

From financial instability to green finance: the role of banking and credit market regulation in the Eurace model

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Abstract We investigate appropriate banking and regulatory policies aimed at pushing the banking sector to shift from speculative lending, the cause of asset bubbles and economic crises, to green investments lending, so as to foster the transition to a more energy efficient production technology. For this purpose, we consider an enriched version of the Eurace model, which includes heterogenous capital goods, allowing for different degrees of energy efficiency in the production technology. Credit money in Eurace is endogenous and limited by Basel capital adequacy regulation on the supply side, while on the demand side it is determined by firms' investments and households' house purchasing. We introduce a differentiation of capital requirements according to the destination of lending, demanding higher bank capital in the case of speculative lending, thus encouraging banks to finance firm investment. As up-to-date capital goods have better energy efficiency in the model design, a higher pace of investment implies also a positive environmental effect. Results suggest that the proposed regulation is able to foster investments and capital accumulation in the short term, improving the energy efficiency of firms. However,

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reducing mortgages with a restrictive regulation has a negative impact on total private credit, and thus on endogenous money supply, weakening consumption and aggregate demand. In the long term, the contraction of total credit becomes stronger, and the negative outcomes on aggregate demand also affect investment. Therefore, in the long run, the positive effects on capital and energy efficiency become negligible, while the main economic indicators deteriorate.

Keywords Green finance · Capital requirements · Energy efficiency · Agent-based modeling

JEL Classification E51 · Q58 · C63

1 Introduction

Achieving the goal to limit global temperature increases below 2 deg C with respect to preindustrial levels, as agreed upon by 195 countries at the United Nations climate change conference, known as COP21, held in Paris in December 2015, will require enormous investments in the green sectors of the economy. Strongest efforts shall be devoted in particular to fostering the transition of energy production from fossil fuels to renewable sources and to the improvement of energy efficiency in buildings, industries and the transportation sector.

The year 2015 marked a new record high for global investments in renewable energy projects that, excluding large hydro-electric projects, amounted to \$ 285.9 billions, more than half of which had been made in the developing world, including China, India and Brazil; see UNEP (2016). However, different studies have pointed out that the size of investment required each year in low carbon sectors to limit the temperature increase to the target should be much higher, i.e. in a range from \$ 650 billions to \$ 1 trillion. (See, e.g., IEA 2012; WEF 2013.) Therefore, there is a relevant so-called green investment gap that needs to be covered. This, however, looks to be a particular challenging task in the present economic environment characterized by low growth in advanced economies and increasing risks in developing ones. Furthermore, green investments are usually characterized by high political uncertainty regarding the real long-term commitment of public policies of support, by a long-term time horizon and very high initial capital costs (Nelson and Shrimali 2014). These features make low-carbon investments unattractive to private investors in the absence of a strong and sizeable long-term commitment by the government to some form of public support.

The most well-known and discussed solution to the low-carbon investment challenge has been the introduction of a price on carbon (Nordhaus 2013; WB 2015), either through a carbon tax, i.e. a tax on the carbon content of goods and services, or through a cap-and-trade system of emissions allowances, with the aim to address the market failure related to the exclusion of environmental costs from the market pricing system. The rationale is that a carbon price would push private agents to internalize correctly environmental costs and therefore to perform the appropriate green investments aimed to reduce them. However, carbon price mechanisms still have

strong political opposition¹ on the grounds that they are harmful for business and can dampen economic growth.

Beside carbon pricing, a new idea that is gaining attention concerns the design of appropriate banking regulation policies aimed to push banks to lend to low-carbon activities so as to ease the green investment gap. (See e.g. Rozenberg et al. 2013; Ferron and Morel 2014; Aglietta et al. 2015; Campiglio 2016.) A banking regulatory framework, where banks that lend to firms undertaking green investments are required to respect looser requirements, could indeed manage to direct credit toward the green sector and therefore reduce the green investment gap. In particular, according to Campiglio (2016), differentiating reserve requirements on the base of the green orientation of the financed investment is the policy most seriously considered. However, the author is also skeptical about the validity of this policy proposal, in particular, in advanced economies, where reserves are not actually binding, because central banks usually control the price of reserves (the interest rate) and not the quantity of reserves, and private banks are never rationed in their reserve demand. This is the reason why the author lays down a new proposal about differentiating capital requirements and not reserve requirements, according to the Basel regulatory framework. The advantage is that capital ratios are actually binding in advanced economies. In particular, Campiglio (2016) states:

An analogous proposal involves setting differentiated capital requirements; that is, imposing different capital adequacy ratios according to the characteristics of the banking institute and the type of lending they provide. Capital requirements are likely to be more effective than liquidity ones in constraining bank lending, as even creating new central bank reserves would not change the capital ratio, or at least not in the way banks desire. Therefore, implementing a regulatory framework where banks that lend to low-carbon (or other socially useful) sectors are required to respect looser requirements could fruitfully manage to direct larger flows of new credit creation toward them. A similar proposal involves calibrating the computation of Basel III risk-weighted capital ratios in a way that low-carbon activities would exert a lower pressure than alternative investments.

To this purpose, the most important contribution of the paper consists in testing this innovative green macro-prudential policy proposal in a computational environment.

In this paper, we investigate the banking regulatory provision that differentiates the capital adequacy ratio according to the type of lending. In particular, we employ an agent-based macro-economic model and simulator to study the effectiveness and the long-run impact on the economy of this type of regulatory provision. A number of agent-based macro models² have been proposed in recent years to address the

¹See, e.g., the repeal of the carbon tax by the new Australian government in 2014 or the debate in the US 2016 presidential race

²A non-exhaustive list could include the K+S model. See Dosi et al. (2010, 2013, 2015), the set of models developed by the Ancona research group (Caiani et al. 2016; Riccetti et al. 2015; Russo et al. 2016), the

known limitations of the traditional DSGE modeling approach in macroeconomics; see Fagiolo and Roventini (2016) for a comprehensive review and comparison of the two approaches. Furthermore, agent-based macro-models have been applied to study climate change economics and investigate related policies; see e.g. Balint et al. (2017) for a compressive review and Farmer et al. (2015) for a general discussion about the potential advantages of agent-based models with respect to integrated assessment models, which are the usual workhorse in the field. In particular, Gerst et al. (2013) and Tonelli et al. (2016) are among the first attempts to address sustainability issues by means of the agent-based approach. The flow-of-fund dynamic Eirin model (Monasterolo and Raberto 2018), where agents are identified with the different sectors of the economy, can be considered among the first pioneering attempts in the same direction.

In this respect, we claim that the agent-based modeling approach is particularly suited to encompass the relevant features needed to address our research question, such as the endogenous nature of money created by the banking system in modern economies. (See e.g. Mcleay et al. 2014; Werner 2014, and the non-equilibrium evolutionary dynamics of the economy (Kaldor 1972; Arthur 2006).)

For the purposes of our study, we employ the agent-based macroeconomic model and simulator Eurace, in particular the most recent version including housing assets, a related market and mortgage lending (Ozel et al. 2016) that we further enrich with two relevant new features to address the research question of the paper.

The first feature regards a new design of banking regulation that follows a proposal by Campiglio (2016), which suggests the adoption of different capital adequacy ratios according to the type of lending that banking institutions provide. Accordingly, we have designed a set of computational experiments characterized by capital requirements for mortgages that can be higher or lower than a reference value, i.e. 10%, which is the basic capital requirement value adopted for firms' loans. The rationale behind this choice is the assumption that loosening credit access for house purchases may produce asset bubbles with destabilizing effects for the real economy, while loans to business firms are aimed at increasing and renewing their capital endowment with positive effects for the productive capacity of the economy and for environmental sustainability.

It is worth noting that our working hypothesis is not strictly a behavioral assumption about the attitude of the different types of borrowers (households or firms) on the use of the borrowed funds for speculation (households) or for productive investments (firms). Indeed, house purchase decision making by households is not driven by any speculative purpose but is mostly random (Ozel et al. 2016). Actually, we are not interested here in households' behavior, but we are more interested in the macroeconomic and credit aspects of the housing market, and in particular in the impact of mortgage loans on the economy as a whole. We do not intend to mimic household behavior in the housing market, but we want to include this market as an important destination of credit in the economy. Therefore, our main research question is about

CC-MABM (Assenza et al. 2015), the Mark I CRISIS model (Klimek et al. 2015; Gualdi et al. 2015), Iceace (Erlingsson et al. 2014), Eurace (Cincotti et al. 2012a) and Eurace@UNIBI (Dawid et al. 2016)

the effects of loose credit conditions, depending on the destination of the borrowed funds. In this respect, we should consider that over-lending to the business sector has downside risks due to increasing insolvency rates for firms' but also positive effects on productive capacity and energy efficiency (in our model) of the economy. By contrast, easy mortgage lending gives rise to price bubbles and incentivizes speculative house purchases.

Both theoretical and empirical studies support our assumption. The relevance of credit dynamics for business cycles is central in Minsky's financial instability hypothesis (Minsky 1986) and has been pointed out by theoretical models within the neoclassical school; see, e.g., Bernanke and Gertler (1989) and Kiyotaki and Moore (1997). Furthermore, more recently, a large number of explanations proposed about the financial crisis highlight the credit boom occurred in the mid 2000s, in particular in relation to mortgage lending practices and the related housing bubble (see, e.g., Keen et al. 2009; Turner 2013; Muellbauer 2015, along with the ensuing sub-prime crisis that is considered the triggering cause of the 2007/2008 financial crisis (Duca et al. 2010). In this respect, extensive empirical research shows the connection between credit and housing bubbles and bursts. (See, e.g., Baker 2008 for US, Xiao and Devaney 2016 for UK and Ruiz et al. 2015 for Spain.)

Finally, the second relevant feature of our model design regards the heterogeneity of capital goods with respect to energy efficiency³ that we assume to be exogenously increasing over time. This new model provision implies that investments in capital goods provide an environmental benefit as the new vintages are characterized by higher energy efficiency and then allow the production of consumption goods at a lower energy intensity per unit of consumption good produced. Investment decision making is then updated accordingly to take into account the intertemporal saving of energy per unit of consumption goods produced due to investment decisions.

The paper is structured as follows: Section 2 outlines the agent-based macroeconomic model we employed and Section 3 presents the computational experiments performed and discusses the relevant results. Concluding remarks are drawn in Section 4.

2 The enriched Eurace model

2.1 Model overview

Eurace is an agent-based macroeconomic model and simulator that has been developed in the last ten years within two EU-funded projects.⁴ (See Cincotti et al. 2010, 2012a; b; Raberto et al. 2012, 2014; Teglio et al. 2012, 2017; Ponta et al. 2018.) The

³It is worth noting the relevance of energy efficiency in the EU environmental policy framework where a 20% increase in energy efficiency by 2020 with respect to 1990 is among the three well-known 20-20-20 targets set by the European Union in 2009; see: <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009D0406>

⁴FP6 European Project EURACE and EU-FP7 project SYMPHONY

baseline Eurace model includes different types of agents: households (HHs), which act as workers, consumers and financial investors; consumption goods producers (CGPs), henceforth firms, producing a homogenous consumption goods; a capital goods producer (KGP); commercial banks (Bs); and two policy makers agents, namely a government (G) and a central bank (CB), which are in charge of fiscal and monetary policy, respectively.

Agents' behavior is modeled as myopic and characterized by limited information, scarce computational capabilities and adaptive expectations. The details about agents' decision making in the baseline Eurace model are described in Teglio et al. (2017). Agents interact through different markets where consumption and capital goods, labor and credit are exchanged in a decentralized setting with disperse prices set by suppliers and based on costs. Moreover, households interact in the housing market. The housing market is characterized by households that sell or buy homogeneous housing units subject to budget constraints. If a prospective buyer needs a mortgage, he can send a request to a bank, which provides the mortgage only if the expected future income of the potential buyer is deemed sufficient to face scheduled mortgage payments and the bank itself satisfies Basel capital requirements conditions. Households can assume the role of buyer or seller in the housing market with an equal exogenous probability. The reason of this random selection is that we are interested on the macroeconomic and credit implications of the housing market, and in particular on the impact of mortgage loans on the economy as a whole. However, we allow also for a special case, called the fire sale case, where households enter the housing market because financially distressed (when mortgages payments have exceeded a given fraction of their income) and are forced to sell their houses at a discounted price in order to reduce mortgage payments and debt burden. Trading in the housing market is decentralized, and prices are posted by sellers, while prospective buyers are randomly queued to choose the available housing unit at the lowest price.

