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A climate stress-test of the financial system

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The urgency of estimating the impact of climate risks on the financial system is increasingly recognized among scholars and practitioners. By adopting a network approach to financial dependencies, we look at how climate policy risk might propagate through the financial system. We develop a network-based climate stress-test methodology and apply it to large Euro Area banks in a 'green' and a 'brown' scenario. We find that direct and indirect exposures to climate-policy-relevant sectors represent a large portion of investors' equity portfolios, especially for investment and pension funds. Additionally, the portion of banks' loan portfolios exposed to these sectors is comparable to banks' capital. Our results suggest that climate policy timing matters. An early and stable policy framework would allow for smooth asset value adjustments and lead to potential net winners and losers. In contrast, a late and abrupt policy framework could have adverse systemic consequences.

Assessing the impact of climate risks and climate policies on the financial system is currently seen as one of the most urgent and prominent policy issues[1,2]. In particular, there is a debate on whether the implementation of climate policies to meet the 2 °C target generates systemic risk or, instead, opportunities for low-carbon investments and economic growth. However, data are scarce and there is no consensus on the appropriate methodologies to use to address this issue. The magnitude of so-called stranded assets of fossil-fuel companies (in a 2 °C economy) has been estimated to be around 82% of global coal reserves, 49% of global gas reserves and 33% of global oil reserves[3]. Moreover, several studies have investigated the role of stranded assets in specific sectors and countries[4–9]. By investing in fossil-fuel companies, financial institutions hold direct 'high-carbon exposures', which for European actors have been estimated to be, relative to their total assets, about 1.3% for banks, 5% for pension funds and 4.4% for insurances[10]. One can compute the value at risk (VaR) associated with climate shocks[11] in the context of integrated assessment models[12] in which aggregate financial losses are derived top-down from estimated GDP (gross domestic product) losses due to physical risks resulting from climate change. Yet, assessing the financial risk of climate policies (often referred to as transition risks) requires estimations of the likelihood of the introduction of a specific policy. However, the likelihood that a climate policy is introduced depends on the expectations of the agents on that very likelihood. Thus, the intrinsic uncertainty of the policy cycle undermines the reliability of the probability distributions of asset returns, also due to the presence of fat tails[13]. Further, it is now understood that interlinkages among financial institutions can amplify both positive and negative shocks[14–16] and significantly decrease the accuracy of our estimation of default probabilities in an interconnected financial system[17]. As a result, calculations of expected losses/gains from climate policies carried out with traditional risk analysis methodologies have to be taken with caution. Here, we develop a complementary approach, rooted in complex systems science, and consisting of a network analysis of the exposures of financial actors[18,19] to all climate-policy-relevant sectors of the economy, as well as the exposures among financial actors themselves, across several types of financial instruments. This analysis is meant as a tool to support further investigations of the potential impact and the political feasibility of specific climate policies[20,21]. To go beyond the mere exposure to the fossil-fuels extraction sector, we remap an existing standard classification of economic sectors (NACE Rev2) according to their relevance to climate mitigation policies, and we analyse empirical microeconomic data for shareholders of listed firms in the European Union and in the United States. We find (see Supplementary Table 6) that while direct exposures via equity holdings to the fossil-fuel sector are small (4–13% across financial actor types), the combined exposures to climate-policy-relevant sectors are large (36–48%) and heterogeneous. In addition, financial actors hold equity exposures to the financial sector (13–25%), implying indirect exposures to climate-policy-relevant sectors.

Results

By targeting the reduction of greenhouse gas (GHG) emissions, climate policies can affect (positively or negatively) revenues and costs of various sectors in the real economy with indirect effects on financial actors holding securities of firms in those sectors. However, the existing classifications of economic sectors such as NACE Rev2 (ref. 22) or NAICS (ref. 23) were not designed to estimate financial exposures to climate-policy-relevant sectors. Therefore, we define a correspondence between sectors of economic activities at NACE Rev2 4-digit level and five newly defined climate-policy-relevant sectors (fossil fuel, utilities, energy-intensive, transport and housing) based on their GHG emissions, their role in the energy supply chain, and the existence in most countries of related climate policy institutions (see Methods and Fig. 1).

The exposures of financial actors (classified according to the standard European Systems of Accounts, ESA (ref. 24)) can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). By combining the breakdown of exposures across instruments with the reclassification

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Table 1 | Absolute (first row, in US$ billions) and relative (second row, percentage of aggregate equity portfolio) exposure of each financial actor type to each sector.

