TECHNISCHE UNIVERSITÄT
CHEMNITZ

Faculty of Economics and
Business Administration

Climate-induced liquidity crises: interbank exposures and macroprudential implications

Paola D'Orazio
Jessica Reale
Anh Duy Pham

Chemnitz Economic Papers, No. 059, June 2023

Chemnitz University of Technology
Faculty of Economics and Business Administration
Thüringer Weg 7
09107 Chemnitz, Germany

Phone +49 (0)371 531 26000
Fax +49 (0371) 531 26019
https://www.tu-chemnitz.de/wirtschaft/index.php.en
wirtschaft@tu-chemnitz.de

Climate-induced liquidity crises: interbank exposures and macroprudential implications

Paola D'Orazio[a,*], Jessica Reale[b], Anh Duy Pham[c]

[a] *Chair of Economics, Faculty of Economics and Business Administration, Technische Universität Chemnitz, Reichenhainer Straße 41, 09126 Chemnitz (Germany)*
[b] *Institute for Macroeconomics, Faculty of Economics and Management, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum (Germany).*
[c] *Department of Computer Science, Hochschule Bonn-Rhein-Sieg, Grantham-Allee 20, 53757 Sankt Augustin (Germany)*

Abstract

Although climate-induced liquidity risks can cause significant disruptions and instabilities in the financial sector, they are frequently overlooked in current debates and policy discussions. This paper proposes a macro-financial agent-based integrated assessment model to investigate the transmission channels of climate risks to financial instability and study the emergence of liquidity crises through interbank market dynamics. Our simulations show that the financial system could experience serious funding and market liquidity shortages due to climate-induced liquidity crises. Our investigation contributes to our understanding of the impact - and possible solutions - to climate-induced liquidity crises, besides the issue of asset stranding related to transition risks usually considered in the existing studies.

Keywords: Agent-Based Modeling, Climate Risks, Prudential Regulation, Interbank Market, Liquidity Crises.

---

[*] Corresponding author. *E-mail address*: paola.dorazio@wirtschaft.tu-chemnitz.de

1. Introduction

As observed in the 2008-2009 Global Financial Crisis (GFC), excessive credit growth and leverage, direct and indirect exposure concentrations, incentives misalignment, and illiquidity constitute the channels through which systemic risk can build up (Helleiner, 2011; Claessens et al., 2013). The inability and unwillingness of banks to provide liquidity to each other played a critical role in the emergence of systemic risk during the GFC (Iori et al., 2008), revealing the *shocks-amplifying* nature of the interbank market in times of crisis (Mitchener and Richardson, 2019). In particular, systemic instability can arise from *systemic illiquidity* triggered by excessive maturity mismatch practices and the inability of banks to roll over their short-term interbank exposures (Ferrara et al., 2019; Montagna and Kok, 2016).

Climate and environmental risks will likely impact the financial system's stability as they become more pervasive and tangible (Carney, 2015; Batten et al., 2016). Since the global financial system will unavoidably become exposed to physical and transition risks, appropriate regulatory and supervisory measures must be in place (D'Orazio, 2023b). The systemic (financial) risk might originate from underestimating and/or underpricing climate risks, resulting in excessive credit provision and excessive concentrations of exposures to climate-related risk-sensitive sectors or financial institutions (Monasterolo, 2020). The materialization of climate risks could lead to a large-scale asset stranding, exposing the financial system to serious funding and market liquidity shortages, which might cause a cascade of liquidity shortfalls propagating through the interbank network (Bolton et al., 2020; van der Ploeg and Rezai, 2020; D'Orazio, 2021). Nevertheless, liquidity risks are frequently overlooked when discussing the impact of climate risks on financial instability (D'Orazio, 2021).

Against this backdrop, we aim to investigate the transmission channels of climate risks to financial instability, study the emergence of liquidity crises through interbank market dynamics, and assess the ability of banks to address climate-induced liquidity shocks by considering alternative prudential instruments. Our analysis relies on a macro-financial agent-based integrated assessment model (AB-IAM) that also features a climate module to account for the interlinkages between the economy

and the climate (Farmer et al., 2015).
The model considers the materialization of climate-related physical risks resulting in a systemic climate shock that impacts firms' and households' risk perception, leading to heterogeneous financial responses. Consequently, agents might prefer to draw down deposits and rely less on external financial resources, resulting in being less profitable. This climate-induced financial response affects banks' liabilities as their access to stable funding (deposits) could be reduced. To replenish their funding sources, banks interact in two segments of the unsecured interbank market diversified by maturity, i.e., overnight and term. We model two interbank matching mechanisms that influence how banks decide to what extent to rely on one segment or the other. First, a *Business as Usual* (BaU) scenario where banks' decisions on the interbank market depend on money market spreads. Second, a *Macro-Prudential* (MP) setting where banks take into account their stability in terms of maturity according to the tenets of the Net Stable Funding Ratio (NSFR) established by Basel III. Interbank exchanges might induce two funding-lending cycles. Banks could end up short-term funding their long-term assets, thus potentially promoting green investments but harming their balance sheet's maturity structure. Alternatively, they could use long-term funds to provide short-term loans, which might favor banks' stability at the expense of the long-term credit provision supporting the low-carbon transition. By considering interbank market dynamics in our AB-IAM, we refrain from assuming a *frictionless* interbank market, thus dissenting from pre-GFC traditions. This modeling choice allows us to account for banks' refinancing vulnerabilities as consolidated features of the banking system's function (Reale, 2022, 2023).

Our simulation results shed new light on the complex relationship - and feedback loops - between climate-related risks, the financial response of economic agents to climate-induced shocks, and financial instability. On the one hand, they emphasize that financial regulators should promote tools to induce a virtuous funding-lending cycle to achieve financial stability and support a low-carbon transition. On the other hand, they show that interdependent interbank exposures - especially the ones related to climate risks - should not be overlooked by policymakers.

The paper is structured as follows. Section 2 reviews existing studies and explains our contribution to the literature. Section 3 presents the model's main characteristics and the scenarios studied in our simulations. Section 4 describes the main results of the model. Finally, Section 5 provides concluding remarks.

2. Related Literature

The central argument of this paper links three strands of literature: the research on macro-financial agent-based and integrated assessment models (AB-IAMs), the literature on the role of interbank markets in addressing liquidity issues, and the more recent research on climate-related financial policymaking.

