DNB Working Paper

No. 625 / February 2019

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DeNederlandscheBank

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* Views expressed are those of the authors and do not necessarily reflect official positions of De Nederlandsche Bank.

Working Paper No. 625

February 2019

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The Heat is on:

A Framework for Measuring Financial Stress under Disruptive Energy Transition Scenarios

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February 2019

Abstract

This paper presents a comprehensive framework for analyzing financial stress under scenarios with a disruptive transition to a low-carbon economy. This stress testing framework is designed to be readily applied by macroprudential supervisors or financial institutions. First, we construct stress scenarios using two dimensions: climate policy and energy technology. Then, we rely on various modeling approaches to derive macroeconomic and industry-specific implications. These approaches include a novel methodology for capturing industry-specific transition risks. Third, we disaggregate EUR 2.3 trillion in assets of more than 80 Dutch financial institutions by industry. Finally, our calculations show that financial losses can be sizeable, as portfolio values can decline by up to 11%. These outcomes suggest that climate-transition risks warrant close and timely attention from a financial stability perspective.

Keywords: climate transition risk, uncertainty, stress test, financial stability

JEL classification: G01, G20, Q43, Q54

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1. Introduction

Climate change is currently one of the most hotly-debated policy issues. Much of the conversation centers on the implementation of the 2015 Paris Agreement. The central aim of this agreement is keeping the rise of global temperature, compared to pre-industrial levels, well below 2 degrees Celsius. By late 2018, around 180 countries have ratified the Paris agreement, and first steps towards implementation are being taken.[2] However, recent estimates by the IPCC (2018) suggest that global warming could already reach levels of 1.5 degrees Celsius between 2030 and 2052, if the current trends were to persist. This finding suggests there is little room for complacency. In particular, reversing the continued growth of greenhouse gas emissions remains a pressing challenge.

As many academic papers emphasize, estimations of climate-change effects are often surrounded by large degrees of uncertainty. At least since the late 1960s, the literature has studied the complex interactions between greenhouse gas emissions, climate change, and economic conditions (Heal, 2017). In principle, it is possible to analyze these interactions by building on standard economic techniques. For instance, the DICE model introduced by Nordhaus (1992a, 1992b) analyzes climate change from the perspective of economic growth theory stretching back to the classic treatment by Ramsey (1928). Changing assumptions regarding, for instance, the path of future GHG emissions, the level of discount rates, the damage function, or the adaptation costs, will easily affect the overall conclusions (see, e.g., discussions in Stern (2007), Goulder and Pizer (2008), Pindyck (2013), Gillingham et al. (2015), Brock and Hansen (2018), Batten (2018), or Nordhaus (2018)).

Uncertainty also features prominently in recent debates on the financial stability implications of climate change. In 2015, Mark Carney argued that the transition to a low-carbon

[2] For details, see also the United Nations web site on climate change: https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement . URL last accessed on 1 February 2018.

economy could lead to risks for financial institutions, if it were to trigger a reassessment of asset values. In addition, he noted that "The speed at which such re-pricing occurs is uncertain …" (Carney, 2015). In a 2019 speech, Philip Lane noted that "… horizon uncertainty remains a central component of the wider macro-financial uncertainty associated with climate change." (Lane, 2019). Third, a report released by the European Systemic Risk Board started its analysis from the observation that "Uncertainty regarding the timing and speed of the required emissions reduction is high." (ESRB, 2016, p. 4). The report then continued with considering a benign scenario as well as an adverse scenario. In the benign scenario, the energy transition was assumed to occur gradually, while in the adverse case, the transition was seen as occurring late and abruptly. A similar scenario-based approach to account for inherent uncertainty is also used by the University of Cambridge Institute for Sustainability Leadership [CISL] (2015). Their report considers four scenarios related to climate change sentiment, which are then used to stress test representative investor portfolios. In recent seminal work on climate stress testing, Battiston et al. (2017) note that "traditional risk analysis is inadequate to deal with the intrinsic uncertainty". Their solution to dealing with uncertainty is rooted in complex systems science and consists of a network analysis of exposures. Using data on over EUR 1 trillion of equity holdings of the largest 50 European banks, Battiston et al. (2017) find that, while direct exposures to fossil fuels are small, the combined exposures to climate-policy relevant sectors are large as well as heterogeneous. These combined exposures can also be amplified by indirect exposures via financial counterparties.