	OCIs (955)	GOV (125)	Individuals (33,733)	Banks (798)	IPFs (6,392)	OFSs (3,081)	NFCs (14,851)	IFs (5,124)
Fossil-fuel	31.17	66.17	98.17	173.29	230.21	185.15	377.30	549.85
(767)	6.02%	11.43%	3.77%	6.34%	7.09%	5.33%	8.06%	6.05%
Utilities	19.32	63.58	21.16	77.02	55.53	65.46	93.09	249.32
(216)	3.73%	10.99%	0.81%	2.82%	1.71%	1.88%	1.99%	2.74%
Energy-intensive	172.84	147.53	766.33	708.30	865.87	1,019.84	1,408.65	2,701.69
(3,956)	33.40%	25.49%	29.47%	25.92%	26.68%	29.36%	30.08%	29.71%
Housing	13.26	15.88	100.57	59.07	85.28	76.60	146.72	189.36
(797)	2.56%	2.74%	3.87%	2.16%	2.63%	2.21%	3.13%	2.08%
Transport	11.43	18.48	55.38	47.67	54.48	69.96	106.67	173.02
(224)	2.21%	3.19%	2.13%	1.74%	1.68%	2.01%	2.28%	1.90%
Finance	127.01	95.33	419.63	684.72	609.11	669.82	702.44	1,532.08
(2,659)	24.54%	16.47%	16.14%	25.06%	18.77%	19.29%	15.00%	16.85%
Other	142.44	171.80	1,139.53	982.46	1,345.08	1,386.27	1,847.40	3,698.41
(6,259)	27.53%	29.68%	43.82%	35.95%	41.44%	39.91%	39.46%	40.67%

Numbers in brackets indicate the number of firms in this group of actors or sectors. OCIs, Other Credit Institutions; GOV, Government; IPFs, Insurance and Pension Funds; OFSs, Other Financial Services; NFCs, Non-Financial Corporations; IFs, Investment Funds.

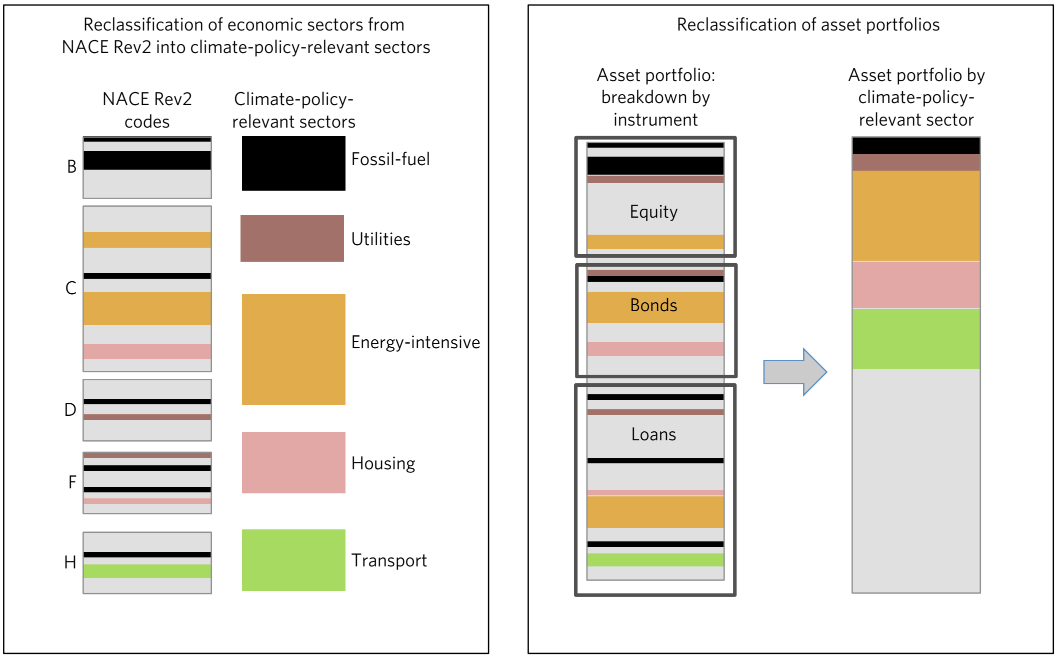

Figure 1 | Diagram illustrating the reclassification of sectors from NACE Rev2 codes into climate-policy-relevant sectors. For more information see the Methods and Supplementary Table 3.

of securities, we compute the total direct exposure of a given financial actor to each climate-policy-relevant sector (see Methods).

Direct financial exposure through equity holdings

To provide empirical estimates of exposures to climate-policy-relevant sectors, we apply our methodology to recent available data sets. Despite their relevance for policy purposes, data about securities holdings of financial institutions, in particular to climate-policy-relevant sectors, is generally scarce, inconsistent or even undisclosed. Along the three main instrument types mentioned above (equity, bonds and loans), at the level of individual institutions only some data of equity holdings are publicly available.

We thus first analyse a sample obtained from the Bureau Van Dijk Orbis database covering all EU and US listed companies and their disclosed shareholders (14,878 companies and 65,059 shareholders) at the last available year, that is, 2015. On the basis of our methodology, we construct the portfolio of each shareholder and we compute its exposure to each climate-policy-relevant sector. To gain insights into the magnitude of indirect exposures we further classify equity holdings in companies belonging to the financial sector. We group shareholders by financial actor type to include, besides the institutional financial sectors from the ESA classification (that is, Banks, Investment Funds, Insurance and Pension Funds) also Individuals, Governments, Non-Financial Companies, Other Credit Institutions and Other Financial Services (Table 1).