2.1. Modeling the climate-economy interaction

The field of Macroeconomic Agent-Based Modeling (M-ABM) has expanded significantly since its inception (Delli Gatti et al., 2008; Arthur, 2014; D'Orazio, 2017), and researchers can currently choose from a wide range of ABM frameworks (Dawid and Delli Gatti, 2018). Agent-based models have also been used to model ecological and environmental systems and are often used to simulate land use and ecosystem management (Bousquet and Le Page, 2004; Page et al., 2013). More recently, they have been applied to investigate concerns relating to climate change, particularly the interactions between climate dynamics and economic dynamics (Farmer et al., 2015; Castro et al., 2020). This new line of research has been motivated by the need to investigate how to tackle climate shocks and their impacts on the macro-financial economy and better inform and guide climate change policy. By considering agent heterogeneity, bounded rationality, market, and social interactions, the AB-IAM approach provides a more accurate description of micro behaviors and interactions among sectors than conventional climate policy models (Farmer et al., 2015).

2.2. Interbank networks and market liquidity

In our paper, we model banks' funding decisions on two segments of the interbank market diversified by maturity – overnight and term. In this sense, our work is related to agent-based models and multilayered networks where multiple interbank maturities are considered, going beyond the usual overnight perspective (Bargigli et al., 2015). Since the GFC, interconnected global banking institutions have gathered greater attention for systemic risk analyses in agent-based applications (Steinbacher et al., 2021). By acknowledging that banks' portfolios with varying maturity profiles are key factors in analyzing systemic risk (Kusnetsov and Maria Veraart, 2019), a vast amount of literature has studied the various maturity segments of interbank networks to investigate the interplay between banks funding liquidity shortages and financial stability (see Alaeddini et al., 2022, for a systematic review). According to Poledna et al. (2015), focusing on a single layer minimizes potential contagion losses compared to a multi-layer network consisting of different types of financial contracts. Montagna and Kok (2016) used a multiplex approach to study systemic risk in an increasingly interconnected European financial system. Their model enables banks to interact among different layers diversified by maturity, with short-term loans reflecting funding risk and long-term loans resulting in counterparty risk. Focusing on secured transactions, Hüser and Kok (2019) provide a multilayer analysis of an interbank network broken down by maturity – and by the degree of securitization of debt instruments – to identify and assess banks' interrelated funding exposures. Similarly, Liu et al. (2018) propose an agent-based model to examine how banks' decisions affect the interbank market structure when interbank contracts can be overnight, short- and long-term. Specifically, banks can decide the maturity of interbank loans through financial targets and lending/borrowing ratios, similar to the approach adopted in our model. Moreover, Halaj and Kok (2015) adopt an agent-based portfolio optimization approach that identifies a liability-side optimization that depends on banks' preferred funding structures[1].

2.3. Climate-related financial policymaking

It is now widely acknowledged that climate change poses existential threats to banks, insurers, and the financial system. Due to financial losses, destruction of production capital, the decline in profitability of exposed firms, and the stranding

---

[1] Despite focusing on funding liquidity risk caused by short-term funding of long-term loans (maturity mismatches), they do not model an explicit maturity structure of interbank assets and liabilities, i.e., they assume the same residual maturity of all items on banks' balance sheets.

of assets related to climate-relevant sectors like, for example, mining and fossil fuels, climate-related financial risks can result in credit, market, liquidity, and insurance risks (Carney, 2015). Consequently, central banks and regulators are expected to assess the performance of financial institutions, report on how they consider social and environmental issues, and offer instructions and rules for how financial institutions impact ecosystems (Batten et al., 2016, 2020). Nevertheless, empirical evidence demonstrates that the financial markets worldwide are mostly misaligned with the objectives of the Paris Agreement and influenced by a so-called ”carbon bias” (D’Orazio and Thole, 2022), which results in carbon lock-in and path dependence and implies the possibility of financial instability threats. Changes to existing regulatory and supervisory structures are currently being discussed (D’Orazio, 2023a,b), but the extent and urgency of the enormous concerns posed by global warming are not adequately addressed (D’Orazio, 2021).

2.4. Our contribution to the literature

Recent contributions have focused on the role of climate risks on the financial system (enriched with interbank dynamics). Among others, Battiston et al. (2017) propose a network-based climate stress-test framework highlighting that interbank claims devaluations are to be considered as important factors to understand how climate risk can build up systemic risk. By extending this methodology, Roncoroni et al. (2021) develop a framework accounting for the interaction between climate transition risks, interbank claims valuation, and fire-sales contagion. However, to our knowledge, the interplay between climate-induced liquidity crises and diversified interbank maturity segments has not been investigated so far. Our paper thus contributes to the existing literature by accounting for banks’ vulnerability to climate-related risks in a macro-financial AB-IAM.

3. The Model

The model consists of three main blocks: a climate module, a macroeconomic module, and a detailed interbank market, as shown in Figure 1.

The macroeconomic module describes an economy populated by multiple economic actors undertaking decisions following discrete-time changes. The

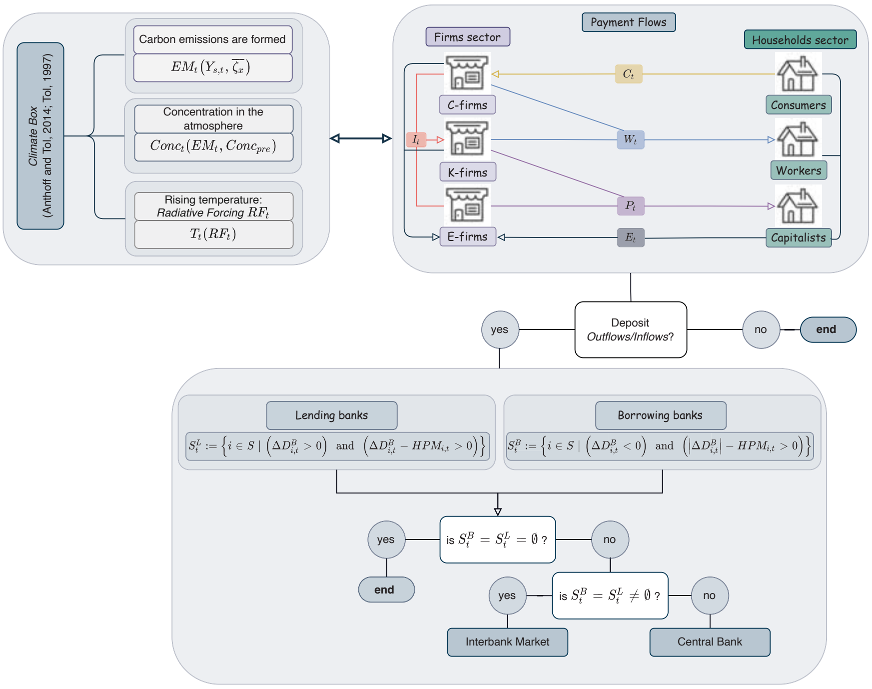

Figure 1: Model overview. Authors' elaborations.

interbank market is populated with heterogeneous banks randomly matched to firms and households. A climate module is introduced to study how climate change affects the economy and how changes in the economy reflect climate changes. As carbon-intensive firms emit CO2 during their production processes, which impacts how CO2 concentration and radiative forcing change over time, the model also considers how the economy and climate interact directly. A climate module is based on the seminal contributions of Tol (1997) and Anthoff and Tol (2014) and describes how the emissions are formed, how they contribute to the increase in carbon concentration in the atmosphere, and the development of the radiative forcing depending on changes in temperatures.