This paper contributes to the emerging literature on financial stability implications of climate change. Currently, only a few studies have taken an integral view on climate risks from a financial perspective. Notable exceptions are the seminal work by Battiston et al. (2017) and CISL (2015). Our contribution is proposing a comprehensive stress test framework for analyzing financial risk under disruptive transition scenarios. In designing this framework, we closely followed current practices on financial stress testing (Basel Committee on Banking Supervision, 2018). This implies that the framework we use can, in principle, be readily applied by financial institutions themselves (in bottom-up stress tests) or by macroprudential supervisors (in top-down stress tests). The stress test framework could facilitate future work on understanding the financial stability implications of the energy transition.[3]

The first important aspect of the framework is that choosing a stress test approach leads to a focus on tail events rather than on a central path projection. The reason is the large degree of uncertainty surrounding climate change and the energy transition. One may argue that the uncertainty is fundamental, in the sense that probabilities of various transition paths cannot even be known.[4] In light of this uncertainty, a stress test can be a useful instrument, as a focus on tail events can, at the very least, help detect potential vulnerabilities that may materialize in the coming few years. The precise probability attached to individual stress scenarios is, in this type of framework, less relevant. Rather, the question is whether the financial system would be robust to a (range of) disruptive transition paths.

The second notable element of our approach is the use of multiple adverse transition scenarios. To build these adverse scenarios, we focus on two key dimensions in the debate on the energy transition, namely the role of climate policy and the availability of alternative technologies. The combination of these two dimensions leads to four disruptive transition scenarios. This number of scenarios is somewhat larger than in regular stress-test exercises, which usually consider either one (e.g. in the stress test for European banks), or sometimes two adverse scenarios (e.g. in the stress tests for U.S. banks). Using four possible adverse scenarios

[3] In addition to transition risks, the financial stability implications of climate change include physical risks. For instance, more frequent flooding or more extreme weather conditions could have a direct impact on insurers. See Carney (2015), de Nederlandsche Bank (2017), or Monnin (2018) for further discussions.

[4] For classic treatments on the distinction between risk (when probabilities can be known) and uncertainty (when probabilities are unknown), see Knight (1921) or Keynes (1921).

is another way in which we take the relatively high level of uncertainty surrounding the energy transition into account.

The third key element of the framework is the construction of so-called transition vulnerability factors that measure transition risks at the industry-level. Considering effects at the industry-level is important, as the consequences of the energy transition will be heterogeneous across types of economic activity. For instance, it will be crucial to distinguish between a bank loan to a petroleum refining company and a loan to a telecommunications company. To make this distinction, we compute factors that measure how much CO_2 is emitted in the production of an industry's final product. These calculations are based on an input-output analysis, thus also taking emission by firms upstream in the value-chain into account.[5] In this way, the transition factors will reflect embodied CO_2 emissions. Using these vulnerability factors will ensure that an industry that needs, for instance, twice as much CO_2 in its production process, will be hit twice as hard by energy transition shocks.[6] While earlier studies generally classify industries as either 'green' or 'brown', our approach can be used to classify the vulnerability of industries on a continuous scale.

To illustrate our stress test framework, we apply the methodology to a granular data set with information on EUR 2.3 trillion of financial assets held by more than 80 Dutch financial institutions. To the best of our knowledge, this study is the first to jointly consider portfolios of corporate loans, bonds and equities. In addition, we analyze transition risks for banks as well as non-banks, namely insurance companies and pension funds. We collected a major portion of this granular data set, namely the information on loan portfolios, via a customized questionnaire

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[5] See, e.g., Wiebe and Yamano (2016) and Owen (2017) for an overview of methodologies for calculating embodied CO_2 emissions.
[6] For other work taking a value-chain perspective, see also the work on the Greenhouse Gas Protocol, https://ghgprotocol.org/standards/scope-3-standard. URL last accessed on 6 February 2019.

among Dutch banks in mid-2018. In addition, we used data on bonds and equities from the Dutch Securities Holding Statistics (SHS).