Figure 2a shows the result of the aggregated exposures in terms of equity holdings in listed companies for each financial actor type. The combined shares of equity holdings held by the financial sector (that is, Investment Funds, Insurance and Pension Funds, Banks, Other Credit Institutions, and Other Financial Services) amount to about 32.4 trillion US dollars, equivalent to 58.7% of total market capitalization.

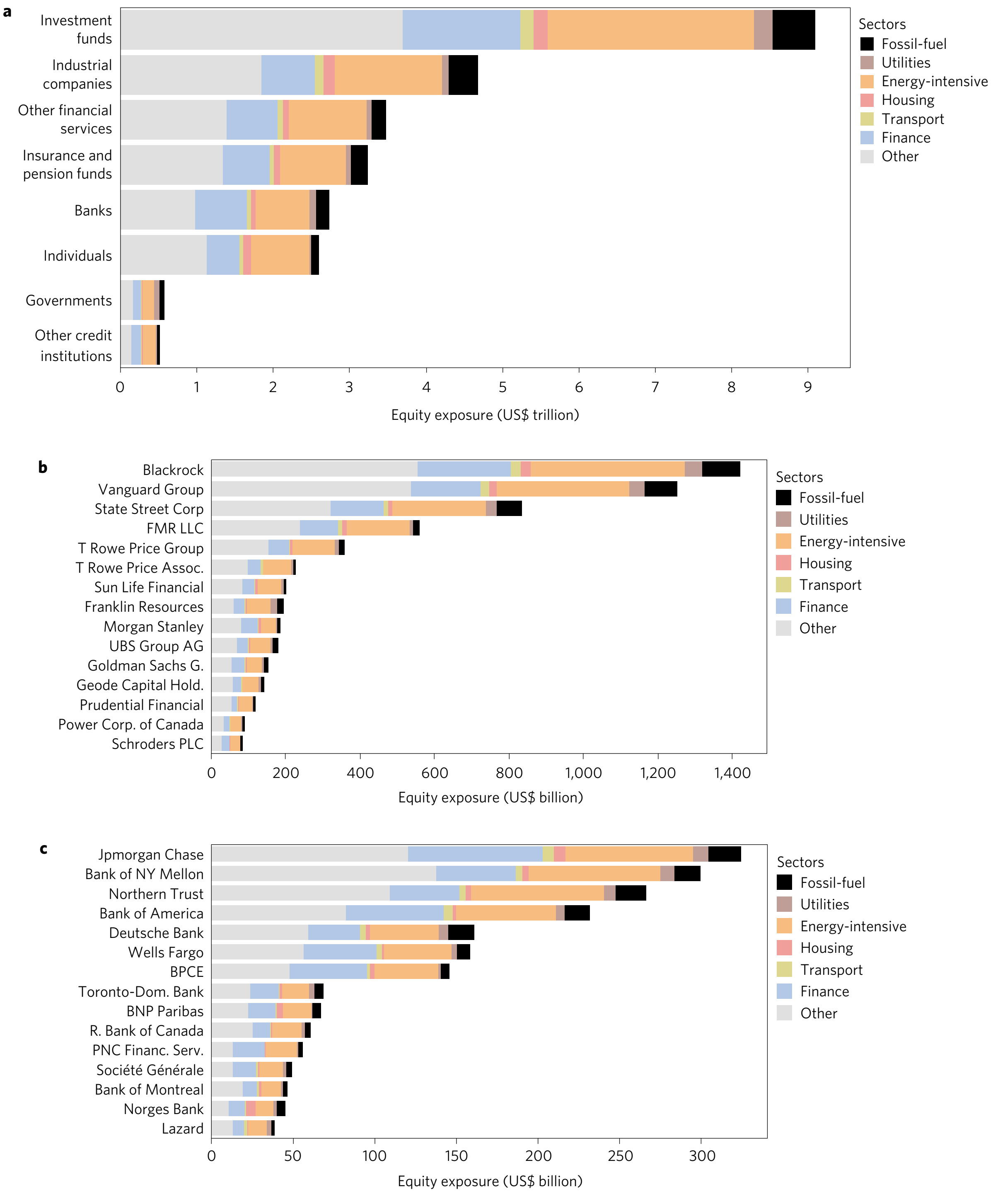

Figure 2 | Equity holdings in EU and US listed companies in 2015 (data from Bureau Van Dijk Orbis). a, Exposures to climate-policy-relevant sectors of aggregate financial actors worldwide. **b**, Exposures to climate-policy-relevant sectors of selected investment funds worldwide (top 15 by size of equity portfolio in the data). **c**, Exposures to climate-policy-relevant sectors of selected banks worldwide (top 15 by size of equity portfolio in the data).

The following findings emerge. First, the relative equity portfolio exposures of all financial actors types to the fossil-fuel sector are limited (that is, ranging from 4.4% for Individuals to 12.9% for Governments) (see Supplementary Table 6). Second, their relative equity portfolio exposures to all climate-policy-relevant sectors are large (that is, ranging from 45.2% for Insurance and Pension Funds, to 47.7% for Governments), and mostly accounted for by the energy-intensive sector. Third, since financial actors' exposures to the financial sector itself range from 13% for Industrial Companies up to 25.8% for Other Credit Institutions, they bear additional indirect exposures to climate-policy-relevant sectors. Within each financial actor type, the standard deviation of exposures across individuals (see Supplementary Table 6) reflects the level of heterogeneity across individuals' portfolio compositions. Examples of individual equity holdings' compositions are shown in Fig. 2b,c for the twenty largest players among investment funds and banks.