3.1. Agents and sectors

The model consists of six types of agents: an energy provider, capital goods firms, consumption-goods firms, households, banking institutions, and the government.

Three interrelated production sectors are considered: the energy sector (E-firm) acts as a monopolist and produces energy either via a carbon-intensive production process or by adopting carbon-neutral[2] sources. The capital goods (K-firm) and the consumption-goods firms (C-firms) are composed of heterogeneous firms that demand labor and energy and ask for bank loans to finance the production of capital goods (K-firms) and/or consumer goods (C-firms). K- and C-firms can be either carbon-intensive or carbon-neutral according to which kind of energy they demand and adopt in their production process.

The household sector is populated by heterogeneous workers – providing labor to the firm sector – and capitalists – i.e., firms' owners – who consume goods and energy, deposit savings, and ask for consumption loans from the banking sector.

A crucial role is played by an interbank market in which heterogeneous banks interact to exchange reserves needed to settle the payment transfers between agents in the real sector. A *relationship banking mechanism* is considered such that once a link is created during the first simulation period (t_0), agents will resort to stable credit lines over the rest of the period.

The government collects taxes on household income and profits and provides unemployment benefits.

3.2. Interactions

During each period of the simulation, agents interact in the following markets:

- A consumption goods market: households interact with C-firms;
- A capital goods market: C-firms and the energy provider interact with K-firms;
- An energy market: households, C-firms, and K-firms interact with E-sector;
- A labor market: households interact with the government and the three types of firms;
- A credit market: firms interact with the financial sector;

---

[2] In the rest of the paper, we will use the terms *carbon-neutral* and *green* interchangeably.

- An interbank market: banks interact to exchange reserves for settling real-sector transactions.

Because of the carbon cycle model in the climate module, CO2 emissions are influenced by real-sector transactions occurring within the production sectors and between firms and households – namely, (i) consumption expenditures (C_t) from households to C-firms, wage payments (W_t) from firms to households, (iii) investments (I_t) from C-firms or E-firm to K-firms, (iv) energy expenditures (E_t) from firms or households to E-firm, and (v) distribution of profits (P_t) from E- and K-firms to capitalist households. If these transactions happen among agents holding deposits at different banks, deposit outflows, and inflows occur. When this happens, the third block of the *interbank module* gets activated. First, we define two sets that classify banking institutions as lending banks – if they received a deposit inflow in excess of their holdings of required reserves – and borrowing ones – if they suffered from a deposit outflow that their existing amounts of reserves holdings could not cover. At this point, two cases can be distinguished: (i) if these two sets are non-empty, then banks engage in reserves exchanges in the interbank market; (ii) if one of the two sets is null or the two sets are of different lengths, banks will access the central bank's standing facilities (see section 3.3).

3.3. The interbank module

Our formalization of the interbank market follows Reale (2022). Accordingly, banks' demand for interbank loans does not originate from prudential regulation but from *payment settlement* purposes. If the payment settlement arises within the same bank's balance sheet, it takes the form of a simple deposit transfer where no exchange of reserves in the interbank market occurs, as the total amount of reserves on the banks' liability side is unchanged. The interbank market intervenes to smooth payment liquidity shocks when consumption and energy expenditures, investments, wage payments, and profits distribution produce deposit outflows/inflows - i.e. when agents engaging in real-sector transactions are not customers of the same bank. Deposit flows allow us to induce a *reserve adjustment process* according to which banking institutions are defined as either lending or borrowing banks. In other words, banks' roles in the interbank market depend on the existence, the value, and the amount of the deposit flows borne by banks due to the conduct of business in the real sector (i.e., C-firms, K-firms, E-sector, and households).

Within an overdraft economy, the settlement of real-sector transactions occurs through *advances* the central bank accommodates banks in shortage of reserves.[3] Deficit banks will then access the interbank market to acquire from surplus banks (if any) the reserves needed to repay the monetary authority for the intra-day credit received.

Let us take into account a generic set of banks $S = \{i_1, \ldots, i_n\}$. In our model, we assume that borrowing banks belong to a proper subset $S^B_t \subsetneq S$ which gets defined at every period after having checked for two conditions, formally defined in equation (a): (i) if a deposit outflow occurs, i.e. when the aggregate change of the bank's customers deposits is negative $(\Delta D^B_{i,t} < 0)$[4], and (ii) if banks' existing holdings of reserves - current *required reserves* $(HPM_{i,t})$ - are not enough to cover the amount of the deposit outflow.

$$S^B_t := \{i \in S|\ (\Delta D^B_{i,t} < 0) \ \text{ and } \ (|\Delta D^B_{i,t}| - \Delta HPM_{i,t} > 0)\} \tag{a}$$

Following the same rationale of the demand side, we define a proper subset $S^L_t \subsetneq S$ of lending banks which derives from the fulfillment of two conditions. First, banks are lenders in the interbank market if they have deposit inflows in the aggregate, since the *loanable amount* on the interbank market (i.e., the amount of funds that can be lent in the market) derive from payment transfers in our model, i.e., when $\Delta D^B_{i,t} > 0$. Second, lending banks supply on the interbank market only the amount of the deposit inflow exceeding their reserve requirement. If the inflow of deposits is insufficient, the lending bank might use the payment transfers received to replenish

---

[3] Central bank's overdrafts are assumed to bear no interest rate (Allen, 2007).

[4] Each bank i has its own set of customers S_i such that $S_i = \{k|\ l_{i,k} = 1, k \neq i\ \forall\ i \in S \text{ and } \forall\ k \in N\}$, with $N = (H_h \cup N_c \cup N_k \cup N_e)$ – where H_h stands for households, N_c for C-firms, N_k for K-firms and N_e for E-firms. Therefore, a generic customer k will enter the set S_i only if a link $l_{i,k}$ has been established at t_0. Please note that customers of bank i cannot be at the same time customers of bank j, that is $S_i \cap S_j = \emptyset$,$\forall\, i, j \in S$ and $i \neq j$. Therefore, the aggregate amount of deposits bank i holds is $D^B_{i,t}$ such that $D^B_{i,t} = \sum_{k=1}^{n} D_{k,t}$, with $k \in S_i$ being all agents holding deposits at the bank i.

its reserve requirement instead of lending in the market. Equation (b) formalizes these two conditions.

$$S_t^L := \{i \in S| \ (\Delta D_{i,t}^B > 0) \ \text{ and } \ (\Delta D_{i,t}^B - \Delta HPM_{i,t} > 0)\} \tag{b}$$

Interbank transactions will occur if and only if $S_t^B = S_t^L \neq \emptyset$. Banks will access the central bank's standing facilities if this condition does not hold. Three possible cases exist in which banks do not interact in the interbank market. First, when there is at least one borrowing bank in need of reserves, but there is no lending bank in the interbank market with excess reserves to lend out – that is, if $S_t^B \neq \emptyset$ and $S_t^L = \emptyset$ – borrowing banks can access the central bank's lending facility. Second, if there are no banks demanding reserves, but there is at least one bank having excess reserves – i.e., when $S_t^B = \emptyset$ and $S_t^L \neq \emptyset$ – lending banks can deposit their excess reserves at the central bank's deposit facility. Third, when the two sets have different lengths – i.e., $|S_t^B| \neq |S_t^L|$ – banks that cannot access the interbank market can rely on the corresponding standing facilities.