As the application focuses on the Dutch financial sector, it is worthwhile to highlight several aspects of the data set. First, the data has a large degree of variation, for instance in terms of types of portfolios (corporate loans, bonds, equities), types of financial institutions (banks, insurers, and pension funds), or individual institutions' characteristics (the portfolios stem from 80 institutions with marked differences, e.g. in terms of size or business model). Second, we consider a combined value of EUR 2.3 trillion in financial assets as sufficiently large to be interesting for an illustration of the stress test framework. Third, Dutch financial institutions are generally integrated into the global financial system, thus also making it important to understand climate-transition risks from the perspective of contagion.[7] Finally, but perhaps most importantly, by showing how the stress test framework could be applied, we aim to facilitate future analyses of climate-transition risks. For instance, our analyses of bond and equity portfolios could relatively easily be applied to financial institutions for which individual security-level holdings data is available. Such further applications would be important follow-up steps in better understanding global transition risks.

When implementing our stress-test methodology using portfolios of Dutch financial institutions, we find that financial stress under disruptive energy transition scenarios can be sizeable. Estimated asset-side losses for the Dutch financial sector as a whole range between EUR 48 billion (in a scenario where only energy technology changes) and EUR 159 billion (in case climate policy and energy technology would both follow a disruptive trajectory). Over all possible outcomes, losses on asset positions could range up to 11%. Under additional assumptions, we also find that declines in supervisory ratios could be substantial. For instance,

[7] Around 50% of the exposures of Dutch banks and insurers is on foreign counterparts. For pension funds, this percentage is more than 80%.

the average CET1 ratio for Dutch banks could decline by as much as four percentage points. Such losses are substantial, suggesting transition risks warrant close and timely attention. When addressed adequately, however, these risks still seem manageable. For insurance companies and pension funds, the asset-side losses are also partly counterbalanced by increases in interest rates that would push down the valuation of liabilities. This interest-rate channel underscores the importance of taking a comprehensive perspective on transition risks that explicitly takes macroeconomic developments into account.

The plan of the paper is as follows. Section 2 describes the financial exposures, in particular those on carbon-intensive industries. Section 3 presents the various elements of the stress-test framework, while Section 4 discusses possible losses on asset positions and supervisory ratios during disruptive energy-transition paths. Section 5 concludes and suggests avenues for future work on climate-related financial stability risks.

2. Financial exposures to carbon-intensive activities

This paper analyzes financial assets with a combined value of EUR 2.3 trillion per ultimo 2017.[8] These asset portfolios were on the balance sheets of 3 banks, 29 insurance companies and 50 pension funds located in the Netherlands at the end of 2017. Our bank sample consists of the three largest Dutch banks: ING Bank, ABN AMRO, and Rabobank. These institutions have a global focus. For instance, the Financial Stability Board considers ING Bank as a Global Systemically Important Institution, while ABN AMRO and Rabobank feature among the 100 largest banks globally. For these three banks, we analyze portfolios of corporate loans, bonds, and equities. Together, these portfolios represent a value of EUR 970 billion, the largest part of

[8] For comparison, this number is roughly equal to the nominal GDP of France or the United Kingdom in 2017, and three times that of the Netherlands.

which consists of the corporate loan book. For insurance companies and pension funds, we focus on equity and bond portfolios. For the pension funds in the sample, we analyze portfolios with a total value of EUR 1,067 billion, while for the insurance companies, we use portfolios with a total value of EUR 219 billion.

Throughout this paper, we use the NACE industry classification to denote the economic activity of the issuer when analyzing individual asset positions.[9] In itself, the NACE industry classification does not indicate whether a particular industry is carbon-intensive in nature. Currently, there is a broad and on-going discussion on appropriate metrics for classifying climate-related exposures (see, e.g., Task Force on Climate-related Disclosure, 2017 or European Commission Technical Expert Group, 2019). However, a universally-accepted classification is not yet available. Rather than starting with a binary distinction between 'green' or 'brown' activities, this paper will use a more granular approach that assigns transition risks to 56 individual NACE industries.[10] We base these vulnerability measures on the carbon emissions used to generate value-added of a particular industry.[11] Using vulnerability factors for 56 industries allows for a precise assignment of transition risks to individual exposures. At the same time, our methodology would, of course, still allow for a further aggregation into broader risk segments.