Climate stress-testing EU largest banks

Several quantitative estimates exist for the macroeconomic impacts of climate change and climate policies[25,26], as well as for the value

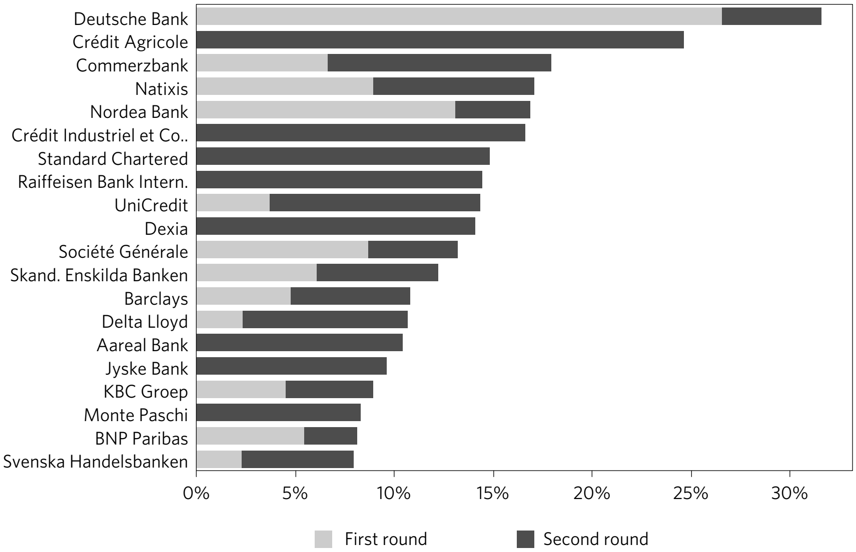

Figure 3 | First- and second-round losses in banks' equity for the 20 most-severely affected EU listed banks, under the Fossil fuel + Utilities 100% shock. Subsidiaries have not been taken into account.

of stranded assets[6]. Accordingly, probabilistic estimates of the climate VaR can be carried out from an aggregate perspective[11]. However, these estimates are too broad to define shock scenarios for individual institutions. At a more granular level, estimates of the value of stranded assets are available in the literature but their sectoral coverage is currently too narrow to inform an analysis of systemic impacts.

To overcome these limitations, we extend the stress-test methodology developed in refs 27,28, which allows one to disentangle the two main contributions to systemic losses. First-round losses are defined as losses in banks' equity due to direct exposures to shocks. Second-round losses are defined as indirect losses in banks' equity due to the devaluation of counterparties' debt obligations on the interbank credit market. The magnitude of second-round effects can vary significantly. Traditional methods (based on ref. 29), yielding small second-round effects, are appropriate only under specific market conditions (that is, full recovery from counterparties' asset liquidation and no mark-to-market valuation of debt obligations). In general, instead, second-round effects can be comparable in magnitude to first-round effects[15,27,28,30].

We illustrate how our methodology can be used to conduct a climate stress-test of the banking system based on microeconomic data at the level of individual banks, by carrying out two exercises on the set of the top 50 listed European banks by total assets (see Methods).

In the first exercise we aim to determine an upper bound on the magnitude of the losses induced by climate policies by considering a set of scenarios in which the whole equity value of the firms in the shocked sector would be lost. We can then compute for each bank the ratio of the exposures to climate-policy-relevant sectors over the banks' capital (that is, banks' equity on the liability side of their balance sheets). Different scenarios consist of different combinations of sectors as indicated in Supplementary Table 8, by increasing levels of shocks' severity. For instance, in the second scenario, 100% of the market capitalization of listed firms both in the fossil-fuel sector and in the utilities sector is lost. Figure 3 shows the losses as a percentage of the banks' capital across the 20 most affected banks as a result of the second scenario from Supplementary Table 8. Light (dark) grey bars indicate the losses from the first- (second-) round shocks. Notice that some banks have no first-round losses but have important losses at the second round. None of the largest banks could default solely due to their exposures to climate-policy-relevant sectors on the equity market. This result implies that even in a severe scenario, there is no systemic impact when considering only the equity holdings channel.

More refined scenarios, allowing one to compute a VaR for each bank, require one to have distributions of shocks across climate-policy-relevant sectors, which are not available in the literature at this stage. As a first step in this direction, in our second exercise, we construct distributions of shocks for the fossil-fuel and utility sectors based on the economic impact assessment of climate policies provided by the LIMITS database[26] and we consider several scenarios of banks' exposures to climate-policy-relevant sectors (see Methods).