On the contrary, when interbank frictions do not occur and transactions run smoothly, we assume that exchanges in the interbank market can occur in two segments diversified by maturity: overnight and term. The interbank matching mechanism in both segments is explained in detail in the following section.

3.4. Scenarios

Our model architecture allows us to investigate how climate-related physical risks affect agents' behavior and financial stability. Accordingly, we simulate the BaU and the MP scenarios in isolation from - and in combination with - a so-called "climate-induced shock": different scenarios are considered to analyze the role of different prudential policies (or the lack thereof) on the stability of the financial system when the materialization of climate-related risks - and resulting damages - are taken into account. We implement two interbank matching mechanisms – the BaU and the MP settings – as described in detail below.

Business as Usual (BaU). Banks are supposed to demand (supply) in the overnight segment a *proportion* of the total amount of needed (available) reserves, based on

a money market conditions parameter that embodies banks' willingness to borrow (lend) overnight on the basis of interest rates profitability. In this scenario, the bank's decision about whether to ask (provide) overnight interbank funds will depend on (i) the interest rate differentials between accessing the central bank's lending (deposit) facility at $\bar{i}^{l}_{cb}$ ($\bar{i}^{d}_{cb}$) and borrowing (lending) on the overnight segment at the overnight rate, and (ii) the interbank interest rates spread.
Banks' access to the term interbank segment is residual as we allow banks to access both segments of the interbank market at the same time (see Abbassi et al., 2014).

Macro-Prudential (MP). In this scenario, banks' search for counterparties in the interbank market depends on the maturities of interbank contracts. Banks' decisions on the interbank market depend on the degree of maturity mismatch in their balance sheets, captured by a regulatory margin of stability ($MS_{i,t}$) defined following the dictates of the NSFR.[5] The $MS_{i,t}$ requires the amount of available stable funds – i.e., *long-term* funds in the liability side of banks' balance sheets – to be at least equal to the amount of required stable funds – the amount of *long-term* assets that *stable* liabilities should back – that is:

$$MS_{i,t} = \frac{a_m \chi_i}{b_m A_i} \geq 1; \tag{c}$$

where (i) χ_i and A_i are respectively the unweighted total amount of liabilities and assets, (ii) a_m is the proportion of available stable funds over total liabilities, and (iii) b_m is the fraction of required stable funds over total assets.[6]

In this model, we link the (un-)fulfillment of the margin of stability at equation (c) with banks' choices about the maturity of interbank loans. A high degree of stability requires either an increase in the amount of long-term liabilities (the numerator) or

---

[5] The NSFR is formalized as the ratio between aggregate liabilities (χ_i) and aggregate assets (A_n), weighted for their residual maturities (a_i and b_n respectively), i.e. $NSFR = \sum_i a_i \chi_i / \sum_n b_n A_n$. The concept of *stability* implied by this ratio refers to the expiration dates of assets and liabilities reflected in the assigned weights a_i and b_i. Liabilities (assets) are categorized according to their degree of stability (liquidity), i.e., the higher the maturity, the higher the weight.

[6] Please note that standing facilities do not enter the computation of the bank's margin of stability, as their associated risk factors are null.

a decreasing volume of long-term assets (the denominator).
Overnight interbank debts compel borrowing banks to enter the market and ask for funds more frequently and reduce the numerator of the margin of stability. For this reason, we assume that banks would borrow overnight when their margin of stability is high. Instead, engaging in term interbank contracts would allow borrowing banks to replenish the required margin of stability when the condition above is not satisfied, as term debts would increase the numerator.
From the perspective of lending banks, we focus on the asset side preferences (the denominator). To satisfy the $MS_{i,t}$, lending banks should lend overnight, – i.e., their required stable funds at the denominator of the NSFR should decrease. The opposite would be preferred if the margin of stability is satisfied. These considerations are embedded in our formalization of interbank demand and supply.

The proportion of overnight interbank demand and supply consists of a money market parameter (as in the BaU scenario) and a bank-specific parameter aimed at reflecting banks' *preferences for maturity.* Maturity preferences ($P_{i,m,t}$) are captured via endogenous target financial ratios as dependent on the magnitude of the margin of stability $MS_{i,t}$. This measure consists of the difference between the *actual* overnight ratio ($ON_{i,t}$) and the *targeted* overnight ratio ($ON^T_{i,t}$).

From the borrowing (lending) bank's perspective, the *actual* overnight ratio $ON_{i,t}$ is defined as the proportion of total overnight interbank liabilities (assets) - i.e., previous period interbank stocks in the liability (asset) side of banks' balance sheet $IB^L_{i,on,t}$ ($IB^A_{i,on,t}$) - over the total amount of liabilities (assets) in banks' balance sheet

$\chi_{i,t}$ $(A_{i,t})$, see equation (1).[7]

$$ON_{i,t} = \begin{cases} \frac{IB^{L}_{i,on,t-1}}{\chi_{i,t}} & if \quad i \in S^{B}_{t} \ \& \ MS_{i,t} < 1 \\ \\ \frac{IB^{A}_{i,on,t-1}}{A_{i,t}} & if \quad i \in S^{L}_{t} \ \& \ MS_{i,t} \geq 1 \\ \\ 1 & \quad otherwise \end{cases} \tag{1}$$

The *targeted* overnight ratio $(ON^{T}_{i,t})$ reflects our considerations about the margin of stability and is defined in equation (2).

$$ON^{T}_{i,t} = \begin{cases} ON_{i,t} \quad if & (i \in S^{B}_{t} \ \& \ MS_{i,t} < 1) \wedge (i \in S^{L}_{t} \ \& \ MS_{i,t} \geq 1) \\ \\ UN & otherwise \end{cases} \tag{2}$$

When borrowing banks $(\forall i \in S^{B}_{t})$ have a very low degree of stability $(MS_{i,t} < 1)$, their demand for overnight interbank loans should be null. To satisfy this condition, we impose a target $ON^{T}_{i,t}$ equal to the actual overnight ratio $ON_{i,t}$ such that $P_{i,m,t} = 0$.[8] When the opposite happens, banks can afford overnight contracts since the regulatory requirement has been satisfied. In this case, the target equals a random number UN picked from the Standard Uniform distribution $U(0,1)$.