One advantage of basing the analysis on NACE codes is that these are often readily available, at the very least within financial institutions themselves, but often also in data sources available for prudential supervisors. For instance, for portfolios of bonds and equities, information on NACE codes could be retrieved from the Eurosystem's Centralized Securities

[9] The NACE methodology has been the standard approach to classifying economic activities in the European Union since the 1970s. Conditional on data availability, different industry classification schemes can be used, e.g. NAICS codes when the focus is on the exposure of United States financial institutions.
[10] Battiston et al. (2017) also use NACE codes in their climate stress-test, but remap these into five climate-policy relevant sectors: fossil, utilities, transport, energy-intensive, and housing.
[11] Details on how we construct these vulnerability factors will follow in Section 3.3 of this paper.

Database (CSDB) using the International Security Identifier Number (ISIN). We complement the CSDB NACE classification with industry classifications from Thomson Datastream by adding NACE codes that were initially missing as well as replacing the NACE codes of securities which the CSDB classifies as a financial (NACE code K.64) if Datastream has a different industry classification for this ISIN.[12]

The Eurosystem Securities Holding Statistics (SHS) contain detailed information – on a security-by-security basis – about the portfolios of various euro area investors. This paper uses information for Dutch financial institutions from the SHS sources. It would presumably be possible for other macroprudential authorities to use the SHS data in an analysis of transition risks for financial institutions located in their respective jurisdictions. For corporate loans, information on NACE codes was not included in standard data reports, but we were able to add this information by approaching banks via a customized questionnaire conducted in mid-2018.[13] For all exposures, the reporting date is ultimo 2017.

Within the Dutch financial sector, the exposure to carbon-intensive industries at the end of 2017 varied between 5% (for insurers) and 13% (for banks). Figure 1 illustrates this variation across the three financial sectors.[14] The height of the bars indicates which percentage of total assets is exposed to carbon-intensive industries. The color coding provides an additional breakdown into two subcategories: mining and petrochemical (in black) and other carbon-intensive industries (in gray).[15] For banks, 13% of the financial assets held at ultimo 2017 were directly exposed to carbon-intensive activities. Exposures to mining and petrochemical

[12] For example, a bond issued by BMW Finance is marked as K.64 in the CSDB, while for our purposes it is more appropriate to assign it to C.29 (manufacturing of motor vehicles), i.e. the industry of the parent company.

[13] Future work could consider including mortgage and commercial real estate portfolios. For the moment, data gaps in measuring the energy efficiency of real estate make it difficult to assess the energy-related risks for these types of portfolios.

[14] For confidentiality reasons, this paper will not discuss results for individual institutions.

[15] This particular distinction between carbon and non-carbon is chosen to connect with earlier work on exposures of Dutch financial institutions (see, e.g., Schotten et al., 2016 or de Nederlandsche Bank, 2017). The former category corresponds to NACE categories B and C19, while the latter includes utilities (NACE code D35), basic industry (C16, C17, C20, and C22-C24), and transport (H49 – H53).

activities were 3% of total analyzed assets, while exposures to other carbon-intensive industries came in at 10%. For insurance companies, 5% of analyzed assets were exposures to industries with carbon-intensive production processes, most of which were exposures to carbon-intensive activities other than mining and petrochemical. For pension funds, the exposures to carbon-intensive activities in December 2017 lay at 8% (3% to mining and petrochemical, and 5% to other carbon-intensive).

[insert Figure 1 around here]

3. Stress-test framework for transition risks

While measuring exposures to carbon-intensive industries is an important starting point, one needs to go further in determining the overall transition risks. Figure 1 suggests that a large part of the exposures of Dutch financial institutions at the end of 2017 were not directly related to carbon-intensive industries. However, this share of the asset portfolio could still be affected by changing macroeconomic conditions under disruptive energy paths. For this reason, our stress test framework takes a comprehensive approach that considers the broader macroeconomic context.

The guiding principle of our approach is to follow, as closely as possible, standard methods for stress testing (see, for example, BCBS, 2018). The overall framework contains, therefore, four parts: a narrative, an economic context, data on exposures, and a set of risk calculations. Staying close to current stress-testing practices facilitates future applications of our framework by other macroprudential authorities or financial institutions.