In particular, we interpret scenarios (2) and (4) in terms of distributions of losses suffered by a 'representative' (average) bank adopting one of two different investment strategies:

- (2) a 'green' bank having all its equity holdings in utilities invested in renewables-based utilities and having no equity holdings in the fossil-fuel sector,
- (4) a 'brown' bank having all its equity holdings in utilities invested in fossil-fuel-based utilities and keeping its equity holdings in the fossil-fuel sector.

Supplementary Table 10 reports the main statistics on the global relative equity loss in the banking system. The results of the two exercises are consistent: the system's VaR in the brown scenario is less than 1% of the total banks' capital. Supplementary Table 3 reports the statistics for the 'representative' brown and green bank: depending on whether their exposure to utilities is mainly concentrated on renewables-based utilities or on fossil-fuel ones and if they are exposed to the fossil-fuel sector, banks might face very different impacts from climate policies. Further, Supplementary Fig. 6 shows the distribution of first-round losses: the brown bank incurs more losses than the green one, but these losses are small in comparison with the equity of the average bank (that is, US$32 billion) and with its total asset (that is, US$604 billion). Finally, Fig. 4a,b reports the VaR for the 20 most affected banks both in the brown and in the green scenario.

The limited magnitude of banks' losses in this exercise is due to the fact that Euro Area banks bear little equity holdings compared with their balance sheet (about 1.2T EUR, that is, 3.8% of total assets and 48% of capital), probably due to higher capital requirements for equity holdings[31]. However, banks bear larger exposures on loans to non-financial corporations (about 4.8T EUR = 13.8% of total assets and 192% of their capital). Unfortunately, Euro Area banks' loans are only available at 1-digit NACE Rev2 aggregation[32]. At this stage,

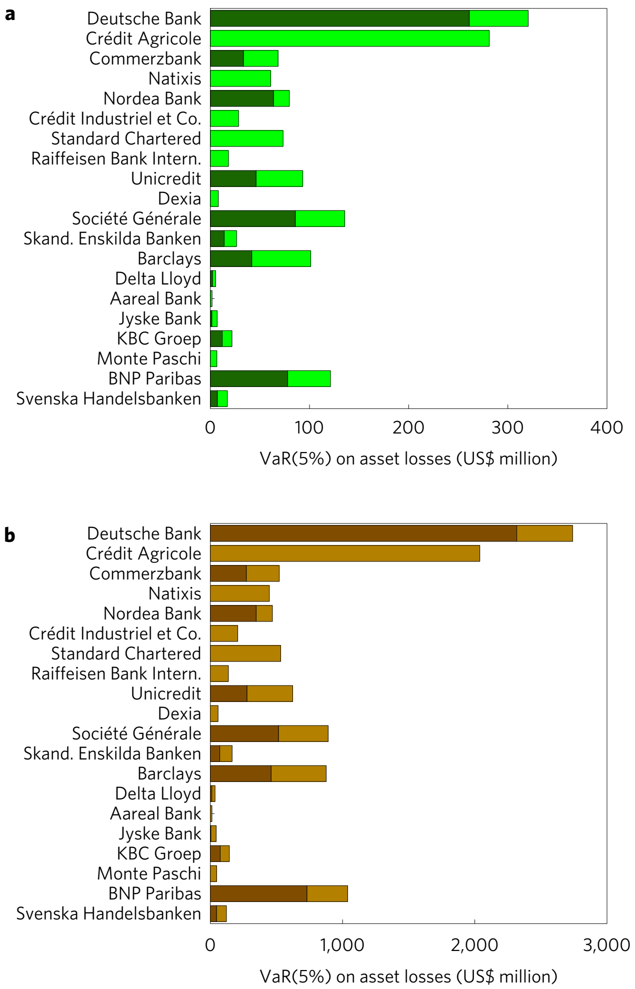

Figure 4 | Individual banks' value at risk under green and brown investment strategies. Value-at-risk at the 5% significance level of the 20 most-severely affected EU listed banks in the data set, under the scenario that they follow the green investment strategy (**a**) or the brown investment strategy (**b**). Darker colour refers to VaR(5%) computed on the distribution of first-round losses only, while lighter colour refers to VaR(5%) computed on the sum of first- and second-round losses.

we cannot compute individual exposures of banks to climate-policy-relevant sectors via their loans. Sector level data for 2014 from the ECB Data Warehouse provide the following aggregate estimations for the banks' exposures on loans as a fraction of banks' capital: 11.4% for fossil and utilities; 28% for energy-intensive; 16% for transportation; 73% for housing. We also need to consider banks' loans to households (presumably mostly granted for mortgages), which add a further 208% of exposures in the housing sector as a fraction of capital.

Better disclosure of climate-related financial exposures[33] would allow one to improve calculations for individual banks. The above considerations suggest that banks would not default solely due to their loan exposures to firms in the fossil-fuel and utilities sectors. However, if climate policies imply higher volatility of loans' values in the energy-intensive and transport sector or in the housing sector and for mortgages, this would translate into volatility of large portions of banks' assets, relative to their capital (16% + 28% = 44% and 73% + 208% = 281%, respectively).