From the lending bank's perspective $(\forall i \in S^{L}_{t})$, when the degree of stability is low – i.e., $MS_{i,t} < 1$ – the amount of required stable funds (long-term assets which require long-term funds on the liability side) should decrease. In this case, the banks

---

[7] Interbank final stocks are defined by the short side of the market for the term and the overnight interbank segment. At the end of each period, we compute banks' interbank assets and liabilities. If at period t bank i is a borrowing bank $(i \in S^{B}_{t})$, the final stock $IB_{on,t}$ is assigned as a liability denoted by $IB^{L}_{i,on,t}$. The corresponding lending bank j, with $j \in S^{L}_{t}$, will have the same stock value registered as an asset $IB^{A}_{j,on,t}$. Term exchanges are handled similarly.

[8] When $P^{borr}_{i,m,t} = 0$, banks' balance sheet structure impairs their ability to borrow overnight for a matter of stability. In this case, their willingness to borrow overnight based on interest rates profitability would not play any role since banks would be obliged to ask for term contracts.

should lend more overnight funds to align the expiration dates of assets and liabilities. The opposite happens when the margin of stability is satisfied.
About the term segment of the interbank market, banks' demand and supply for term interbank loans is residual – as already assumed in the BaU scenario.

The determination of interbank market interest rates follows Reissl (2018) and Reale (2022), who assume a simple clearing mechanism dependent on the central bank's corridor, excess demand/supply and on an exogenous sensitivity to market disequilibrium dynamics.

Climate-induced damages to the financial sector. Recent literature suggests that higher climate-related uncertainty could lead firms to postpone investments and households to increase precautionary savings (see, e.g., Drudi et al., 2021). According to existing empirical evidence, the latter is especially relevant as it translates into a higher reliance on cash and a lower tendency of deposit holdings, posing a threat to global financial stability (Stix, 2013). A growing body of literature shows that individuals withdraw money from their bank accounts as a self-insurance measure following the materialization of natural disasters such as floods or hurricanes. This, in turn, forces the banking system to face negative funding shocks, even resulting in bank runs and banks being unable to roll over their short-term debts (see Skidmore, 2001; Brei et al., 2019; Bayangos et al., 2021, among others).

Drawing on this evidence, we investigate the response of households and firms to climate damages and study the implications of their saving and borrowing decisions on the bank's balance sheets and the financial sector's stability. The protocol to implement the climate shock is as follows.

First, we define a damage function (Ω) based on Nordhaus (2008, 2010, 2017) that depends on the temperature T_t observed at time t.

Second, by taking advantage of the agent-based methodology adopted in our approach, the damage deriving from changing temperatures is applied to the deposits held by single consumers h (Eq. 3) at a generic bank j:

$$D^j_{h,t,d} = \Omega(D_{h,t-1} + Y_{h,t} - C_{h,t}); \tag{3}$$

where $D^j_{h,t,d}$ denotes the deposits the consumer h holds in her bank account at time t

after the computation of the damage (d) shock Ω, $D_{h,t-1}$ are previous period deposits, $Y_{h,t}$ is available income and $C_{h,t}$ is consumption expenditure.

The same logic applies to the loan demand of single firms x (Eq. 4) at a generic bank j:

$$L^{D,j}_{x,t,d} = \Omega[\max(VC_{x,t} - D_{x,t}, 0)]; \tag{4}$$

where $L^{D,j}_{x,t,d}$ denotes the loan demand the firm x asks at time t to the bank after taking into account the damage (d) shock Ω, $VC_{x,t}$ are the variable costs of the firm x at time t, and $D_{x,t}$ are its deposits at time t.

4. Results

Simulations are used to investigate the impact of the shocks to deposits and loans on the financial sector's stability and the real economy. We report the results for a time span of 12 years[9] and distinguish between alternative specifications; when the climate shock is activated, we choose the same t (i.e., $t = 250$) in every scenario for comparability of results.

We start by inspecting the interbank volumes as shown in Figures 3 - 6. When the MP scenario is activated, the materialization of a physical climate risk directly impacts banks' decisions on the interbank market. Households' and firms' reaction to climate risks translates into a (combined) reduction of banks' assets, altering their margins of stability.

In light of the interbank module formalization (see section 3.3), two main cases can be distinguished. First, the impact on the margin of stability ($MS_{i,t}$) might be positive: if the amount of required stable funds (denominator) is greater than the amount of available stable funds (numerator), the change in the NSFR would lead (i) lending banks to supply reserves on the term segment and (ii) borrowing banks to demand overnight funds. When these decisions occur simultaneously, a short-run funding of a long-run lending cycle could emerge, which potentially promotes green investments but further deteriorates banks' stability and their maturity structure. When the opposite occurs, banks could end up using long-term funds to provide

---

[9] We note that each t corresponds to a month.

short-term loans, which might favor banks' stability at the expense of the long-term credit provision supporting the low-carbon transition.

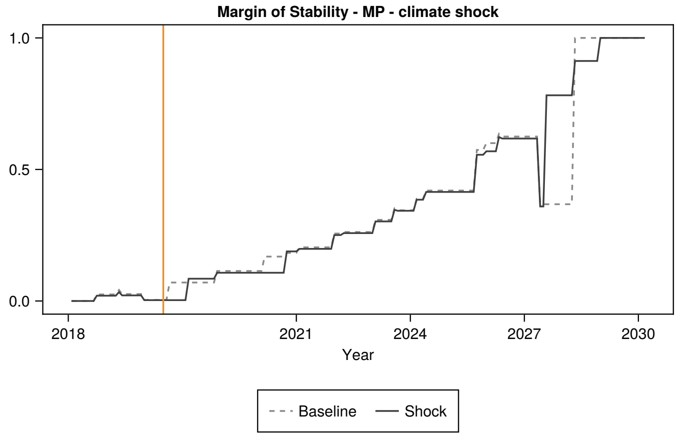

Figure 2: Evolution of banks' margin of stability in the MP scenario. The vertical orange line indicates the time step in which the shock materializes.