We first provide narratives for four scenarios that capture crucial uncertainties regarding the energy transition. Then, we consider the economic context from both a macroeconomic and an industry-level perspective. Here, we will now discuss in detail how we measure the transition vulnerability measures for the NACE industries. The third step in the framework focuses on exposures, which were already introduced in Section 2. In the fourth and final step, we calculate financial losses using standard risk methods. Figure 2 gives an overview of this multi-step stress-test framework.

[insert Figure 2 around here]

Before describing the various elements of the framework in more details, we highlight a number of challenges in designing an energy-transition stress test. Discussing these challenges will be instructive for those who are considering their own analyses of transition risks. Three challenges were already identified by Campiglio et al. (2018). First, sufficiently detailed data is not always readily available. This will most likely remain an issue for future work, although we have argued that for some (e.g. macroprudential supervisors), existing data sources such as the Securities Holding Statistics could be used as a starting-point. In addition, we note that the data on NACE industry classifications for corporate loans were available at Dutch banks, suggesting that data to conduct future analyses is, in principle, available at financial institutions.

Second, we agree with Campiglio et al. (2018) that it remains difficult to identify which assets are exposed to transition risks. In this paper, we address this issue by constructing vulnerability factors for 56 NACE industries. Future work could, in principle, directly build on our calculations for these vulnerability factors. Of course, choosing this route has implications in terms of data requirements, and, in addition, not everyone might agree with the assumptions underlying our calculations. For the moment, however, our solution to this problem can help furthering the discussion, especially as long as no agreed-upon taxonomy is available.

Third, Campiglio et al. (2018) rightly point to challenges in terms of modeling the interactions between climate, the macroeconomy, and the financial sector. Ideally, we would use a model that has sufficient detail to speak to the realities of the energy transition. A wide array of models is available to study the interactions between climate change and economics. In addition to integrated assessment models (Nordhaus, 1992b; Farmer et al., 2015), traditional approaches include computable general equilibrium models (Antimiani et al., 2015) or input-output frameworks (Su et al., 2010). More recently, climate-change analyses have started using agent-based models or stock-flow consistent models (Monasterolo and Raberto, 2018; Dafermos et al, 2018). For our purposes, it is crucial that model outcomes can be readily used for the analysis of financial stress, meaning that the model generates output that we can introduce into standard risk models. Though much interesting research is taking place in this area, it is still not straightforward to connect climate-change models to risk models. This paper uses a multi-country macroeconometric model, as this type of model is often used to generate economic scenarios for stress tests.[16] [17]

To these three challenges, we would add that constructing a narrative is also more complex than in standard stress tests exercises, as the focus shifts to drivers that are non-standard in economics. Rather than giving shocks to house prices, unemployment, or interest rates, the scenarios need to take a rather diverse set of transition-related factors into account. In addition, there is less historical data to rely on, making it more difficult to assess to what extent particular shocks should be seen as plausible or too severe. To construct narratives that are

[16] The macroeconometric model that we use (NiGEM) was also suggested for these purposes in earlier work by the ESRB (2016, p. 16).
[17] Of course, challenges two and three are also interrelated. In principle, and perhaps ideally, one could use a modeling approach that includes industry-level dynamics. This would mean that steps II.a and II.b of our framework could be integrated into one modeling step.

sufficiently plausible, we first conducted a close literature review, followed by many conversations with climate experts to cross-check the narratives.

We now turn to a description of the stress test framework. In what follows, we have often decided to focus on the intuition behind the various elements in our stress-test framework. An extensive overview of technical details is available in Vermeulen et al. (2018).[18]

3.1 Scenario design

We use scenarios that focus on climate policy and energy technology, as a close reading of the literature suggests that these will be key drivers of the transition to a low-carbon economy (see also CISL (2015) or ESRB (2016)). The scenarios generate economic stress by making assumptions on two key points. First, whether or not climate policy will take an active stance towards mitigating CO_2 emissions. Second, whether or not there will be technological breakthroughs that increase the efficiency of renewable sources of energy.[19]