Indirect exposures of European financial actors

By cross-matching aggregate balance sheet information for financial actors (from ECB Data Warehouse) with equity holdings (from Orbis), the following findings emerge for the Euro Area. First, the major direct exposures to climate-policy-relevant sectors of investment funds and pension funds are concentrated in equity holdings, while for banks they are concentrated on loans. Interestingly, bond holdings are only a minor channel of direct exposure to climate-policy-relevant sectors because outstanding bonds issued by non-financial firms in the Euro Area amount to about 1 trillion Euro, that is, about only one-fifth of the values of equity shares issued by the same type of firms. Indeed, only less than 7% of bonds are issued by firms in the real sectors, with roughly 40% issued by governments and another 45% issued by financial institutions.

Second, financial actors bear also indirect exposures to climate-policy-relevant sectors. For instance, pension funds hold an exposure of about 25% of their total assets in equity shares of investment funds, which in turn have an estimated exposure of about 25% of total assets in equity holdings of climate-policy-relevant sectors. Pension funds also hold an exposure of 15% of their total assets in bonds and loans to banks, which, on the basis of the previous section, hold an estimated exposure of about 14% of total assets to climate-policy-relevant sectors. In contrast, the direct exposure of pension funds to climate-policy-relevant sectors through equity holdings is about 8% of total assets. These findings imply that shocks on the fossil sector and increased volatility on asset values in the other climate-policy-relevant sectors could affect non-negligible portions of pension funds' assets through both direct (8.3%) as well as indirect exposures (about 8%).

Conclusions

By remapping the existing classification of economic activities (NACE Rev2) into newly defined climate-policy-relevant sectors, we find that direct and indirect exposures to such sectors represent a large portion of financial actors' equity holdings portfolios (in particular for investment funds and pension funds). Moreover, exposures represent a portion of banks' loan portfolios comparable to banks' capital. Further, we develop a network-based climate stress-test methodology that can be used to derive statistics of losses for individual financial actors, including VaR. We illustrate the methodology on a sample of the top 50 largest EU banks taking into account first- and second-round effects of shocks to their equity portfolios.

Our findings suggest that the implementation of climate mitigation policies is key, both in terms of timing and expectations. The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk. In contrast, in a scenario in which the implementation of climate policies is uncertain, delayed and sudden[2,10] (for example, as a reaction to increased frequency of extreme weather events and to align with the COP21 agreement), market participants would not be able to fully anticipate the impact of policies. In this case, given the large direct and indirect exposures of financial actors to climate-policy-relevant sectors, this might entail a systemic risk because price adjustments are abrupt and portfolio losses from the fossil-fuel sector and fossil-based utilities do not have the time to be compensated by the increase in value of renewable-based utilities. These two scenarios and their corresponding VaR are illustrated by the loss distributions for a 'green' and a 'brown' investing strategy in our climate stress-test on EU banks.

Moreover, the fact that financial actors bear large exposures to climate-policy-relevant sectors implies that climate mitigation policies could increase volatility on large portions of their portfolios. Climate mitigation policies are commonly thought to have an adverse effect on the value of assets in the fossil-fuel sector[5], as well as an adverse effect on the whole economy (see Ch. 6 of ref. 25). However, a transition to a low-carbon economy could also have net positive aggregate effects[34]. Overall, the effects of climate policies are likely to vary across firms and sectors: for example, the renewable energy and the energy efficiency sectors are expected to increase massively in market share (see ref. 35, IEA report 2015; IRENA Annual Review 2016), while real-estate assets can increase or decrease in value, depending on their energy performance (see Supplementary Table 6.7 in ref. 25). Further, stock price volatility in climate-policy-relevant sectors can increase as a result of: technological innovation[36,37], increased competition[38] and policy uncertainty[39]. Therefore, climate policy could lead to winners and losers (in absolute terms) across financial actors, depending on the composition of their portfolios.

Overall, our network analysis of financial exposures highlights that financial actors' portfolios are both interdependent and largely exposed to the outcome of the climate policy cycle. This implies the possibility of multiple equilibria without a clear way to assign *ex ante* probabilities for each equilibrium to occur. Therefore, while climate-related financial information disclosure is crucial for risk evaluation, a stable policy framework is necessary to resolve the multiplicity of possible outcomes. To this end, a network-based, conditional VaR approach represents an advancement in the analysis of climate-policy risks and their implications for the financial sector.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

All authors contributed to the writing of the manuscript, as well as material and analysis tools. G.V. and S.B. also performed the data analysis.

Additional information

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Competing financial interests

The authors declare no competing financial interests.