The full details about the housing market in Eurace as well as the different conditions for mortgages lending and their effects on the housing price and the economy can be found in Ozel et al. (2016). Appendix A1 of this paper reports the most relevant features of the housing market in Eurace.

In order to investigate the appropriate banking and regulatory policies aimed at forcing the banking sector to move away from speculative lending, the cause of asset bubbles and economic crises, to the financing of the green sector, an enriched Eurace model has been designed. The new model includes an energy sector, where electricity production is based on fossil fuels. In particular, electricity is an additional production factor used by consumption goods producers, which use heterogeneous capital goods characterized by endogenous electricity efficiency. Finally, we designed banks' capital requirements to vary according to the type of lending, i.e. loans to business firms or mortgages to households.

Consumption goods producers (CGPs) need electricity, in addition of labor and capital, as a production input. The electricity efficiency of the production process is not constant but depends on the composition of the capital goods vintages in the capital endowment of every firm (CGP). The lower the average age of capital goods of a firm, the higher the energy efficiency of production, or equivalently, the lower

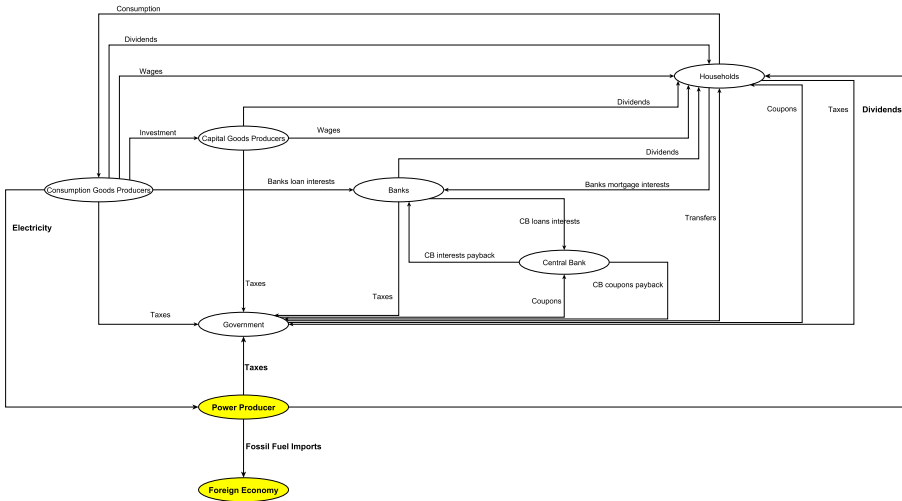


Fig. 1 Graphical representation of the Eurace model’s structure in terms of agents’ classes and current account monetary flows

the energy intensity of production, i.e. the amount of electricity/energy⁵ required per unit of output.

Banks’ capital adequacy ratios have been differentiated with respect to the type of lending, namely loans to business firms or mortgages to households for house purchases.

Figure 1 shows a graphical representation of the model’s structure, where the novel features are highlighted with respect to the previous versions. In particular, rectangles represent the different type of agents and arrows the relations among them in terms of current account monetary flows. The new features are highlighted in bold and yellow and consist in the energy sector schematized by the power producer and the foreign economy.

The following two subsections will provide the modeling details about the use of energy sector and the energy efficiency of the production sector as well as about the differentiation of banks’ capital requirements.

2.2 The energy sector and energy efficiency

We assume that to produce the amount q_{C_f} of consumption goods, firm f needs an appropriate number of employees and an appropriate capital endowment, as fixed by the Cobb-Douglas technology; see Teglio et al. (2017, Appendix, Eq. 8). In this new setting, the firm also needs an amount of energy, say q_E , determined by the equation:

$$q_E = \epsilon_f q_{C_f} ,$$

⁵In the paper, we will use the terms electricity and energy interchangeably, with no distinction.

where ϵ_f is a firm-specific energy intensity variable that gives the energy amount required per unit of output. We assume no substitutability between energy and the other two inputs, i.e. labor and capital. CGPs are never rationed in their energy demand, which is immediately delivered by the power producer agent⁶ on request at a price p_E determined by a fixed mark-up μ_E on the price of fossil fuels, p_O . The price of fossil fuels is exogenously given and assumed to be subject to an exponentially monthly growth rate ξ_O .

Energy costs p_{EQE} are a variable cost that is taken into account by the firm in addition to labor costs, interest rates and capital depreciation in the determination of unit costs of output; see Teglio et al. (2017, Appendix, Eq. 10). Thus energy costs have also an impact on consumption goods prices.

Energy intensity ϵ_f is determined by the different vintages of capital goods owned by firm f . We assume that each unit of capital goods, when employed in the production process by the firm, requires an amount of energy per unit of output, i.e. an energy intensity ϵ_K , that depends on the time the capital good has been manufactured by the capital goods producer (KGP) and delivered to the firm (CGP). In particular, we assume that, due to technological progress,⁷ the capital goods producer is able to manufacture capital goods characterized by an energy intensity ϵ_K which decreases exponentially over time at the monthly rate ξ_K .

The energy intensity of each firm then decreases over time according to the size and timing of its investment decisions. When a firm f makes an investment ΔK_f , its energy intensity decreases according to the weighted average:

$$\epsilon_f = \frac{\widehat{\epsilon}_f K_f + \epsilon_K \Delta K_f}{K_f + \Delta K_f}, \quad (1)$$

where $\widehat{\epsilon}_f$ was the electricity intensity characterizing the production process of the firm before the investment, while ϵ_K is the electricity intensity of the new vintages of capital goods ΔK_f .

As ϵ_K is supposed to decrease exponentially over time due to an exogenously given technological progress, firm specific electricity intensity ϵ_f improves over time due to new investments; therefore, investment decision making, based on net present value calculations, needs to take into account not only the additional positive cash flows from sales due to the higher productive capacity, as stated in Teglio et al. (2017, Appendix, Eq. 3), but also the negative cash flow related to the energy expenses due to the additional output, as well as the positive cash flows given by the savings of energy expenses per unit of output because of the lower average ϵ_f . In particular,

⁶The power producer (PP) agent is a very stylized agent that imports fossil fuels from the foreign sector at price p_O and produces electricity on request with no labor force needed. PP profits are given by the aggregate amount of energy consumed by the production sector, multiplied by difference between between p_E and p_O . PP profits are paid out to shareholders (households) in the Eurace economy.

⁷This assumption is supported by empirical evidence. In particular, the latest Energy Efficiency Market Report by the International Energy Agency points out that global energy intensity improved by 1.8% in 2015 and by 1.5% in 2014, while the average yearly improvement was around 0.6% in the decade between 2003 and 2013 (IEA 2016).

firm f chooses the investment ΔK_f that maximizes a net present value NPV given by three terms as follows:

$$NPV = NPV^{old} + PV^{(1)} + PV^{(2)}, \tag{2}$$

where NPV^{old} takes into account the present value of additional future revenues, due to the expanded production capacity, net of the present cost of capital, as showed in Teglio et al. (2017, Appendix, Eq. 3), whereas $PV^{(1)}$ and $PV^{(2)}$ are given by the following equations:

$$PV^{(1)} = - \sum_m \frac{p_E \epsilon_f \Delta_m q_{C_f}}{\left(1 + \frac{r_{K_f}}{12}\right)^m} \tag{3}$$

$$PV^{(2)} = + \sum_m \frac{p_E \Delta \epsilon_f q_{C_f}}{\left(1 + \frac{r_{K_f}}{12}\right)^m} \tag{4}$$

where r_{K_f} is the yearly weighted average cost of capital for firm f , $\Delta_m q_{C_f}$ is the additional output⁸ at future month m given by the planned investment, $\Delta \epsilon_f$ is the decrease in energy intensity due to investments and q_{C_f} is the previous production level. Therefore, Eqs. 3 and 4 assess the present value of additional expected cash flows related to energy expenses, following the investment in new capital goods. In particular, the additional production amount $\Delta_m q_{C_f}$ at month m , due to investment, entails an additional energy cost of amount $p_E \epsilon_f \Delta_m q_{C_f}$, where p_E is the expected energy price and ϵ_f is the present energy intensity (after investment). Equation 3 computes $PV^{(1)}$, i.e. the present value of negative cash flows following these higher energy expenses due to the output increase. Furthermore, the investment in new capital goods provides an increase in energy efficiency and a consequent energy intensity decrease $\Delta \epsilon_f$ that entails positive⁹ monthly cash flows of amount $p_E \Delta \epsilon_f q_{C_f}$ due to the saving of energy costs, Eq. 4 computes $PV^{(2)}$, i.e. the present value of these positive cash flows related to the energy savings following the reduced energy intensity value ϵ_f applied to the previous output level q_{C_f} .

2.3 Differentiation of banks' capital requirements

Following the provisions of the Basel capital regulations, bank agents in Eurace are characterized by minimum capital requirements, i.e. by a minimum ratio between equity (net worth) and risk-weighted assets that each bank must satisfy. The rationale for capital requirements is to provide a minimum capital buffer that should be employed to cushion loans or mortgages write-offs and consequent equity losses so as to reduce the likelihood of incurring in negative equity and insolvent banks. In particular, in the Eurace model, we state that a bank b , when receiving a new loan request from a firm or a new mortgage request from a household, is allowed to fulfill

⁸It is worth noting that the additional output is assumed to be a decreasing function of m to take into account the investments depreciation; see Teglio et al. (2017, Appendix, Eq. 5).

⁹ $\Delta \epsilon_f$ shall be considered in absolute terms.

the request only if its equity base E_b is higher than a fraction Ψ of its risk-weighted portfolio of loans and mortgages, including the new prospective loan or mortgage, i.e. only if the following condition holds:

$$E_b \geq \Psi \left(\sum_i \omega_i a_i + \omega_{a^*} a^* \right), \quad (5)$$

where Ψ is the capital adequacy ratio, i.e. a policy parameter ranging from 0 to 1, set by the regulatory authority, ω_i is the risk weight of any existing asset a_i (loan or mortgage) of the bank, and a^* is the new prospective asset (loan or mortgage) with its risk weight ω_{a^*} .

A lower capital adequacy ratio Ψ implies a looser credit regulation policy and a higher likelihood of boom and bust credit cycles with direct effects on the economy. The role of capital requirements for the determination of credit supply and the boom and bust cycles in the Eurace model has been thoughtfully explored. (See Cincotti et al. 2012b; Raberto et al. 2012; Tegli et al. 2012.) In particular, we performed different computational experiments by varying the leverage α of the banking system, defined as the inverse of the capital adequacy ratio, i.e. $\alpha = 1/\Psi$, in a setting where credit is characterized by loans to firms only. Our experiments showed that, while loose capital requirements (relatively low ψ , i.e. high α) may induce a credit-driven boom in the short run, the over-levered firms may face at some point¹⁰ in the future the impossibility to sustain the increasing interest payments with consequent default cascades that are furtherly amplified by the ensuing rationing of bank credit. (See Raberto et al. 2012; Tegli et al. 2012.) Furthermore, we also explored the potential benefits of a macroprudential approach to banks' capital regulation that would allow varying capital requirements depending on some measures of the business cycle, such as unemployment, the credit to GDP ratio or the credit growth rate; see Cincotti et al. (2012b).