On climate policy, many papers point out that greenhouse gas emissions are a classic example of economic externalities. The standard approach to addressing this type of market failure is introducing either Pigouvian taxes or quantity restrictions, or a combination of both (see, e.g., Goulder and Pizer, 2008; Tol, 2009; or Hassler et al., 2016). There is currently a wide range of settings in which these climate policies are used. For instance, the European Union Emission Trading Scheme (EU ETS) sets a cap on the total amount of certain greenhouse gases, and companies can subsequently trade emission allowances with one another. Since 2008, the Canadian province of British Columbia uses price measures, by applying a carbon tax to all fossil fuel combustion in the province (see, e.g., Beck et al. 2015 for further details). Sweden

[18] Additional information and further details on modeling are available upon request.
[19] We focus on breakthroughs rather than gradual technological progress, as we are analyzing short-term disruptive transition paths.

already introduced a carbon tax in 1991, which is levied on all fossil fuels in proportion to their carbon content. The tax rate is currently well over EUR 100 per ton fossil carbon dioxide emitted.[20]

On technology, many papers have recognized that fossil fuels still play a central role in production processes. At least since the 1970s, the literature has included measures of energy use in the estimation of production functions (e.g. Griffin and Gregory, 1976; Prywes, 1986 or Chang, 1994). Traditionally, the focus was on the degree of substitutability between energy, capital and labor. Generally, empirical analyses find that substitution elasticities are closer to zero than to one (Van der Werf, 2008). This would imply relatively high costs for climate adaptation policies (Henningsen et al., 2018). More recently, the focus has shifted to including measures for green energy in analyzing drivers of technical change. For instance, Fried (2018) analyses a dynamic, general equilibrium model that has endogenous innovation in fossil, green, and non-energy inputs.

We combine these two dimensions of climate policy and energy technology to construct four stress scenarios. These scenarios should not be seen as actual forecasts. Rather, as in regular stress-testing exercises, we consider tail events to detect potential vulnerabilities that may materialize in the coming few years. It is also important to note that our stress-test approach leads to scenarios that differ in nature from the IPCC Representative Concentration Pathways (see, e.g., IPCC, 2014). For instance, our scenarios have a shorter time horizon (IPCC pathways run up to 2100) and focus on economic trajectories (IPCC pathways also explore physical, biogeochemical, and socio-economic conditions). Constructing additional scenarios is helpful to analyze current vulnerabilities regarding current exposures of financial institutions. In addition, the IPCC pathways would offer little macroeconomic details, for instance in terms of

[20] Further details on the Swedish carbon tax are available at https://www.government.se/government-policy/taxes-and-tariffs/swedens-carbon-tax/. URL last accessed on 15 January 2019.

country-specific shocks to unemployment, which are an essential input for existing stress-test models.

Given the paucity of historical evidence to guide us, it is not immediately obvious how to parametrize the shocks in our four scenarios for the energy transition. However, given that our philosophy is to run a stress test, we presumably have some leeway in focusing on severe shocks. This is already evident in our first scenario, where we make the assumption that policymakers decide on a set of global measures that lead to a world-wide increase of carbon prices by $100 per ton of CO_2 emitted. Such an increase would be large compared to current levels of carbon pricing, and it may be questioned if such a set of measures could indeed be implemented on a global scale any time soon. However, an increase of $100 does not seem that extreme when compared to estimates of the social cost of carbon. Indeed, it is not difficult to find estimates for the social cost of carbon within the next decade that go up to a few hundred dollars per ton (see discussions in IPCC, 2014; Poelhekke, 2017; Tol, 2018). The second scenario assumes a strong positive shock to energy technology. It includes short-run supply-side disruptions that arise by the sudden availability of a new renewable-energy technology. This new technology is assumed to allow for more efficient generation and storage of green energy. More specifically, the new technology allows the share of renewable energy in the total energy production to double over a five-year horizon. This shock is severe given the scenario horizon, though some predict that already by the 2030s renewable energy sources will play a dominant role in energy production (see, e.g., Creutzig et al., 2017, or IEA, 2017). A third scenario considers the combined effects of a policy and technology shock. It assumes that both shocks occur simultaneously, but it does not assume an endogenous response of policy shocks to technological shocks or vice versa. While endogenous feedbacks between both shocks are possible, it is not clear what the direction should be.[21] With the fourth scenario, we explicitly focus on the uncertainty that surrounds much of the debate on the energy transition. This scenario assumes that climate policy will not take a more active stance and that no new technologies become available. Rather than treating this scenario as a *business-as-usual* outlook, the key notion is that economic agents become more cautious in the absence of clear steps towards a greening of the energy system.[22] This uncertainty makes consumers and firms reluctant to invest, because the profitability of the assets depend on policy decisions. Furthermore, stock-market investors will require a higher risk premium to compensate for elevated levels of risk.