Methods

Identifying climate-policy-relevant sectors in the real economy. Many climate policies target the reduction of GHG emissions (in particular in non-carbon neutral processes). To identify the climate-policy-relevant sectors we group economic activities with the following logic. We start from the top sectors by direct GHG emissions according to Eurostat (scope 1 CO_2 equivalent), which includes activities across sectors such as utilities, transports, agriculture, manufacturing and households. We also include the mining sector, although it has small direct emissions according to the scope 1 classification, because all the emissions of the three above sectors derive directly or indirectly from the fossil-fuel extraction when accounting from the supply side[40]. We then take into account the so-called carbon leakage risk classification, which according to the EC Directive 2014[41] identifies activities (mostly within manufacturing) for which either costs or competitiveness is heavily affected by introduction of a carbon price. It can be easily verified that the traditional NACE Rev2 (but the same holds for NAICS) classification of economic activities is not well-suited for a climate-policy analysis. For instance, some activities classified under B-Mining and quarrying, such as 'B7.1-Mining of iron ores', are not so relevant for climate policies. In contrast, some activities classified under C-Manufacturing, such as 'C19.2-Manufacture of refined petroleum products' or transport 'H49.5-Transport via pipeline', are more relevant to the fossil-fuel sector from the criterion of economic scenarios resulting from climate policies. Furthermore, some activities that pertain to the housing sector from a policy perspective fall into different NACE Rev2 sectors such as F—Construction and L—Real estate.

All the considered economic activities can be divided into three categories: (1) suppliers of fossil fuels, (2) suppliers of electricity (3) users of either fossil fuels or electricity. We can further divide the third category according to the traditional policy areas: transport, housing and manufacturing. While suppliers of fossil fuels are mostly negatively affected by GHG emission reduction policies, the other categories can be affected positively or negatively depending on the energy source utilized (fossil fuel versus renewable). On the basis of all the above information, we can finally remap all the economic activities from the 4-digit NACE Rev2 classification into the following climate-policy-relevant sectors: fossil, utilities, transport, energy-intensive, housing. The complete mapping from NACE Rev2 4-digits codes is provided in Supplementary Information.

Assessing direct exposures of financial actors. Since our goal is to assess the exposure of financial actors to the climate-policy-relevant sectors in the real economy, we group financial actors into financial institutional sectors according to the standard ESA classification: banks, investment funds, insurance and pension funds. The exposures of each financial actor can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). More formally, denoting by A_i the total assets of financial actor i, and by $\mathbb{S}$ the set of climate-policy-relevant sectors, we can write

$$A_i = \left(\sum_{S \in \mathbb{S}} \sum_{j \in S} \alpha_{ij}^{\text{Equity}} + \alpha_{ij}^{\text{Bond}} + \alpha_{ij}^{\text{Loan}} \right) + R_i \tag{1}$$

where the terms α_{ij} denote the monetary values of the exposures of i in the securities associated with economic actors j for the different types of instruments and R_i is a residual accounting for the exposure to other sectors and instruments not considered in our analysis.

Although instrument types have different risk profiles, it is informative to look at the total exposure of financial actors to a given sector across all instruments. For instance, we can compute in this way the full exposure of a given bank to the fossil sector, by summing up all of its equity holdings, bonds and loans exposures to this sector. If we denote by α_{iS} the total exposure of actor i to sector S, we can write $\alpha_{iS} = \sum_{j \in S} \alpha_{ij}^{\text{Equity}} + \alpha_{ij}^{\text{Bond}} + \alpha_{ij}^{\text{Loan}}$.

In addition to the exposures of individual financial actors, we are also interested in the aggregate exposure of an entire financial institutional sector F to a given climate-policy-relevant sector, $A_{FS} = \sum_{i \in F} \alpha_{iS}$. Finally, the total direct exposure of the financial system in the totality of climate-policy-relevant sectors is $A_{\mathcal{FS}} = \sum_{F \in \mathcal{F}} \sum_{i \in F} \alpha_{iS}$, where $\mathcal{F}$ denotes the set of institutional financial actors.

Assessing indirect exposures of financial actors. A large portion of total assets held by financial institutions are in fact securities issued by other financial institutions (for example, about 40% for banks in the Euro Area). Moreover, about 25% of total market capitalization is invested in equity issued by companies in the financial sectors, and about 40% of the bond market is represented by outstanding obligations issued by financial institutions.

As a result, there is a potential systemic risk that can materialize through the so-called second-round effects[16,17]. For instance, first-round effects may induce directly the bankruptcy of a financial institution that then defaults on its obligations towards its financial counterparties. Second-round effects refer to financial contagion effects including, but not necessarily, further defaults. More generally, the accounting practice of mark-to-market implies that the deterioration of the balance sheet of a financial institution has a negative impact on the market value of its obligations held by its counterparties. Mark-to-market and, in particular, credit valuation adjustment, is recognized as a major mechanism of financial distress propagation; during the 2007/2008 financial crisis, it accounted for two-thirds of losses among many financial institutions (see ref. 42). More formally, in the breakdown of total assets, we can distinguish the securities issued by firms in the financial sectors (whose values depend on their own assets' values) from those issued by firms in the climate-policy-relevant sectors to obtain

$$A_i = \left(\sum_{j \in \mathcal{F}} \alpha_{ij}^{\text{Equity}}(A_j) + \alpha_{ij}^{\text{Bond}}(A_j) + \alpha_{ij}^{\text{Loan}}(A_j) \right) + \left(\sum_{k \in \mathcal{A}/\mathcal{F}} \alpha_{ik}^{\text{Equity}} + \alpha_{ik}^{\text{Bond}} + \alpha_{ik}^{\text{Loan}} \right) + R_i \tag{2}$$