In the present study, we differentiate the capital adequacy ratio according to the type of credit provided, i.e. loan or mortgage. In particular, if the request received by bank b is for a new loan $\hat{\ell}_f$ by firm f , we stipulate that the bank is allowed to grant the loan only if the following relation holds:

$$E_b \geq \Psi_L \left(\sum_i \omega_i a_i + \omega_{\hat{\ell}_f} \hat{\ell}_f \right), \quad (6)$$

whereas in case there is a request for a mortgage $\hat{\mu}_h$ made by household h , the mortgage is granted only if

$$E_b \geq \Psi_M \left(\sum_i \omega_i a_i + \omega_{\hat{\mu}_h} \hat{\mu}_h \right), \quad (7)$$

where $\sum_i \omega_i a_i$ in both Eq. 6 and 7 is the usual risk weighted portfolio of existing loans and mortgages of the bank and in principle $\Psi_L \neq \Psi_M$.

¹⁰This could be considered what is usually known as Minsky moment; see Minsky (1986).

In Eq. 6 and 7 we propose a banking regulation that works with two thresholds, depending on the nature of the loan. If Ψ_M is higher than Ψ_L , mortgage loans require a capital adequacy ratio higher than the one required for loans to firms. Therefore, a bank could be in the situation of fulfilling the capital requirements for firms' loans but not for mortgages. In particular, when the amount of risky assets of a bank becomes high, thus raising bank's leverage, loans are preferred to mortgages and the proposed banking regulation becomes effective.

3 Computational experiments

A number of computational experiments were performed in a simulation setting characterized by 3,000 households, 50 consumption goods producers, three banks, one capital goods producer, one power producer, one government, and one central bank. Table 1 reports the values of the parameters characterizing the housing and the energy sectors. The whole set of parameter values of the model is available in Teglio et al. (2017).

The aim of the computational experiments is to assess the impact of differentiating banks' capital requirements based on the type of credit provided, i.e. between mortgages to households for house purchase and loans to firms for productive investments. The rationale behind this choice is the assumption that house purchases are made mostly for speculative purposes and may produce asset bubbles with destabilizing effects, while loans to business firms are aimed to increase their capital endowment with long-run positive effects for the productive capacity of the economy. Banking regulation should then favor lending to business firms with respect to lending for house purchases, e.g. through setting lower capital requirement in the former case. A similar proposal has been set out by Campiglio (2016) to spur green investments, at the expenses of speculative ones, as an alternative to carbon taxation.

To investigate the issue, we have designed a set of computational experiments characterized by capital requirements for mortgages that can be higher or lower than a reference value, i.e. 10%, which is the basic capital requirement value adopted

Table 1 Housing and energy sectors parameters values used in the simulations

Symbol	Parameter	Value
Φ	Probability for a household to be active in the housing market	0.5
θ_{fs}	Fire sale threshold as a fraction of household's income	0.6
θ_d	Mortgage default/write-off threshold as a fraction of household's income	0.7
ψ_{up}	Maximum percentage increase of sale price offer	2.5%
ψ_{down}	Maximum percentage decrease of sale price offer (fire sale case)	5%
DSTI	Debt service-to-income ratio	0.5
ξ_O	Monthly growth rate of fossil fuel price	0.5, 0.0, -0.5%
μ_E	Energy price mark-up on fossil fuel price	100%
ξ_K	Monthly exponential de-growth rate of capital goods energy intensity	0.2%

for business loans. In our model design, investments in capital goods provide also an environmental benefit, as the new vintages are characterized by higher energy efficiency.

In the following, we use the maximum leverage allowed to banks, henceforth α , i.e. the inverse of the capital requirement ratio Ψ , to parameterize the computational experiments, as it is more intuitive. In particular, the value of α is set to 10 (the inverse of 10%) for all types of loans during the first year of any simulation, while since the second year α is differentiated into a α_L for business loans and a α_M for mortgages. The maximum allowed leverage α_L is then kept at 10 for loans to firms, whereas, in the case of mortgages, α_M is changed to a lower or higher value in the range from 0 to 20 and the new value is maintained for the rest of the simulation. The values assumed by α_M are (0, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 17, 20). It is worth noting that the grid for α_M is not equally spaced from 0 to 20 but is more dense around $\alpha_M = 8$, where indeed we observe the most interesting behavior of the observed economic variables.

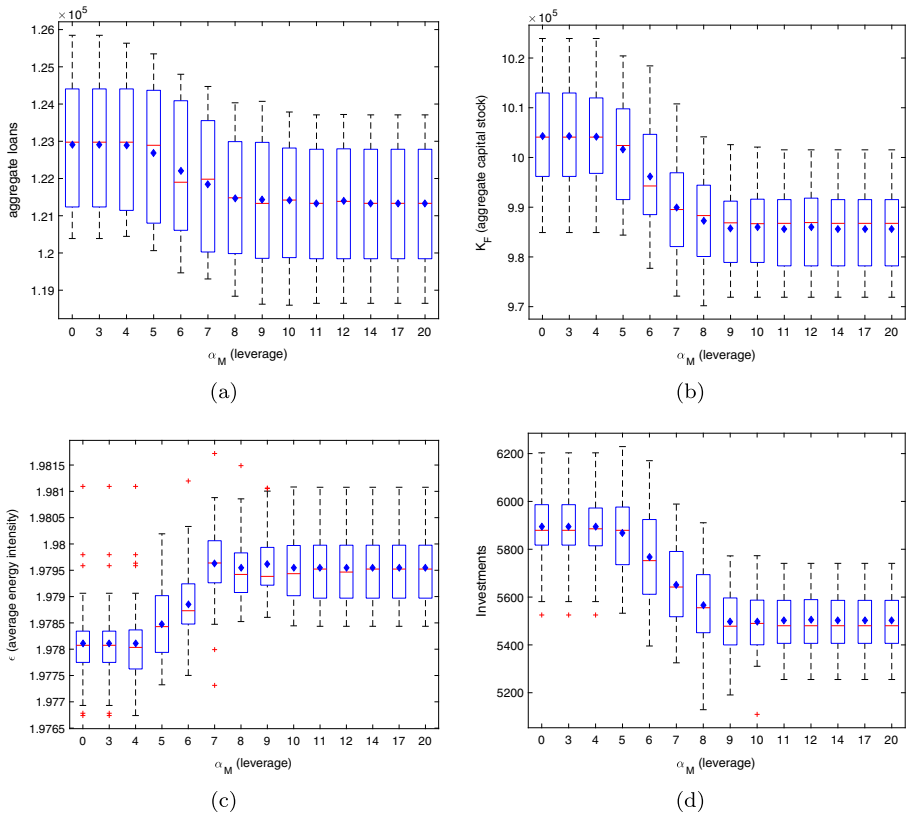


Fig. 2 The four panels represent aggregate loans (a), aggregate capital stock (b), average energy intensity (c) and aggregate investments (d), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 50 seeds (simulations). As for energy intensity and capital stock, we report the value at year six instead of the time average along the five years period

Furthermore, it should be considered that zero is quite an extreme value that α_M can assume, as it means that no more mortgages are granted.

For any value of α_M considered, 50 different simulations have been performed, depending on the seed of the pseudorandom number generator. Figures 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 show the distribution of some relevant economic variables for any value of α_M considered. In particular, the distributions are represented as boxes that include all the values from the 25th to the 75th percentile and with horizontal segments and diamond markers that represent the median and the mean of the distribution, respectively. Box-plots also include whiskers extending to the most extreme data points not considered outliers, while outliers are plotted individually.

For every seed (simulation), we consider the time average over two given time periods in order to differentiate a short run and a long run. In this respect, the box-plot figures can be organized into two different groups, where the first group, from Figs. 2 to 6, reports the time averages from year two to year six included, i.e. the first five years after the differentiation of capital requirements, while the second group, from Figs. 7 to 11, presents the time averages over the following ten years, i.e. from year

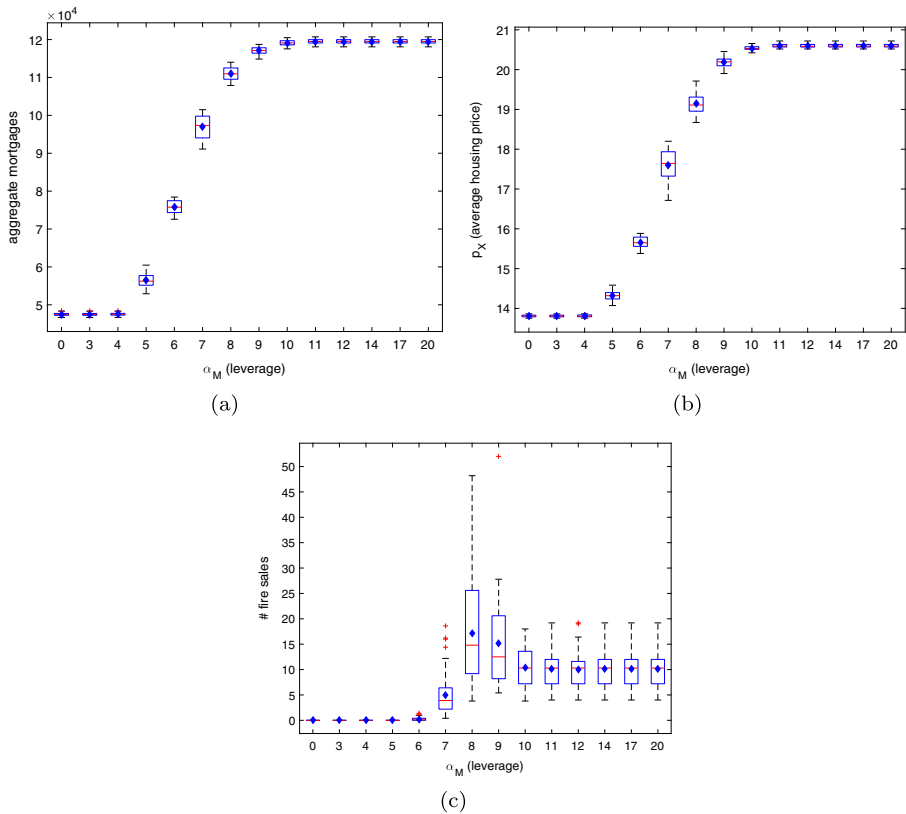


Fig. 3 The three panels represent aggregate mortgages (a), average housing price (b), and the number of average fire sales (c), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 50 seeds (simulations)

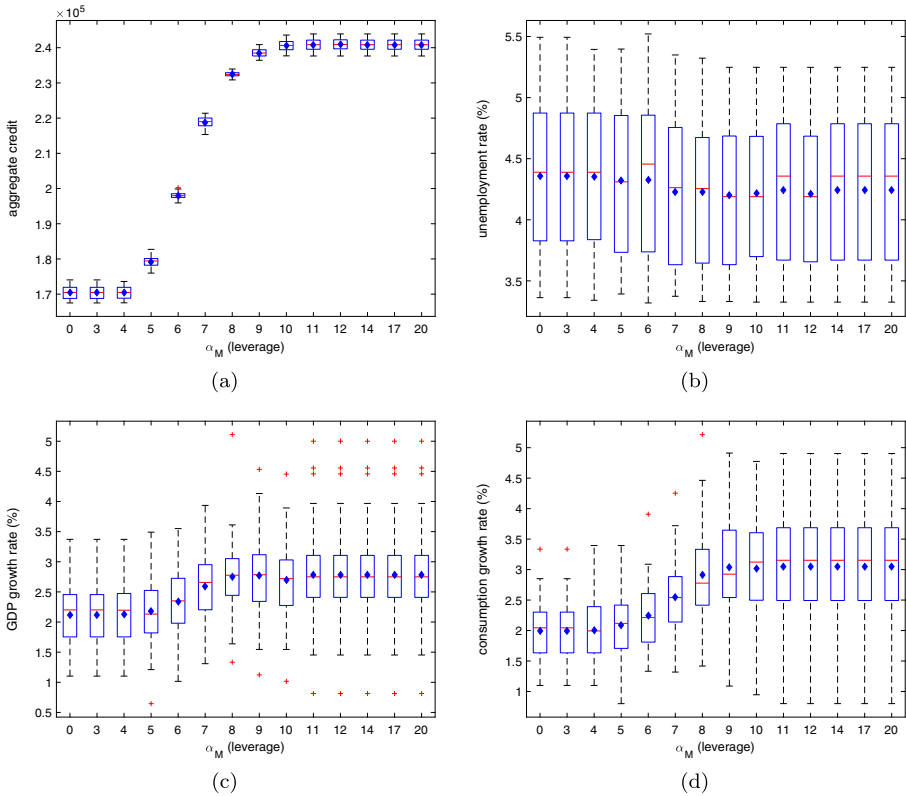


Fig. 4 The four panels represent total credit (loans + mortgages) (a), the real GDP growth rate (c) and the real consumption growth rate (d), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 50 seeds (simulations)

seven to year 16. The first simulation year has not been considered in the computation of the time averages because in this period α_M is not yet differentiated but set to 10 in all cases. To conclude, results have been divided into two periods that can be considered as a short/medium run period for the first five years and a long-run period for the following 10 years.