3.2 Macroeconomic contexts

As discussed in Section 1, there is no single overarching framework that both has the required level of detail and can easily connect climate-change variables to frameworks for financial-sector vulnerabilities. We use, therefore, a mixture of modeling approaches. To generate macroeconomic contexts for the stress scenarios, we rely on a multi-country macroeconometric model (block II.a in Figure 2). One reason for choosing such a model is that it readily provides those variables that would be included in standard stress-test exercises, such as GDP, unemployment and interest rates. These variables would be key risk drivers for financial institutions' exposures. In addition, a multi-country model allows us to study the effects of global shocks to policy and technology, while at the same time allowing us to use outputs measured at the country level. We will use this information, for instance, when we

[21] A carbon tax could stimulate innovation by rendering traditional technologies more expensive. However, a carbon tax may actually be detrimental to innovation, if it were to reduce the amount of funds available for research and development. See, e.g., Kemp and Pontoglio (2011).
[22] There is an obvious parallel with the literature on policy uncertainty. See Baker, Bloom, and Davis (2016).

consider country-specific shocks to risk-free rates. The specific model that we use is NiGEM, a model developed and maintained by the National Institute of Economic and Social Research.[23]

We translate the scenario narratives to NiGEM inputs as follows. In the two scenarios with an increase of the CO_2 price, we map this shock to the prices of non-renewable energy sources – that is coal, oil, and gas – which are model variables in NiGEM. For calibration, we convert the $100 increase to the amount of CO_2 emitted per burnt barrel of oil, or its equivalent in terms of coal or gas. For example, we use the fact that burning a gallon of crude oil emits 10.3 kg CO_2.[24] Hence, burning a barrel of crude oil, which contains 42 gallons, emits 432 kg CO_2. A CO_2 price increase of $100 per ton would therefore raise, as a first approximation, the oil price by $100*0.432 = $43.20.[25]

The two scenarios that incorporate a technology shock focus on supply-side disruptions through a process of creative destruction. These disruptions are driven by the sudden availability of a new, green technology. In NiGEM, we change the production function specification, so that production relies less on fossil fuels. We change the production function by multiplying fossil energy use with a new scaling variable (WD_{GREEN}). Once WD_{GREEN} becomes larger than one, the model implicitly incorporates a new green technology, by allowing the generation of an equal amount of energy (i.e. Joules) to use less fossil fuel inputs. We increase WD_{GREEN} from 1 up to 1.25 during the five year scenario horizon. Given this shock, the share of fossil fuels required to produce an amount of energy falls by 20% at the end of the five year horizon. Second, we model a depreciation of that part of the existing capital shock

[23] For details, see https://nimodel.niesr.ac.uk . URL last accessed on 1 February 2018.
[24] These emission factors are from https://www.epa.gov/sites/production/files/2015-07/documents/emission-factors_2014.pdf . URL last accessed on 21 January 2019.
[25] For coal and natural gas, we need some additional steps. For coal, we know that 0.21 tons of coal are equivalent to one barrel of oil. Burning a ton of coal coke emits 3,107 kg CO_2 (1 short ton emits 2,819 kg and 1 short ton is about 0.9 metric tons). So, burning a "barrel" of coal emits 653 kg CO_2, which implies a price increase of $65.3. For natural gas, we use the fact that it emits 0.054 kg CO_2 per standard cubic foot (scf). We can use the fact that 5801 s.c.f. are equivalent to one barrel of oil. So, we can now compute that burning a "barrel equivalent" of gas emits 316 kg CO_2. The price increase for natural gas due to the CO_2 tax would then be $31.6.