In the BaU scenario depicted in Figures 3 and 4, banks' recourse to the overnight interbank segment is higher independently of the materialization of the climate shock. However, the shock encourages the term segment, as the volumes exchanged in the overnight one stabilize at lower levels. The trend is reversed when banks decide on their funding sources according to the NSFR (MP scenario). Not only do term exchanges outweigh overnight loans, but the climate shock also leads to a higher peak for long-run funding and greater variability between the two segments. The higher recourse to term exchanges in both cases triggers the increasing trend of banks' margin of stability. Figure 2 suggests that immediately after the materialization of the shock, banks experience a slightly lower degree of stability, which, however, stabilizes more rapidly.

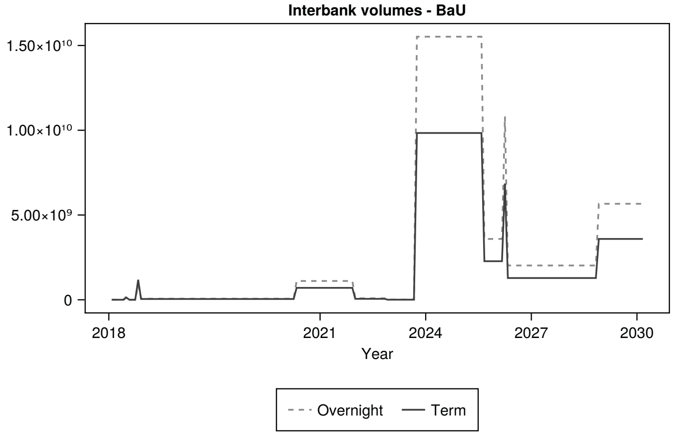

Figure 3: Interbank volumes BaU scenario without climate shock.

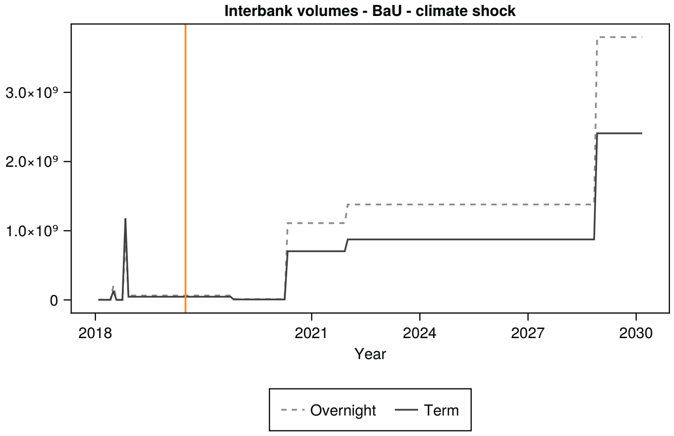

Figure 4: Interbank volumes BaU scenario.

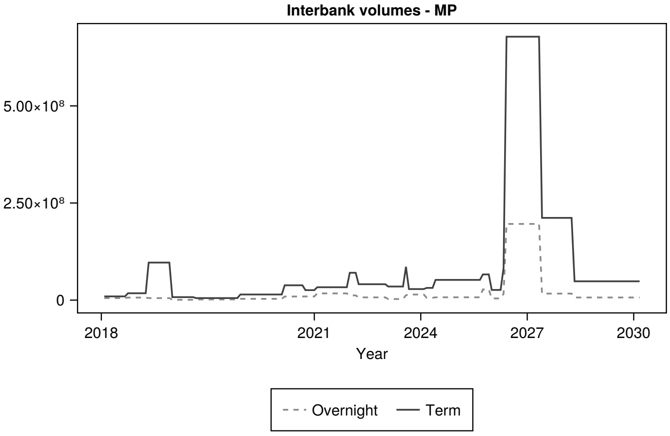

Figure 5: Interbank volumes MP scenario.

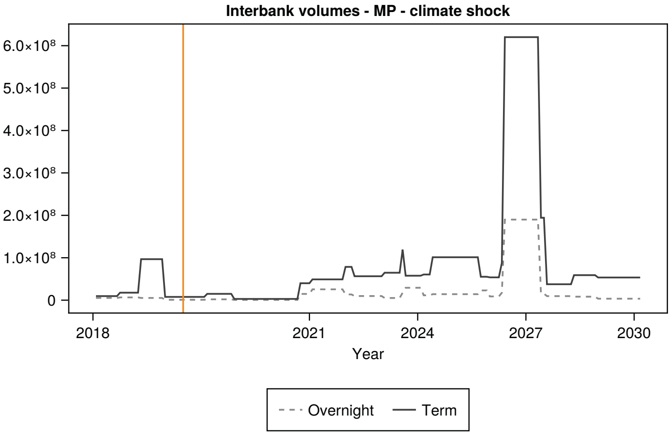

Figure 6: Interbank volumes MP scenario.

We additionally investigate the effect of changes in interbank market liquidity on real investments, as shown in Figures 7 and 8. We distinguish between high-carbon short-term investments and carbon-neutral long-term investments. Overall, high-carbon investments are higher than green investments in all settings. The difference between the two types of investments is particularly visible when comparing the dynamics of the BaU scenarios (top plots in the Figures 7 and 8).

Interestingly, we observe no changes in high-carbon investments after introducing the NSFR in the MP scenario; the results shown in the bottom plot of Figure 7 are very similar to those reported in the top plot. In the case of green investments, we observe more striking differences after introducing the prudential regulation; in particular, we note that green investments increase after introducing the policy and after considering the climate shock.

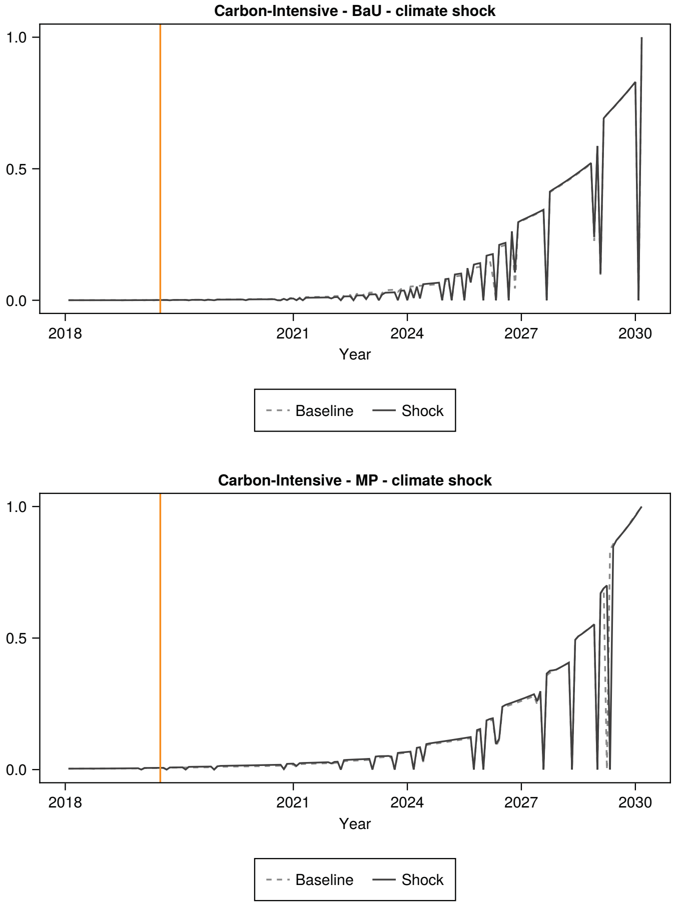

Figure 7: High-carbon investments: BaU and MP scenarios.