The first time window has been set to five years because this is the time span where the effects of the change of α_M are observed to be more relevant and statistically significant on productive investments. In particular, in panel (a) of Fig. 2, we can observe that both the average and the median values of the loans distribution have clearly higher values when α_M is lower than 8. We employ the Wilcoxon rank sum test to verify the null hypothesis that the data reported for different values of α_M are taken from distributions with equal medians. If we assume the null hypothesis that the distributions of loans for $\alpha_M = (0, 3, 4)$ have the same medians of the distributions for $\alpha_M \geq 6$, this is rejected at the significance level of 5%. Therefore, a regulatory action that decreases substantially the maximum allowed leverage (or, equivalently, increases the capital requirements) for speculative investments, here

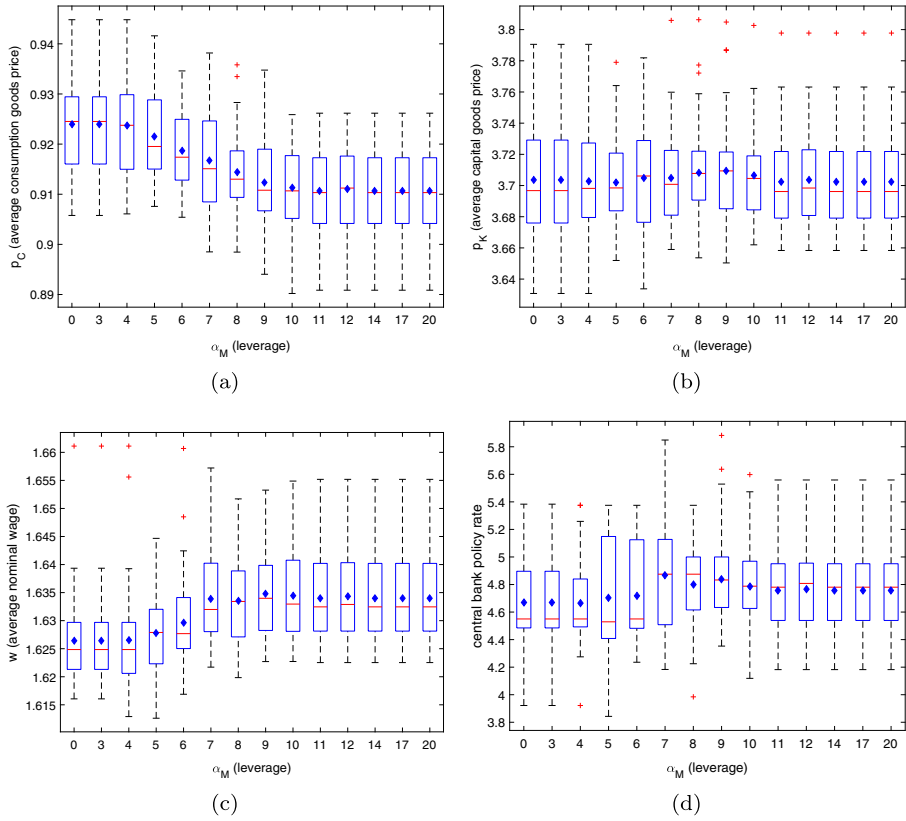


Fig. 5 The four panels represent consumption goods price level (a), capital goods price level (b), nominal wage level (c) and central bank interest rate (d), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 50 seeds (simulations)

proxied by mortgage debt for house purchase, is effective in diverting credit from speculative to productive investments, at least in the short run (first five years). This is also evident when we observe investments and the aggregate capital stock of the economy, panel (b) and (d) of Fig. 2, as well as the average energy intensity ϵ , i.e., the amount of required energy for unit of output, panel (c) of the same Figure. The higher pace of investments for low α_M , because of more credit available, implies newer vintages for firms' capital goods and therefore lower energy intensity on average for the aggregate capital endowment. Panel (b) of Fig. 2 shows that the medians of the distribution of the aggregate capital stock in the economy are clearly higher for values of α_M lower than 9. In particular, we observe a downward transition of the accumulated capital stock from $\alpha_M = 4$ to $\alpha_M = 9$. According to the Wilcoxon rank sum test, the difference is statistically significant at the significance level of 1%. Consistently, we get a lower average energy intensity for lower α_M ; see panel (c) of Fig. 2. Also in this case, the difference is statistically significant. It is worth noting that the

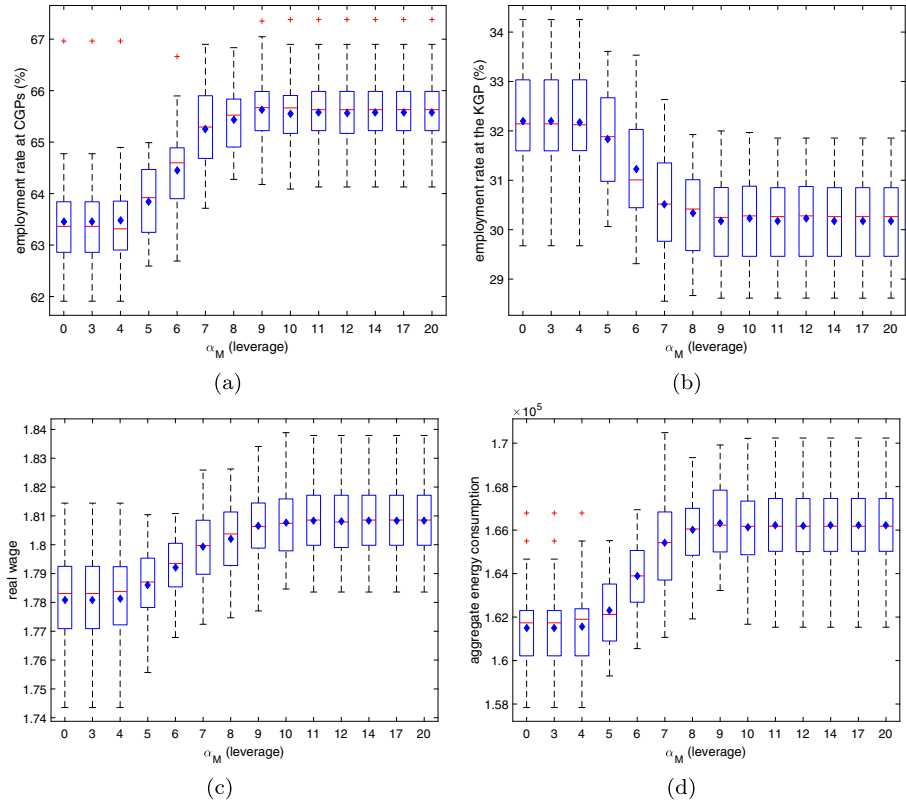


Fig. 6 The four panels represent the employment rate in the consumption goods sector (a), the employment rate in the capital goods sector (b), the real wage level (c) and the aggregate energy consumption (d), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 50 seeds (simulations)

differences in the main variables of Fig. 2 are statistically significant in the range of α_M from four to nine, confirming that this is a quite critical transition interval.

Figure 3 presents the main results related to the housing market. In particular, we can observe that, as expected, the aggregate amount of mortgages (panel a) is very sensitive to the value of α_M as well as the average housing price (panel b). The looser the banking regulation for mortgages, the higher the average housing price, therefore increasing the likelihood of credit-driven housing market bubbles and raising the instability of the housing market. In particular, the increase in the average numbers of fire sales in the housing market, as pointed out by panel (c) of Fig. 3, is due to the growing difficulty faced by some households to make mortgage payments. This increases the probability of housing bubble bursts, with possible destabilizing effects on the real economy through the lending channel.

Ozel et al. (2016) present a detailed discussion about the effects of credit regulation on the housing market dynamics in Eurace and the possible destabilizing effects of housing bubble busts on the real economy.

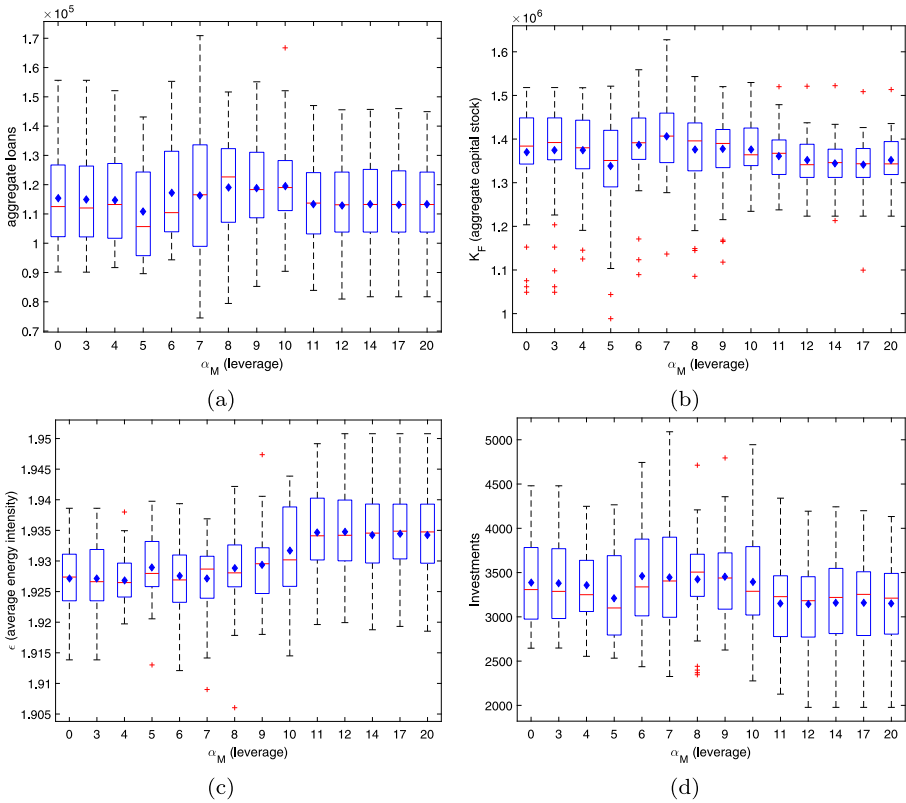


Fig. 7 The four panels represent aggregate loans (a), aggregate capital stock (b), average energy intensity (c) and aggregate investments (d), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 50 seeds (simulations). As for energy intensity and capital stock, we report the value at year 16 instead of the time average along the ten year period

Figure 4 presents the effects of the differentiated loan *versus* mortgage requirements on the real economy. While the medians of the distribution of unemployment rates (panel b) do not exhibit both graphically and statistically significant differences for different values of α_M , we can clearly observe from panel (c) that GDP growth rates are significantly higher for $\alpha_M \geq 8$. For lower values of α_M , we have observed already higher investment rates, as pointed out by higher levels of loans and capital accumulation showed by panel (a) and (b) of Fig. 2, respectively. The difference in GDP growth rates can be only explained by a even greater difference in the consumption growth rates that should offset the contribution to GDP by higher investment rate at low α_M . This is actually what we observe in panel (d) of Fig. 4. Therefore, the increase of investments rates is realized at the expense of consumption growth rates; but while, on the one hand, the combined effect looks neutral for unemployment, on the other hand, it is not neutral for GDP growth rates, pointing out an important drawback of increasing capital requirements for mortgages. We argue that the explanation of this finding is twofold and concerns both supply and demand side aspects. On