where $\mathcal{A}$ denotes the set of all actors and, again, $\mathcal{F}$ denotes the set of institutional financial actors. When we consider the above equation for many financial actors simultaneously, equation (2) becomes a system of coupled equations in the asset values. In the spirit of analysing the short-term effects of a deviation in the values from an initial face value of the securities, the terms $\alpha_{ij}^{\text{Instrument}}(A_j)$ can be written as the product $\alpha_{ij}^0 f_{ij}(A_j)$, where α_{ij}^0 represents the face value of the security at the initial time and $f_{ij}(A_j)$ represents the valuation of the security with respect to its face value. While the exact functional form of f_{ij} depends on the instrument type and the pricing model used for the valuation of the security, it is possible nevertheless to infer certain useful properties. Consider for instance a chain of exposure in which the financial actor i holds bond securities issued by the financial actor j, who in turn holds securities issued by a firm k in the climate-policy-relevant sector. From the equations above it follows that

$$\frac{\partial A_i(A_j(A_k))}{\partial A_k} = \frac{\partial A_i(A_j)}{\partial A_j} \frac{\partial (A_j)}{\partial A_k} = \alpha_{ij}^0 \alpha_{jk}^0 \frac{\partial f_{ij}}{\partial A_j} \frac{\partial f_{jk}}{\partial A_k} \tag{3}$$

Without loss of generality, in line with widely used pricing models such as those based on the Merton model for the value of debt obligations, the functions f_{ij} are non-decreasing in the value of the assets of the issuer j, that is, $df_{ij}/dA_j \geq 0$, because the ability of the issuer to pay either dividends or interest rates to its creditor generally increases with the issuer's total assets, everything else the same.

It follows that, as long as the terms df_{ij}/dA_j are not too small and comparable across instruments, the indirect exposure to a climate-policy-relevant sector along chains of financial actors is determined by the product of the face value of the exposures along the chain, $\alpha_{ij}^0 \alpha_{jk}^0$, where each exposure corresponds to the strength of the link between the two nodes. The result can be generalized to longer chains, although we focus on length two in this work. Therefore, the problem of identifying the largest indirect exposure of a given path length is mathematically equivalent to the graph-theoretical problem of finding the path(s) with the largest product of link weights along the path in a weighted graph.

Distribution of shocks. To infer a distribution of shocks on the fossil-fuel and utilities sector we use the LIMITS database[26], which provides economic impact assessments of climate policies using a set of economic models and several scenarios that take into account the stringency of climate policy and the timing of its implementation. Results are reported as time series of forecasted production level for each sub-sector with a five-year interval up to 2050. In particular we analyse the estimated time series of the share of fossil fuels and renewables in primary and secondary (electricity) energy consumption. Out of the time series, one can infer a distribution of shocks by considering each change in market share from one period to the next as corresponding to an observation of a shock for the respective sub-sector. Hence, one obtains one shock per period per scenario and per model, for a total of 5,421 shocks. From an economic viewpoint, interpreting these shocks on market shares as shocks on equities amounts to make the following simplifying assumptions. First, the share of nominal expenses on energy is constant (that is, the demand elasticity of substitution is 1). Second, the value of equity in a sub-sector is proportional to total income. Third, market valuation is based on one-period (five years) ahead expectations. The shocks can then be interpreted as the impact on market valuation of a previously unanticipated policy measure. The extent to which these shocks will materialize depends on the ability of agents to anticipate policy measures. The shock scenario we describe in the paper corresponds to a setting in which informational imperfections prevent agents from smoothly adjusting their expectations. The alternative scenario emphasized in the conclusion corresponds to a situation where a stable policy framework would allow financial actors to smoothly adjust their expectations. In this case, climate-induced systemic risk would not materialize. Supplementary Fig. 6 shows the resulting distribution of the variation in asset value for a brown bank (investing in fossil-fuel primary sector and fossil-fuel-based utilities) and a green bank (investing in the renewable utilities sector only).

Data. Data on equity holding were obtained through the Bureau Van Dijk Orbis database. We collected a sample covering all EU and US listed companies and their disclosed shareholders with voting rights as of the end of the last available year, that is, 2014. After some consistency checks, we end up with 14,878 companies and 65,059 shareholders. By grouping the exposures by investor we thus reconstruct portions of their equity holding portfolios, within the limitations of the available data. Further details on the data set and the methodology are provided in the Supplementary Information. Data on the balance sheets of the top 50 listed European banks are obtained from the Bureau Van Dijk Bankscope database. Data include for each bank its total lending and borrowing to other banks. Exposures of a bank to individual other banks are not publicly available and have been estimated on the basis of existing methodologies (see literature in ref. 28). Data on GHG and CO_2 emissions of sectors have been obtained from Eurostat statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics). Data on financial exposures at the sectoral level have been obtained from the ECB Data Warehouse (http://sdw.ecb.europa.eu).

Data availability. The data that support the findings of this study are available from Bureau Van Dijk (Orbis database) but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors on reasonable request and with permission of Bureau Van Dijk.

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