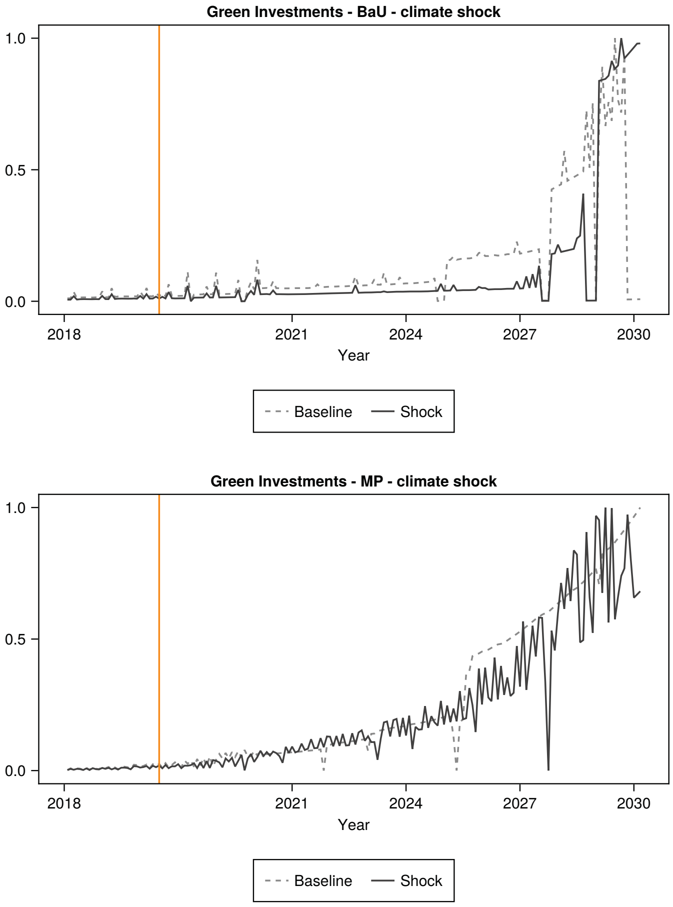

Figure 8: Carbon-neutral investments: BaU and MP scenarios.

Finally, we highlight an interesting finding after combining the results of the interbank market and firms' investment dynamics. Given the higher proportion of term funding and the increasing trend of green loans in the MP scenario, the materialization of the climate shock might induce an unexpected "long-run funding of long-run lending" virtuous cycle, which could promote banks' stability and sustain the low-carbon transition. However, we observe that carbon-intensive investments still grow at very high rates, flooding banks' balance sheets with an excessive amount of short-term assets that are not accounted for in the calculations of the NSFR. Given the high level of stable funding – i.e., term interbank loans – the downward peak of the margin of stability in Figure 2 (around the year 2027) can only be ascribed to a temporary increase in banks' required stable funds (the denominator), i.e., the long-term carbon-neutral investments in our setting. This transitory descending trend is not prevented by the high amount of available stable funds because the level of short-term investments is still too high, revealing a potential virtuous cycle that does not have the full potential to emerge yet.

5. Concluding remarks

Existing literature emphasizes the importance of climate risks for central banks and financial regulators; however, few contributions have addressed the financial stability implications of climate risks in a macro-financial agent-based modeling setting. Moreover, the study of the emergence of climate-induced liquidity risks is not addressed yet in the literature. Against this backdrop, this paper aims to study the emergence of climate-related financial instability with a particular focus on liquidity issues.

The contribution of our study to the existing literature is threefold. First, it sheds new light on the complex relationship - and feedback loops - existing between climate-related risks, the financial response of economic agents to climate-induced shocks, and financial instability. Second, it helps to understand the role of (liquidity) prudential regulations by considering different policy and climate scenarios. Third, it serves as a policy laboratory to study the effectiveness of alternative policy mixes.

Our simulations show that the financial system could experience serious funding and market liquidity shortages due to climate-induced liquidity crises, confirmed by existing empirical literature. In our view, our investigation contributes to our understanding of the impact - and possible solution - to climate-induced liquidity crises, besides the issue of asset stranding related to transition risks usually considered in the existing studies. Moreover, our findings point to a need to carefully account for the potential impact of climate shocks on the financial sector stability and distinguish between carbon-intensive and carbon-neutral financial assets as they imply different maturities and, thus, different risks.

References

Abbassi, P., Fecht, F., Bräuning, F., Peydro, J.L., 2014. Cross-Border Liquidity, relationships and Monetary Policy: Evidence from the Euro Area Interbank Crisis. Deutsche Bundesbank Discussion Paper 45.

Alaeddini, M., Madiès, P., Reaidy, P.J., Dugdale, J., 2022. Interbank money market concerns and actors' strategies—A systematic review of 21st century literature. Journal of Economic Surveys.

Allen, W.A., 2007. The Scope and Significance of Open-Market Operations, in: Mayes, D., Toporowski, J. (Eds.), Open Market Operations and Financial Markets. Routledge, Taylor and Francis Group, New York. chapter 3, pp. 36–53.

Anthoff, D., Tol, R.S., 2014. The climate framework for uncertainty, negotiation and distribution (FUND): Technical description, version 3.6. FUND Doc.

Arthur, B.A., 2014. Complexity Economics: A Different Framework for Economic Thought, in: Complexity and the Economy. Oxford University Press, pp. 1–29.

Bargigli, L., Di Iasio, G., Infante, L., Lillo, F., Pierobon, F., 2015. The multiplex structure of interbank networks. Quantitative Finance 15, 673–691.

Batten, S., Sowerbutts, R., Tanaka, M., 2016. Let's Talk About the Weather: The Impact of Climate Change on Central Banks. Bank of England Working Paper 603.

Batten, S., Sowerbutts, R., Tanaka, M., 2020. Climate Change: Macroeconomic Impact and Implications for Monetary Policy, in: Ecological, Societal, and Technological Risks and the Financial Sector. Springer, pp. 13–38.

Battiston, S., Mandel, A., Monasterolo, I., Schütze, F., Visentin, G., 2017. A climate stress-test of the financial system. Nature Climate Change 7, 283–288.