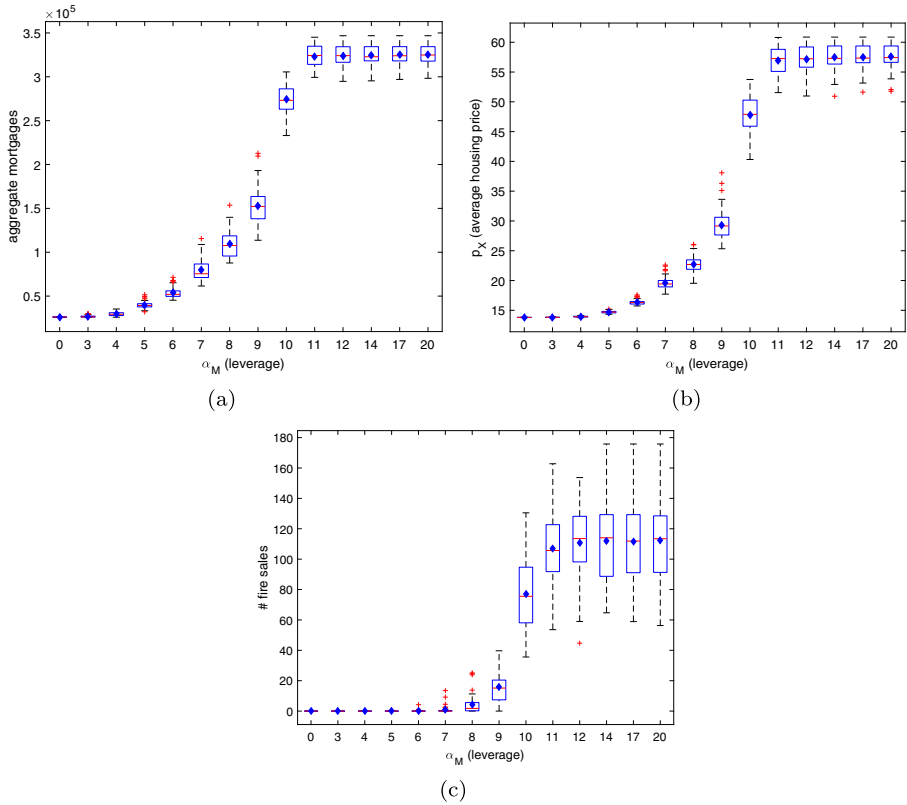


Fig. 8 The three panels represent aggregate aggregate mortgages (a), average housing price (b), and the number of average fire sales (c), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 50 seeds (simulations)

the supply side, we understand that fostering investments requires additional labor force employed at the capital goods producer; however, due the internal dynamics of the economy, the overall net result is not a reduction of unemployment but a sort of crowding out effect that diverts the labor force from the consumption goods sector to the capital goods one; see in particular panel (a) and (b) of Fig. 6. On the demand side, we observe that the reduction of mortgages at low α_M is not fully compensated by the increase of loans, as the total aggregate credit in the economy, i.e. the sum of mortgages and loans, reported by panel (a) of Fig. 4, exhibits a strong increase for high values of α_M similar to the one of mortgages. Our previous studies (see, e.g., Raberto et al. 2012; Teglio et al. 2012; Cincotti et al. 2012b) have shown how the level of credit in the economy, i.e. the level of credit money endogenously generated by the banking system, positively affects economic growth, at least in the short term. This happens through the supply side channel, i.e. the availability of resources to firms for investments, as well as through the demand channel, via the higher capital income of households, as shareholders of highly profitable banks, and via the higher general money supply that automatically translates to higher nominal demand.

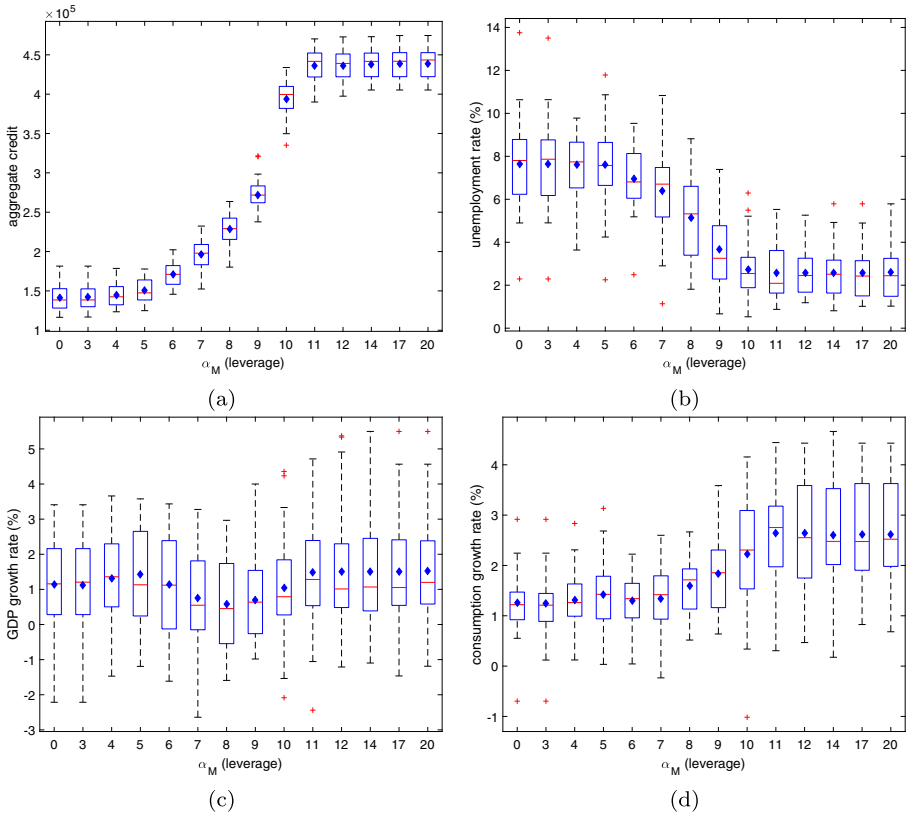


Fig. 9 The four panels represent total credit (loans + mortgages) (a), the unemployment rate (b), the real GDP growth rate (c) and the real consumption growth rate (d), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 50 seeds (simulations)

Furthermore, both our recent work (Ozel et al. 2016) and empirical evidence (ECB 2013, pag. 21, Chart D) point out that mortgages seem positively cross-correlated with economic activity and, differently from loans, seem to lead the business cycle.

Figure 5 shows the effects of the policy on prices, i.e., the consumption and the capital goods price level, the nominal wage and the central bank policy rate. The main result is that, while the distribution of capital goods prices is both graphically and statistically independent of the value α_M (see panel (b)), both consumption goods prices (panel a) and nominal wages (panel c) depend on it, yet in an opposite way. It is worth noting that the level of nominal wages in the model depends on the labor market status; in particular, when unemployment is low, firms may face labor shortage and then compete to attract workers by rising their wage offer. (See Dawid et al. 2014; Teglio et al. 2017 for more details on the Eurace labor market.) The distribution of unemployment rates looks scarcely dependent on α_M (see panel (a) of Fig. 4); however, the median values of nominal wage does depend on α_M (see panel (c) of Fig. 5). This evidence can be explained considering that the higher α_M , the tighter the labor market competition among CGPs, as shown by the employment rate in the

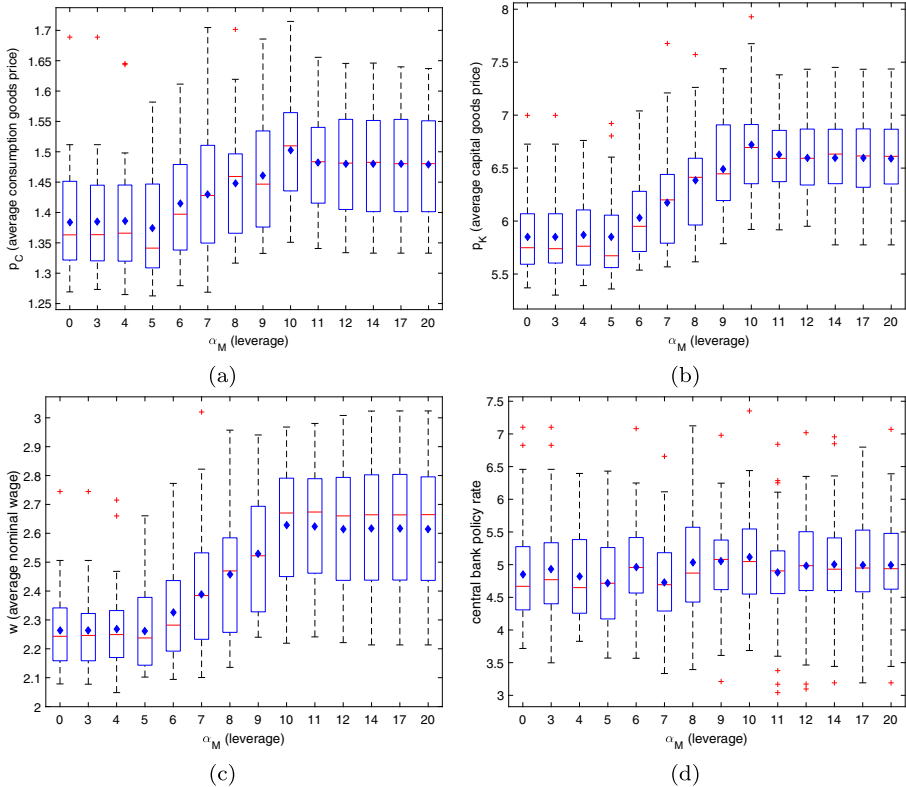


Fig. 10 The four panels represent consumption goods price level (a), capital goods price level (b), nominal wage level (c) and central bank interest rate (d), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 50 seeds (simulations)

consumption good sector (see panel (a) of Fig. 6); on the other hand, at low α_M , the competitive effort to attract workers mainly regards the capital good sector, which is characterized by just one single player, differently from the consumption goods sector, where many agents operate.

Interestingly, higher labor costs do not translate into higher consumption goods prices. Indeed, CGPs apply mark-up pricing where unit costs are given by labor costs, energy cost and debt service cost, where the first two costs are variable costs and the latter is a fixed cost; see Teglio et al. (2017) for more details on the Eurace mark-up pricing. Therefore, higher consumption goods prices are clearly explained by the interests cost of the higher debt burden to which CGPs are subject at lower α_M (see panel (a) of Fig. 2). Higher consumption goods prices combined with lower nominal wages have, of course, a depressing effect on real wages, as also reported on panel (c) of Fig. 6, thus pointing out another negative consequence of a policy aimed at increasing capital requirements limited to mortgages.

