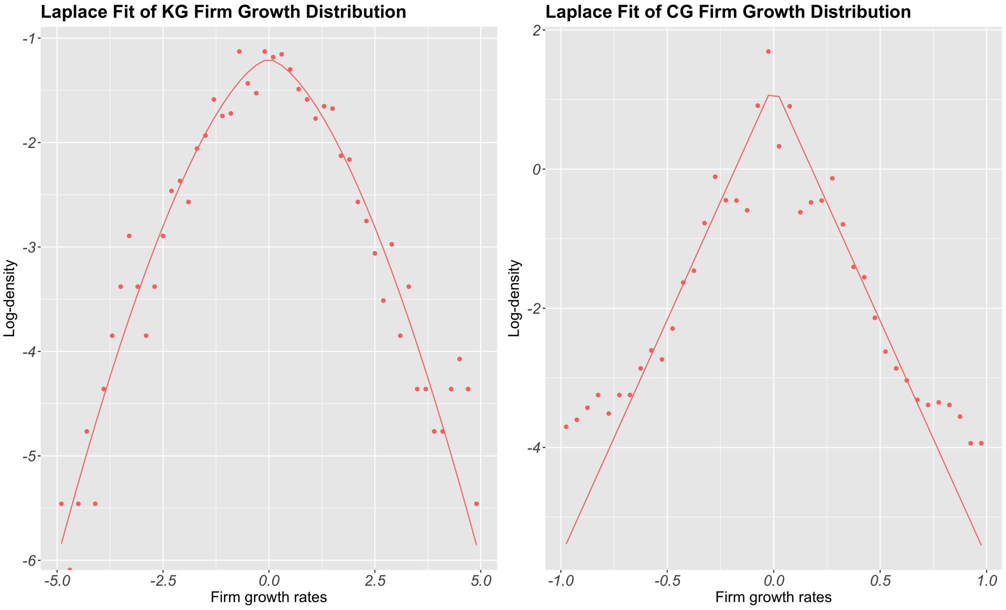

Figure 13: *Laplace fit of the growth rate distributions of firms. Left: capital goods sector. Right: consumption good sector.*

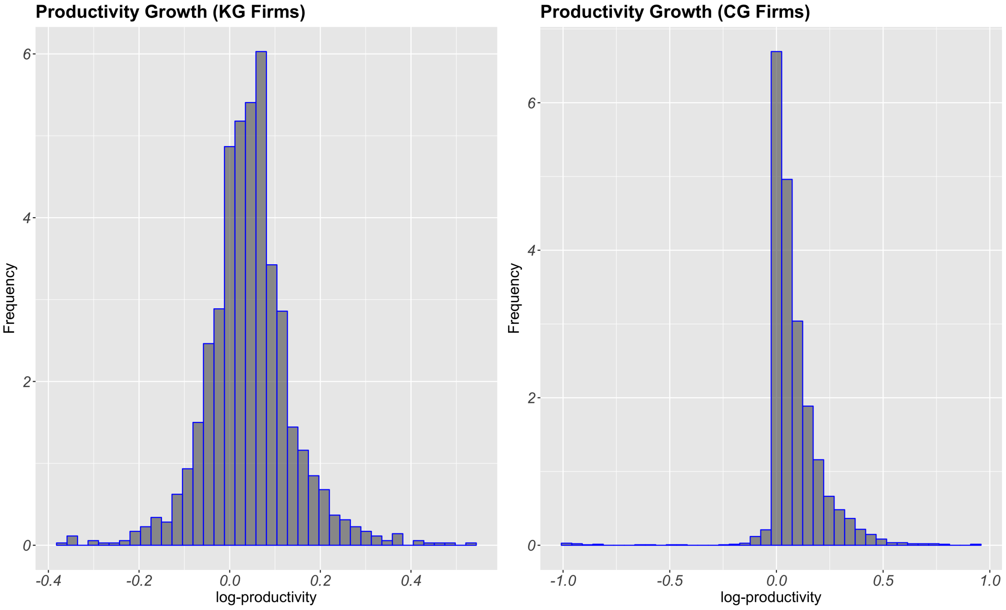

Figure 14: *Productivity growth distributions. Left: capital goods sector. Right: consumption good sector.*

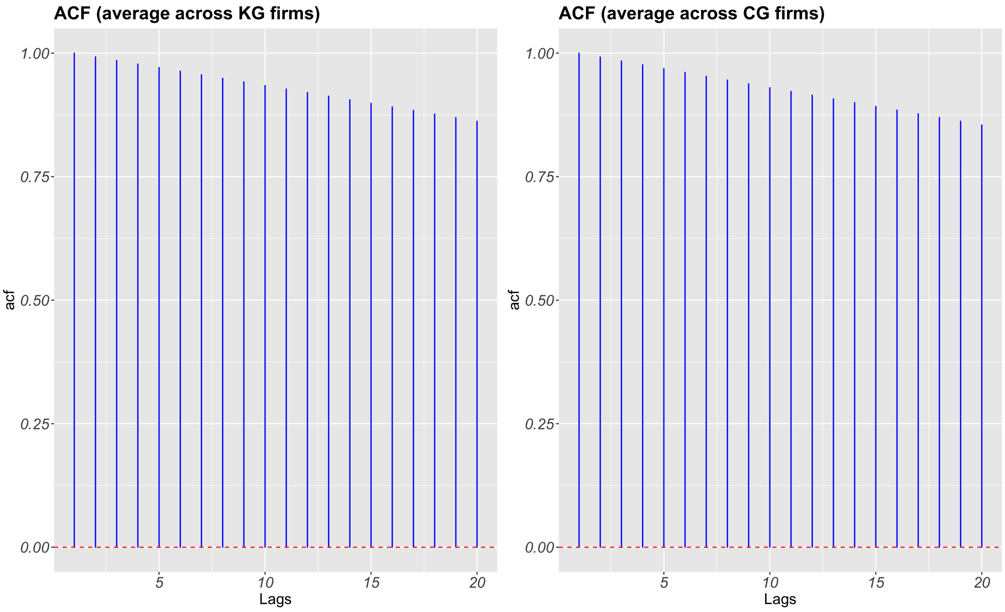

Figure 15: *Productivity persistence, measured by the average (across firms) auto-correlation function. Left: capital goods sector. Right: consumption good sector.*