Bayangos, V.B., Cachuela, R.A.D., Del Prado, F.L.E., 2021. Impact of extreme weather episodes on the Philippine banking sector—Evidence using branch-level supervisory data. Latin American Journal of Central Banking 2, 100023.

Bolton, P., Després, M., da Silva, L.A.P., Samama, F., Svartzman, R., 2020. The green swan. Bank for International Settlements.

Bousquet, F., Le Page, C., 2004. Multi-agent simulations and ecosystem management: a review. Ecological modelling 176, 313–332.

Brei, M., Mohan, P., Strobl, E., 2019. The impact of natural disasters on the banking sector: Evidence from hurricane strikes in the Caribbean. The Quarterly Review of Economics and Finance 72, 232–239.

Carney, M., 2015. Breaking the Tragedy of the Horizon–climate change and financial stability. Speech given at Lloyd's of London 29, 220–230.

Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., van den Bergh, J., 2020. A review of agent-based modeling of climate-energy policy. Wiley Interdisciplinary Reviews: Climate Change 11, e647.

Claessens, S., Ghosh, S.R., Mihet, R., 2013. Macro-prudential policies to mitigate financial system vulnerabilities. Journal of International Money and Finance 39, 153–185.

Dawid, H., Delli Gatti, D., 2018. Agent-Based Macroeconomics, in: Hommes, C., LeBaron, B. (Eds.), Handbook of Computational Economics. Elsevier. volume 4, pp. 63–156.

Delli Gatti, D., Gaffeo, E., Gallegati, M., Giulioni, G., Palestrini, A., 2008. Emergent Macroeconomics. An Agent-Based Approach to Business Fluctuations. Springer Verlag, Milan.

D'Orazio, P., 2017. Big data and complexity: Is macroeconomics heading toward a new paradigm? Journal of Economic Methodology 24, 410–429.

D'Orazio, P., 2021. Towards a post-pandemic policy framework to manage climate-related financial risks and resilience. Climate Policy 21, 1368–1382.

D'Orazio, P., 2023a. Are current prudential frameworks up to the challenge of climate risks? Intereconomics 58, 96–101.

D'Orazio, P., 2023b. Climate change and macro-financial risks: financial policy responses for an orderly low-carbon transition. Environmental Research: Climate 2, 013002.

D'Orazio, P., Thole, S., 2022. Climate-related financial policy index: a composite index to compare the engagement in green financial policymaking at the global level. Ecological Indicators 141, 109065.

Drudi, F., Moench, E., Holthausen, C., Weber, P.F., Ferrucci, G., Setzer, R., Nino, V.D., Barbiero, F., Faccia, D., Breitenfellner, A., et al., 2021. Climate Change and Monetary Policy in the Euro Area. ECB Occasional Paper No. 2021/271.

Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A., 2015. A Third Wave in the Economics of Climate Change. Environmental and Resource Economics 62, 329–357.

Ferrara, G., Langfield, S., Liu, Z., Ota, T., 2019. Systemic illiquidity in the interbank network. Quantitative Finance 19, 1–17.

Halaj, G., Kok, C., 2015. Modelling the emergence of the interbank networks. Quantitative Finance 15, 653–671.

Helleiner, E., 2011. Understanding the 2007–2008 Global Financial Crisis: Lessons for Scholars of International Political Economy. Annual review of political science 14, 67–87.

Hüser, A.C., Kok, C., 2019. Mapping Bank Securities across Euro Area Sectors: Comparing Funding and Exposure Networks. ECB Working Paper No. 2273.

Iori, G., De Masi, G., Precup, O.V., Gabbi, G., Caldarelli, G., 2008. A network analysis of the Italian overnight money market. Journal of Economic Dynamics and Control 32, 259–278.

Kusnetsov, M., Maria Veraart, L.A., 2019. Interbank Clearing in Financial Networks with Multiple Maturities. SIAM Journal on Financial Mathematics 10, 37–67.

Liu, A., Mo, C., Paddrik, M., Yang, S., 2018. An Agent-Based Approach to Interbank Market Lending Decisions and Risk Implications. Information 9, 132.

Mitchener, K.J., Richardson, G., 2019. Network Contagion and Interbank Amplification during the Great Depression. Journal of Political Economy 127, 465–507.

Monasterolo, I., 2020. Climate Change and the Financial System. Annual Review of Resource Economics 12, 299–320.

Montagna, M., Kok, C., 2016. Multi-Layered Interbank Model for Assessing Systemic Risk. ECB Working Paper No. 1944.

Nordhaus, W.D., 2008. A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press.

Nordhaus, W.D., 2010. Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences 107, 11721–11726.

Nordhaus, W.D., 2017. Revisiting the social cost of carbon. Proceedings of the National Academy of Sciences 114, 1518–1523.

Page, C.L., Bazile, D., Becu, N., Bommel, P., Bousquet, F., Etienne, M., Mathevet, R., Souchere, V., Trébuil, G., Weber, J., 2013. Agent-Based Modelling and Simulation Applied to Environmental Management, in: Simulating social complexity. Understanding Complex Systems. Springer, pp. 499–540.

van der Ploeg, F., Rezai, A., 2020. The risk of policy tipping and stranded carbon assets. Journal of Environmental Economics and Management 100, 102258.

Poledna, S., Molina-Borboa, J.L., Martínez-Jaramillo, S., van der Leij, M., Thurner, S., 2015. The multi-layer network nature of systemic risk and its implications for the costs of financial crises. Journal of Financial Stability 20, 70–81.

Reale, J., 2022. Interbank market and funding liquidity risk in a stock-flow consistent model. Metroeconomica 73, 1–37.

Reale, J., 2023. Merchants of debt at the extreme overnight: Re-considering monetary theories via rollover-induced interbank frictions. Review of Political Economy 0, 1–18.

Reissl, S., 2018. Monetary Policy and Prudential Regulation in a Hybrid AB-SFC Model with Heterogeneous Expectations. ExSIDE Working Paper Series, No. 08-2018.

Roncoroni, A., Battiston, S., Escobar-Farfán, L.O., Martinez-Jaramillo, S., 2021. Climate risk and financial stability in the network of banks and investment funds. Journal of Financial Stability 54, 100870.

Skidmore, M., 2001. Risk, natural disasters, and household savings in a life cycle model. Japan and the World Economy 13, 15–34.

Steinbacher, M., Raddant, M., Karimi, F., Camacho Cuena, E., Alfarano, S., Iori, G., Lux, T., 2021. Advances in the agent-based modeling of economic and social behavior. SN Business & Economics 1, 1–24.

Stix, H., 2013. Why do people save in cash? Distrust, memories of banking crises, weak institutions and dollarization. Journal of Banking Finance 37, 4087–4106.

Tol, R.S., 1997. On the optimal control of carbon dioxide emissions: an application of FUND. Environmental Modeling & Assessment 2, 151–163.