To summarize our findings so far, the strategy of increasing capital requirements for mortgages has proven to be successful in fostering investments and capital

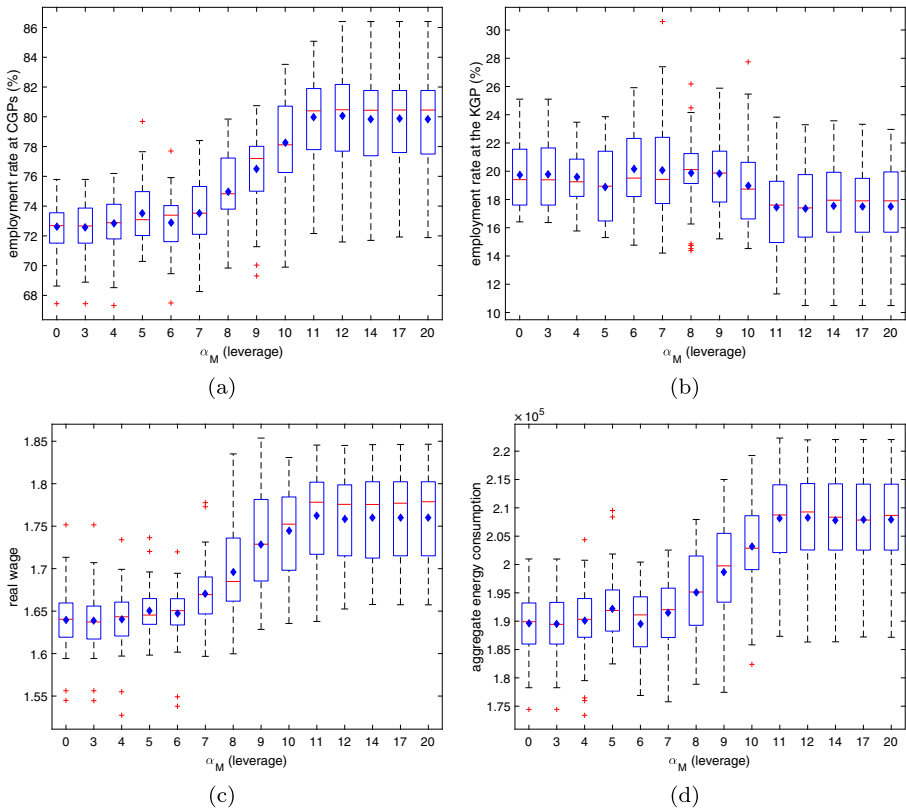


Fig. 11 The four panels represent the employment rate in the consumption goods sector (a), the employment rate in the capital goods sector (b), the real wage level (c) and the aggregate energy consumption (d), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 50 seeds (simulations)

accumulation in the short term (five years), and consequently in improving energy efficiency (reducing energy for unit of output) of firms because of the newer vintages of capital goods available. However, these results are achieved at some welfare costs for households, which can be summarized in lower consumption growth rates and purchasing power.

The next part of the paper examines whether these results are confirmed in the long run, i.e., in the following 10 years. Figures 7–11 present the distributions as box-plots of the same economic variables presented in Figs. 2–6, yet in a different time period, i.e. from year seven to year 16, instead of from year two to year six. Figure 7 shows that, while the distribution of energy intensity (panel a) still exhibits both a graphically and statistically significant pattern for different values of α_M , the distribution of loans, capital stock and investments, are less affected in the long run than in the short run. This means that, during the 10 year period, some counterbalancing force in the economic system is seriously weakening the effects of a regulation, which is *de facto* reducing total mortgage loans (as shown in Fig. 8). We think that this counterbalanc-

ing effect is mainly due to the lower amount of total credit in the economy, which in turn reduces the level of endogenous money. In the long run, when α_M is decreased in order to limit mortgages, the economy suffers from the demand side. Consumption growth is critically reduced and consumption goods producers have therefore to scale down production and employment. We see that the unemployment rate is increasing in the long run, from an average of 2% to an average close to 8% when mortgages are hindered. In the first five years, the aggregate credit for low α_M values is reduced by a 30% with respect to high α_M values, while in the next ten years, the difference grows to 66%, showing that the loss in mortgages and endogenous money accumulates during the years undermining aggregated demand. (See Ozel et al. 2016 for further details.) Actually, consumption growth rates suffer a 50% loss in the long run when α_M is low, against a 33% loss in the short run. It is also worth noting that investment decision-making by firms is based on net present value calculations, where expected demand plays a crucial role (see Teglio et al. 2017 for further details). This explains to some extent why total loans depend on consumption, and why we do not observe a significant increase of loans when a mortgage-restricting policy is adopted.

Thus, our simulations show that, in the long run, the effects of a mortgage-restricting policy are mainly negative. For very low values of α_M the policy is basically freezing the housing market (see the patterns related to the level of mortgages and the housing price in Fig. 8), with negative outcomes for the real economy, as shown in Fig. 9. For higher values of α_M , the mortgage markets re-activates, showing of course more instability, characterized by increasing fire sales. In the long term, the advantage for lower leverages in term of capital stock accumulation during the short term is no more valid. It still exists an advantage in term of energy efficiency, with an environmental benefit related to energy consumption, however at the price of an increasing welfare costs, which, in the long term, does not concern only purchasing power and consumption rates but also unemployment rates.

Finally, we performed a robustness check allowing for different fossil fuel price trends. In particular, we considered a constant price trend ($\xi_O = 0$) and a negative monthly exponential growth $\xi_O = -0.5\%$ (downward trend), which are compared with the monthly price growth rate $\xi_O = 0.5\%$ (upward trend) that has been used to obtain the previous results.

It is worth noting that the 0.5% monthly growth rate, i.e. an annual growth rate more than 6%, encompasses the wide range of forecasts about the oil price made by relevant international institutions. In particular, the U.S. Energy Information Administration¹¹ (EIA) long-term forecasts set the oil price annual growth rate at 3% in real term and at 5.1% in nominal term from now to 2050. By contrast, previsions by the World Bank¹² up to 2030 are much more conservative and characterized by an annual growth rate of only 2.1% in nominal term and then by a substantial stability if the oil price is measured in constant US dollars. Finally, the IMF projections,¹³ limited to

¹¹<https://www.eia.gov/outlooks/aeo/pdf/appa.pdf>

¹²<http://pubdocs.worldbank.org/en/678421508960789762/CMO-October-2017-Forecasts.pdf>

¹³<https://www.imf.org/en/Publications/WEO/Issues/2017/09/19/~media/Files/Publications/WEO/2017/October/pdf/main-chapter/tblparta.ashx>

2018, point out that the oil price for the year to come should remain stable in nominal terms, around 50 USD per barrel. These forecasts are very different from each other, even in the long term, thus highlighting the intrinsic difficulty in correctly predicting future oil price fluctuations; see e.g. Baumeister and Kilian (2016). We therefore think that it would not be particularly meaningful to stick to a particular forecast and then to calibrate the system to its value. Actually, agent-based macro-models are fruitfully employed as computational laboratories to perform what-if analysis about how the economy is affected by a particular hypothesis (e.g. on the annual growth rate of oil price) and how some economic policy will work under the same hypothesis, without any strong claim that this hypothesis will be the one observed in the real world. In accordance with this perspective, we have considered the highest value, among the official forecasts examined, for the growth rate of oil price and we have then performed additional computational experiments considering both a constant price and a decreasing trend for fossil fuels. The main outcomes, collected in Figs. 12 and 13, show that all the essential results of the paper are confirmed, and that the impact of the “green capital requirements differentiation” policy does not depend on the price trend of fossil fuel. The box-plots have been organized in two figures. Figure 12 reports the time averages from year two to year six included, i.e. the first five years after the differentiation of capital requirements, while Fig. 13 presents the time averages over the following ten years, i.e. from year seven to year 16.

Figure 12 clearly shows how inflation of fossil fuel price affects directly the level of consumption goods prices. In turn, the level of prices affects all the nominal values of the economic indicators. For example, we note that the amount of nominal loans raises with the price. We can also note that loans are increasing with “green incentives” (low α_M) in the three considered cases. The same holds for the accumulation of firms’ capital stock, which is always higher when “green incentives” are stronger. Therefore, the main result on the energy intensity is also confirmed. The higher capital stock level (the plot represents real units of capital stock) for higher fossil fuel prices can be explained by two main arguments. From the supply side, “green incentives” favor loans to firms over mortgages, as previously discussed, decreasing firms’ chance to be rationed in the credit market and therefore raising the probability carrying out investments successfully. From the demand side, the higher inflation in consumption price, driven by fossil fuel price inflation, increases the expected nominal profits and leads to a higher demand for capital goods and loans.

The other main results of the paper are also confirmed. For instance we see in Fig. 12 an employment shift from consumption goods producers to capital goods producers when α_M decreases. This result is due to the higher activity of the KGP, and is not altered by different price trends.

Concerning the long run outcomes of the simulations, what has been observed in the paper, is still valid. The housing market freezing for low α_M , causes a credit contraction that finally affects employment and economic activity. In Fig. 13, both the credit contraction and the higher unemployment rate are visible.

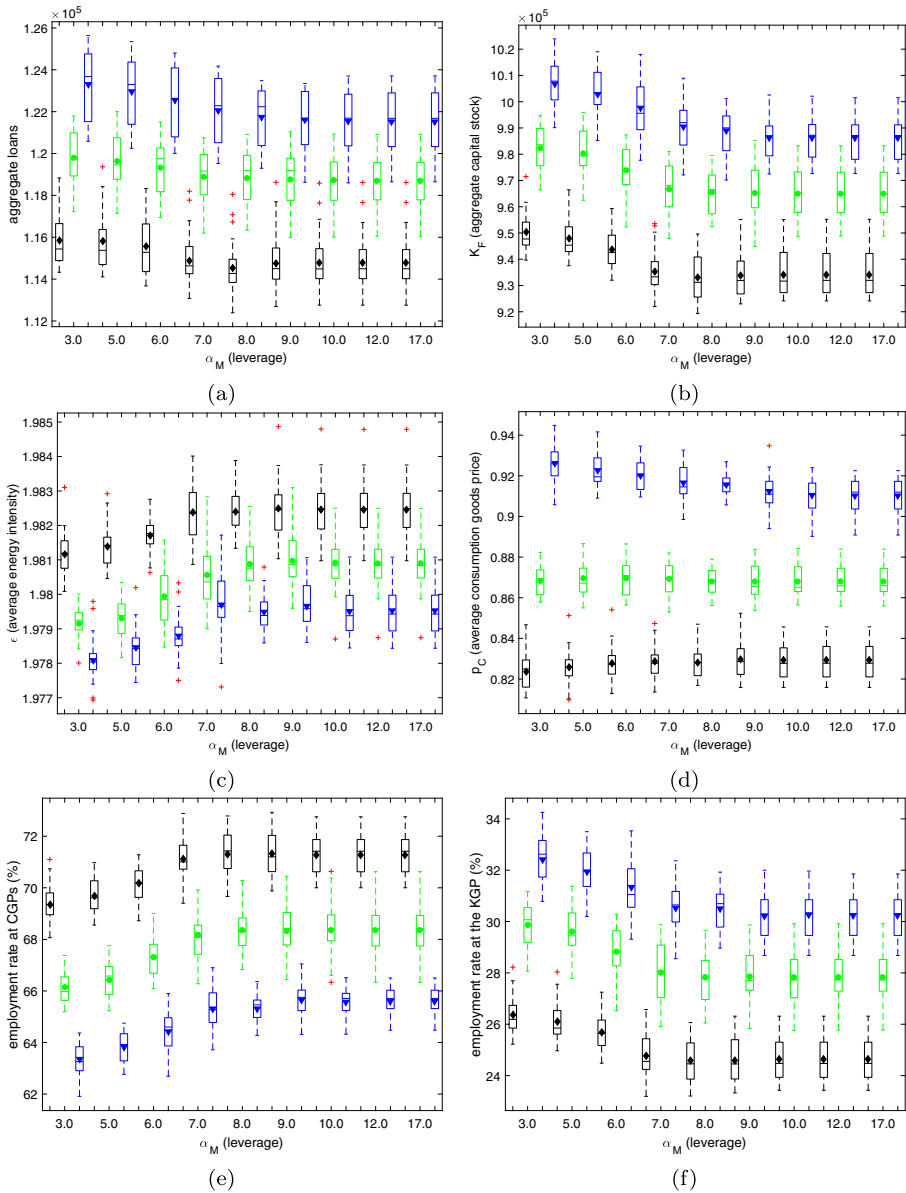


Fig. 12 The six panels represent the aggregate loans (a), the aggregate capital stock (b), the average energy intensity (c), the consumption goods price level (d), the employment rate in the consumption goods sector (e), the employment rate in the capital goods sector (f), respectively. The boxplots report for each value of α_M considered the time averages from year two to year six for any of the 25 seeds (simulations). The black boxplots represent the case of decreasing fossil-fuel price ($\xi_o = -0.5\%$), the green boxplots represent the case of constant fossil-fuel price ($\xi_o = 0.0\%$) and the blue boxplots the case of increasing fossil-fuel price ($\xi_o = 0.5\%$), considered in the previous figures. The diamond marker represent the mean in the black case, the circle marker in the green case and the triangle in the blue case

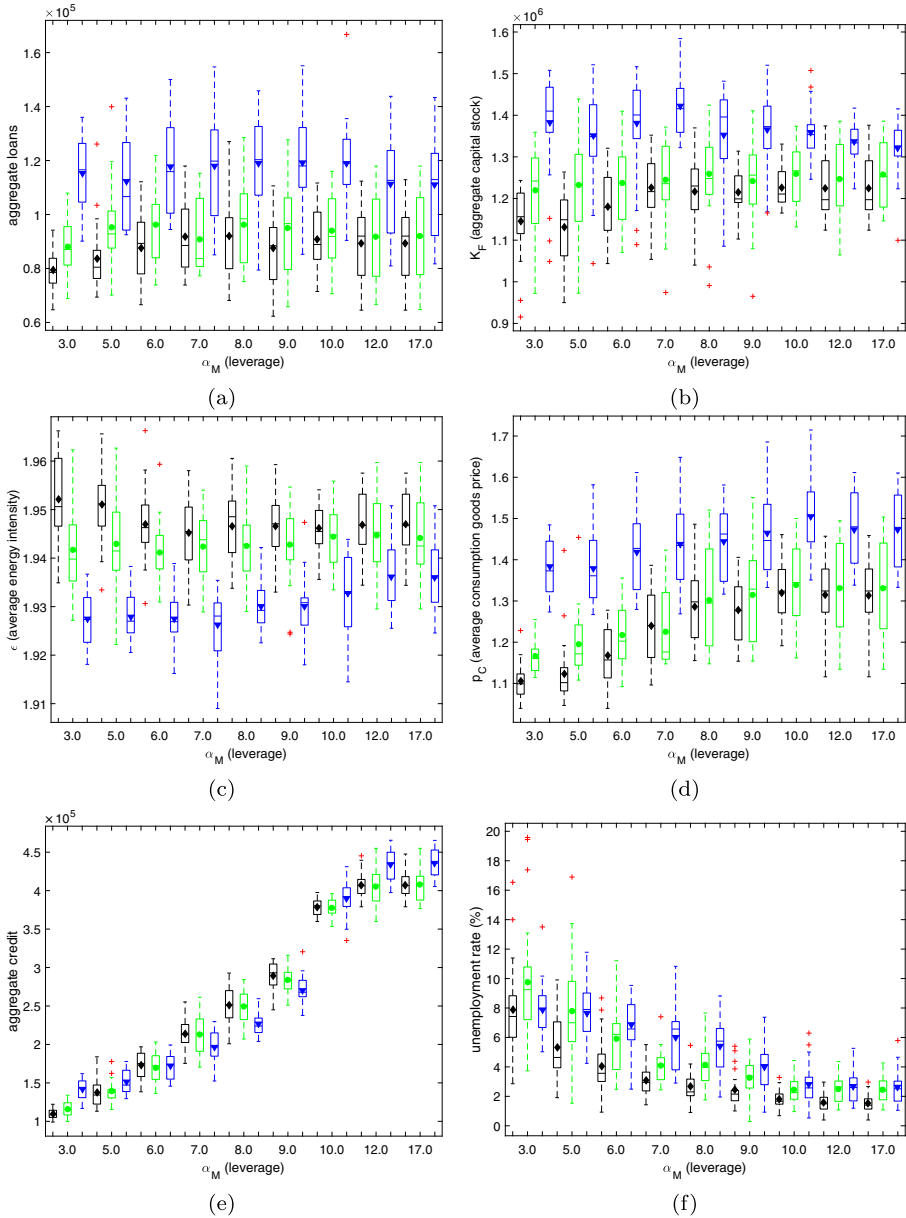


Fig. 13 The six panels represent the aggregate loans (a), the aggregate capital stock (b), the average energy intensity (c), the consumption goods price level (d), total credit (loans + mortgages) (e), the unemployment rate (f), respectively. The boxplots report for each value of α_M considered the time averages from year seven to year 16 for any of the 25 seeds (simulations). The black boxplots represent the case of decreasing fossil-fuel price ($\xi_o = -0.5\%$), the green boxplots represent the case of constant fossil-fuel price ($\xi_o = 0.0\%$) and the blue boxplots the case of increasing fossil-fuel price ($\xi_o = 0.5\%$). The diamond marker represent the mean in the black case, the circle marker in the green case and the triangle in the blue case

4 Concluding remarks

Inspired by some recent proposals, aimed at promoting green investments at the expense of speculative ones, we designed a set of computational experiments within the agent-based model Eurace. We devised a simple regulation for banks in order to incentivize loans to firms with respect to real estate mortgage lending. The regulation consists in demanding higher capital requirements for banks in the case of mortgages, thus encouraging banks to give loans to firms. As up-to-date capital goods have better energy efficiency in the model design, a higher pace of investments implies lower energy intensity per unit of produced consumption goods, energy savings and a positive environmental externality. Simulations' outcomes suggest that the regulation is successful in promoting investments and capital accumulation in the short term, and consequently in improving energy efficiency of firms. However, these results are achieved at some welfare costs for households, which can be summarized in lower consumption growth rates and purchasing power. The reason is that reducing mortgages with a restrictive regulation has a negative impact on the total private credit in the economy, and therefore on the endogenous money supply. This, in turn, reduces consumption and aggregate demand.

In the long term, the contraction of total credit increases, and the negative outcomes on aggregate demand become more serious, reducing firm investments. Therefore, in the long run, the positive effects on capital and energy efficiency become negligible, while the main economic indicators show a period of recession.

Furthermore, in line with previous experiments, our model shows the important role of endogenous money in the economy. Mortgages and loans represent the crucial way to channel money to households, and if they are hindered, all the economy suffers, reaching higher unemployment rates. Besides, the model has also shown that a loose regulation of mortgages can lead to instability in the housing market with negative repercussion on the real economy. This means that a fine tuned regulation that keeps into account the business cycle dynamics is probably needed. Our next step will be to implement this fine tuning, considering macro-prudential rules, or more sophisticated regulations with the goal to foster green investments, on the one hand, and to provide enough credit to sustain the performance of the economy, on the other hand.

Furthermore, it is worth discussing the scope and the limitations of our study. To the best of our knowledge, this is the first attempt to validate through computational experiments a recently proposed banking regulatory framework (Campiglio 2016) aimed to foster green investments. An agent-based macroeconomic model environment, where endogenous money created by the banking system plays a crucial role in determining economic dynamics, has been employed for this purpose. Important simplifying assumptions that may limit the validity of our results have been made. In particular, we assume an exogenously given technological progress that grows the energy efficiency of capital goods. This assumption has been quite common among the seminal contributions in climate change economics (see e.g. Nordhaus 1994; Nordhaus and Boyer 2000; Stern 2009), which have been mostly

focused on computable general equilibrium models with exogenous technology. More recently, Acemoglu et al. (2012) and Acemoglu et al. (2016), building on pioneering work on the interaction between endogenous innovation and environmental policies (see e.g. van der Zwaan et al. 2002; Popp 2004), introduce a comprehensive growth model with environmental constraints characterized by endogenous and directed technical change, showing, among other things, that models characterized by exogenously-given technological progress overstate the economic costs of environmental regulation. The overestimation of environmental policy costs, which in our setting can be identified as the observed long-run growth gap in the case of strict bank capital regulation for mortgage lending, may in principle occur also in our model, where technological progress is exogenously given. However, it is worth remarking that the Acemoglu et al. model is very different with respect to the model discussed in this paper, both in term of modeling approach (general equilibrium versus out-of-equilibrium dynamics) and policy instrument (carbon tax and research subsidies versus banking regulation); therefore, we argue that this problem is not necessarily present in our analysis. Furthermore, we point out that while the energy efficiency of up-to-date capital goods is exogenously given, the average energy efficiency of each consumption goods producer is path dependent and endogenously determined by its investment choices. Therefore, our model construction takes into account at the level of the single firm the path dependency of technological endowment, as in the Acemoglu et al. model. In any case, future model developments will address the issue of endogenous technological change.

Finally, while the policies investigated by Acemoglu et al. can be considered as market-based policies, i.e. characterized by monetary incentives and price signals, the bank capital adequacy ratio policy employed in our experiments can be classified among the command-and-control policies, i.e. based on the setting of quotas and quantity thresholds. Many studies have compared the effects of market-based and command-and-control policies (see e.g. Hepburn 2006; Goulder and Parry 2008) for extensive comparisons. Recently, Lamperti et al. (2015), building on the model by Acemoglu et al. (2012), showed that command-and-control interventions guarantee policy effectiveness irrespectively of the timing of their intervention, differently from market-based ones that instead are characterized by bounded window of opportunity.

Our future research will surely investigate the effectiveness of a carbon tax in fostering capital goods investments by firms to raise their average energy efficiency and will compare the results with the command-and-control policy adopted in this study.

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Conflict of interests The authors declare that they have no conflict of interest.

Appendix

A1 - The housing market

The housing market is active every first day of the month. Households play the role of buyers and sellers in the market and can sell or buy one housing unit at a time; housing units are homogeneous. The market is characterized by decentralized exchange and posted prices set by sellers.

Household decision making about house purchase and sale is mainly subject to random behavior in order to give more relevance to the credit implications and their impact on the economy as a whole, rather than on the behavioral aspects of the housing market. In particular, the parameter Φ sets the probability for each household to be active in the housing market the first day of each month, unless the household is financially distressed, i.e. he is facing mortgage payments (interests + principal) higher than a given fraction θ_{fs} of his income (labor + capital), where both mortgage payments and income refer to the last quarter. If randomly selected to be active, the household can assume the role of buyer or seller with equal likelihood. By contrast, if financially distressed, say the fire sale case, we stipulate that the household enters the market to sell one housing unit at a discounted price with respect to the last average market price, so as to increase the likelihood that a transaction takes place, in order to reduce the mortgage burden as well as the debt service. Furthermore, in the case the ratio between quarterly mortgage payments and quarterly income is higher than the threshold θ_d , where $\theta_d > \theta_{fs}$, then the household defaults on his mortgages, which are partially written-off with a consequent loss on the balance sheet of the lending bank.

If a household is randomly selected to enter the housing market with a seller role, then he posts one of his housing units for sale at higher price than the previous month average market price. In particular, the selling price is higher by a percentage value, which is a random draw uniformly distributed between 0 and ψ_{up} . This model feature can be justified based on the assumption that households randomly selected for the seller role do not have any particular necessity to liquidate their housing units. Therefore, we make the reasonable assumption that they are considering the sale of a housing unit only if they can realize a small random gain with respect to the latest average housing market price. Conversely, if a household enters the market with a seller role because financially distressed (fire sale case), then to facilitate liquidation, we assume he posts one of his housing units for sale at a lower price than the previous average market price by a percentage value that is a random draw uniformly distributed between 0 and ψ_{down} .

Households that have been randomly selected as buyers are randomly queued and in turn select to purchase the cheapest available housing unit. A transaction takes place at the posted sale price if the household is able to get a mortgage from a bank to cover the entire value of the house. Therefore, for the sake of simplicity, we assume that all granted mortgages are characterized by a loan-to-value (LTV) ratio equal to one, and so households do not use their liquidity when buying a housing unit but just money borrowed from a bank. This modeling feature has been chosen in

order to avoid a direct and simultaneous interaction of the housing market purchasing behavior with the saving and investing decision in the financial market. In the case a transaction takes place, the selling agent repays back to the bank the mortgage associated with the sold housing unit. The housing market session closes when all buyers had their turn or there are no more houses for sale. A new housing price is then computed as the average of realized transaction prices.

Banks can provide variable-rate mortgages to households; the annualized mortgage rate is determined on a monthly basis as a mark-up on the rate set by the central bank. Households are due to reimburse the mortgage over a period of 30 years through monthly mortgage payments which include both the interests and the principal installment. Principal installments for each mortgage are constant over the repaying period and are computed as a ratio between the initial mortgage amount and 360, i.e. the mortgage duration in months. Monthly interest payments are determined by the outstanding mortgage principal and the annualized mortgage rate divided by 12, i.e., the number of months in a year. Banks, whenever they receive a mortgage request by a household, assess his capability to afford mortgage repayments by comparing household's net income (both labor and capital) earned in the last quarter with household's expected quarterly mortgage payments, including both old outstanding mortgages and the new requested mortgage. Banks grant the requested mortgage provided the capital requirement rule is fulfilled and the ratio between expected quarterly mortgage payments of the household and his latest net quarterly income is lower or equal than a pre-determined threshold, which is called debt-service-to-income (DSTI) ratio.

A2 - Stocks and flows accounting

This section provides a compact description of the model according to the "stock-flow consistent" approach along the lines introduced by Godley and Lavoie (2012). This approach allows us to check the consistency between stocks and flows in the model, both at the level of the single agent and at the aggregate one, in line also with post-Keynesian stock-flow-consistent modeling approach; see also Caverzasi and Godin (2015).

A detailed description of the behavioral rules characterizing each agent is reported in Teglio et al. (2017), whereas the details of the housing market mechanism are illustrated in Ozel et al. (2016).

Here, we present three matrices that show:

- Agent class balance sheets
- Sectorial balance sheet
- Stock and monetary flows among sectors.

In particular, Table 2 reports the balance sheets of each agent class that populates the Eurace economy. Table 3 shows all assets and liabilities for each sector (here a sector is the aggregate set of agents belonging to the same class). Finally, Table 4, called transaction flow matrix, shows all the stock and monetary flows among sectors.

Table 2 Agent class balance sheets

Agent class	Assets	Liabilities
Household <i>abbrev.</i> : HH <i>index</i> : $h = 1, \dots, N_{Hous}$	Liquidity: M_h Stock portfolio: $\sum_b n_{E_{h,b}} p_{E_b} +$ $\sum_f n_{E_{h,f}} p_{E_f} +$ $n_{E_{h,K}} p_{E_K}$ $n_{E_{h,PP}} p_{E_{PP}}$ Gov Bonds: $n_{h,G} p_G$ Housing units: X_h	Mortgages: U_h Equity: E_h
Consumption Goods Producer <i>abbrev.</i> : CGP <i>index</i> : $f = 1, \dots, N_{Firm}$	Liquidity: M_f Capital goods: K_f Inventories: I_f	Debt: $D_f = \sum_b \ell_{f,b}$ Equity: E_f
Capital Goods Producer <i>abbrev.</i> : KGP	Liquidity: M_K	Equity: E_K
Power Producer <i>abbrev.</i> : PP	Liquidity: M_{PP}	Equity: E_{PP}
Bank <i>abbrev.</i> : B <i>index</i> : $b = 1, \dots, N_{Bank}$	Liquidity: M_b Loans: $\mathcal{L}_b = \sum_f D_{fb}$ Mortgages: $U_b = \sum_h U_{b,h}$	Deposits : $D_b = \sum_h M_{b,h} + \sum_f M_{b,f} + M_{b,K}$ Standing facility with the central bank: $D_b = \ell_{b,CB}$ Equity: E_b
Government <i>abbrev.</i> : G	Liquidity: M_G	Outstanding government bonds value : $D_G = n_G p_G$ Equity: E_G
Central Bank <i>abbrev.</i> : CB	Liquidity: M_{CB} Loans to banks: $\mathcal{L}_{CB} = \sum_b D_{CB,b}$ Gov Bonds: $n_{CB,G} p_G$	Outstanding fiat money: $Fiat_{CB}$ Deposits: $D_{CB} = \sum_b M_{CB,b} + M_{CB,G}$ Equity: E_{CB}

Balance sheets of any class of agents populating the Eurace economy. Balance sheet entries in the table have a subscript character, that is, the index of the agent to which the variable refers. In some cases, we can find two subscript characters, where the second one refers to the index of the agents' representing the balance sheets counterparts. For instance, D_f refers to the total loans of firm f , i.e. a liability, and \mathcal{L}_b refers to the total loans of bank b , i.e. an asset. $\ell_{f,b}$ refer to the loans issued by banks b to firms f . Of course $\sum_b \mathcal{L}_b = \sum_f D_f$ represents a balance sheet identity that is verified along the entire simulation. $n_{E_{h,x}}$ represents the number of outstanding equity shares of agents x held by households h . The market price of the equity shares is given by p_{E_x} . The stock portfolio's value of household h is then computed as: $\sum_x n_{E_{h,x}} p_{E_x}$. Government bonds' number and market price are given by n_G and p_G , respectively

A3 - Agent class balance sheets

The balance sheets of any class of agents populating the Eurace economy is shown in Table 2. Each agent is characterized by liquidity M in the assets side and by equity

Table 3 Sectorial balance sheet matrix

	Sectors							Σ
	Non-financial private agents (NFPAs)				Policy makers			
	HHS	CGPs	KGP	PP	Bs	G	CB	
Tangible capital	$+X_H PX$	$+K_F PK$						$+X_H PX + K_F PK$
Inventories		$+I_F PC$						$+I_F PC$
Debt(-) / Credit(+)	-Mortgages	-Loans			+Loans +Mortgages -Loans _{CB}		+Loans _{CB}	0
Liquidity:								
NFPA	$+M_H$	$+M_F$	$+M_K$	$+M_{PP}$	$-D_B$			0
Banks/Gov					$+M_B$	$+M_G$	$-D_{CB}$	0
Central Bank							$+M_{CB,0}$	$+M_{CB,0}$
Gov Bonds	$+n_G^H PG$					$-n_G PG$	$+n_G^B PG$	0
Equity Shares (+) /	$+ \sum_j n_{E_j} PE_j$	$-E_F$						$+ \sum_j n_{E_j} PE_j - E_F$
Net worth (-)	$+n_{E_k} PE_k$		$-E_K$					$+n_{E_k} PE_k - E_K$
	$+n_{E_{pp}} PE_{pp}$			$-E_{PP}$				$+n_{E_{pp}} PE_{pp} - E_{PP}$
	$+ \sum_b n_{E_b} PE_b$				$-E_B$			$+ \sum_b n_{E_b} PE_b - E_B$
	$-E_H$					$-E_G$	$-E_{CB}$	$-E_H - E_G - E_{CB}$
Σ	0	0	0	0	0	0	0	0

Subscripts represent the index of the agent to which the stock refers. Uppercase indexes are used when the stock refers to the whole sector, e.g. F refers to the sectors of all CGPs, whereas lowercase subscripts are used when it refers to the single agent (for instance in the case of sums). Finally, superscript characters are introduced in the case of government bonds units n_G , i.e. n_G^H and n_G^B , because the balance sheet counterpart (in the asset side) is held by two sectors, i.e. households and central bank. It is worth noting that the foreign sector is not represented in the matrix as no balance sheet interlinkages are assumed with the domestic sectors

Table 4 Sectorial transaction flow matrix of agents populating the EURACE economy

	HHs	CGPs	KGP	PP	Bs	G	CB	Σ
Current Account								
Consumption	-	+						0
Electricity		-		+				0
Fossil Fuels				-				-
Wages	+		-					0
Transfers	+					-		0
Investment			+					0
Taxes	-		-		-	+		0
Dividends	+		-		-			0
Coupons	+					-	+	0
CB coupons payback						+	-	0
Banks loan interests					+			0
Banks mortgage interests	-				+			0
CB loans interests					-		+	0
CB interests payback					+		-	0
Net cash flow	=	=	=	=	=	=	=	=
	Savings	Profits	Profits	Profits	Profits	Surplus	Seigniorage	-

Table 4 (continued)

Capital Account	HHs	CGPs	KGP	PP	Bs	G	CB	Σ
Net cash flow	+Savings	+Profits	+Profits	+Profits	+Profits	+Surplus	+Seigniorage	-
Δ Capital	$+\Sigma_f \Delta K_f / PK$	$+\Sigma_f \Delta K_f / PK$	$-\Delta K_K / PK$	$-\Delta K_{PP} / PPP$				0
Δ Credit	+ Δ Mortgages	+ Δ Loans			- Δ Mortgages - Δ Loans + Δ Loans _{CB}		- Δ Loans _{CB}	0
Δ Issue of new shares / bonds	$-\Sigma_f PE_f \Delta n_{E_f}$ $-PG \Delta n_G$	$+\Sigma_f PE_f \Delta n_{E_f}$			+ $PG \Delta n_G$			0
Δ Quantitative easing	$+PG \Delta n_G^{OE}$						$-PG \Delta n_G^{OE}$	0
Δ Private Liquidity & Δ Banks' deposits	$-\Delta M_H$	$-\Delta M_F$	$-\Delta M_K$	$-\Delta M_{PP}$	+ ΔD_B			0
Δ Banks / Public Liquidity & Δ Central bank deposits					$-\Delta M_B$	$-\Delta M_G$	+ ΔD_{CB}	0
Δ CB Liquidity / Δ Fiat Money	0	0	0	0	0	0	+ ΔM_{CB} $-\Delta$ Fiat _{CB}	0
Σ	0	0	0	0	0	0	0	0

Note that HHs stands for Households, CGPs stands for Consumption Goods Producers, KGP stands for the Capital Goods Producer, PP stands for the Power Producer, Bs stands for banks, Gov stands for Government and CB stands for Central Bank. For the sake of compactness, the foreign sector is not represented in the table; however, the minus sign in the sum column highlights the net deficit of the economy due to the fossil fuels import expenses

E in the liabilities side. Households are characterized by a portfolio of stock shares and government bonds and by housing units in the assets side and by mortgages in the liabilities side. Capital goods and inventories, in the assets side, and debt, in the liabilities side, characterize the consumption goods producer class. The assets side of the bank agent is defined by loans and mortgages whereas the liabilities side by deposits and debt. Issued bonds are a liability for the government. Finally, the Central Bank is characterized by loans and government bonds in the assets side and deposits and fiat money in the liabilities side.

A4 - Sectorial balance sheets

Table 3 shows, in a compact way, the relation among sectors. In details, a plus (minus) sign corresponds to agents' assets (liabilities) and each column can be read as the aggregated balance sheet of a specific sector. Rows show liabilities and the corresponding claims (assets) among sectors, thus generally adding up to zero. Exceptions are capital and inventories, accumulated by CGPs, housing units belonging to households and households' equity shares, which are issued by CGPs, KGP, power producer and banks and do not add up to zero because of the difference between market price and book value of equity.

Finally, it is worth noting that, in Table 3, the difference between fiat money (on the liability side) and central bank liquidity (on the asset side) is always constant (and equal to the initial central bank liquidity $M_{CB,0}$). Fiat money is the money created by the central bank to provide loans to commercial banks when they are in liquidity shortage, or to buy government bonds in the secondary market, through quantitative easing operations. Households that sell government bonds to the central bank deposit the sale proceeds at their own banks, while the money lent to banks by the central bank is lent to households of firms, then in turn deposited again in the banking sector. Therefore, in both cases, the liquidity of the banking sector is increased by an amount equal to the new fiat money created and this additional liquidity is deposited by banks at the central bank, increasing central bank liquidity by an amount equal to the Fiat money originally created. It is worth noting, however, that the money supply in the economy can vary independently from the fiat money created by the central bank, because it endogenously raises every time a bank grants a new loan or mortgage and it decreases when the loan or mortgage is paid back.

A5 - Stock and monetary flows among sectors

All the stock and monetary flows among agents are described in the transaction flow matrix (Table 4), where the current account describes the flows of revenues (plus sign) and payments (minus sign) that agents get and make. Rows show the monetary flows among agents. The result of agents' transactions is the net cash flow.

The capital account section of Table 4 describes the balance sheet changes related to each sector.

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