that relies on fossil-fuel intensive technologies. The technological breakthrough will make these older technologies obsolete, which temporarily increases the depreciation rate of the existing capital stock. We write-off 6% of the capital stock in the first year and 4% in the second year of the scenario. This is modeled as an exogenous increase of the depreciation rate.[26]

In the scenario that incorporates a confidence shock, the key idea is that economic agents become more cautious in absence of clear steps forward in terms of climate policy or energy technology. This scenario builds on the literature on the macroeconomic effects of policy uncertainty. The uncertainty works via three channels. First, there is a loss of consumer confidence, which leads consumers to delay purchases and increase precautionary savings. Second, the uncertainty makes businesses more cautious which increases required returns. Third, investors become more cautious, which we implement by increasing the equity risk premium by 1 percentage point (compared to a current level for the Netherlands of around 6%). We implement the consumption and investment shocks for the set of around twenty countries that have detailed equations for consumption and investment. The equity risk premium shock is implemented for all countries in NiGEM.

The outcomes of the macroeconomic-model simulations indicate that the four transition narratives would, as expected, indeed have significant macroeconomic consequences. Figure 3 illustrates this point by showing impacts for two key macroeconomic indicators for the Dutch economy that we will use in the stress-test models. For each scenario, the figure shows effects for GDP (top panel) and ten-year interest rates (bottom panel). These impacts are presented as deviations from levels in a baseline projection.[27] In line with current stress-testing practices, we

[26] The shock is calibrated based on the current share of capital goods used in a number of energy-intensive industries: mining, energy supply, manufacturing, cement production, and transport vehicles. Currently, this share is around 15% of the Dutch total capital stock. We assume that 40% of these capital goods needs to be written-off. Furthermore, since the new technology has a broad impact, we assume that 5% of the remaining capital stock needs to be written off as well over the scenario horizon.
[27] As baseline, we use the standard forecast included in NiGEM release v1.18b.

plot macroeconomic effects for a simulation horizon of a number of years. Over this horizon, Dutch GDP could decline by between 1% and 5% compared to the baseline (Figure 3, panel a). On impact, i.e. in the first year of the simulation, the GDP effect would be relatively large under either a policy shock scenario (i.e. with $100 higher carbon prices) or a confidence scenario (i.e. when uncertainty decreases consumption and investment). In both cases, GDP would decline by more than a percentage point. Turning to interest rates, the effects would be particularly large in the two scenarios (i.e. under a *policy* and a *double shock*) where climate policy takes an active stance. On impact, long-term interest rates would lie more than a percentage point above baseline levels, which would have strong effects on the value of bond portfolios. This increase in interest rates is in line with the inflationary nature of these scenarios: the carbon tax increases production costs and, in the end, consumer prices. In response, the central bank increases policy rates, while higher inflation expectations lead to an increase in long-term interest rates.

[insert Figure 3 around here]

3.3 Mapping macro outcomes to industries

In the next part of the framework (element II.b in Figure 2), we construct factors that measure transition risks at the industry-level. These so-called transition vulnerability factors allow us to map some of the macroeconomic results from NiGEM – namely those for interest rates and equity indices – to 56 NACE industries. Technically, the vulnerability factors are based on the embodied emissions of the final goods and services in each industry. To calculate embodied emissions, we use information from EXIOBASE (version 2015). This is a global and detailed input-output database that covers a wide range of countries and industries. It allows us to combine detailed information on CO_2 emissions per industry with data on value-added. EXIOBASE is often used to study the environmental effects of final consumption of products. As EXIOBASE also uses NACE codes, it offers a way to connect directly to the granular data on financial institutions' exposures.[28]

Focusing on embodied emissions means that we not only account for the emissions by the producer of the final goods and services, but also for emissions by firms upstream in the value chain. Thus, by using embodied CO_2 emissions, industries with final goods and services that require a lot of CO_2 emissions in the overall production process will be hit harder. To give an example, for the car industry (NACE industry C29), our value-chain perspective would, of course, factor in the CO_2 emissions of assembling a car, but also those emissions related to producing car components, such as rubber (NACE industry C22) for manufacturing tires.

To transform embodied emissions into transition vulnerability factors, the embodied CO_2 content of the final goods and services of a particular industry is weighted by the share of those final goods and services in global value added. This weighted embodied CO_2 is then normalized, so that the weighted average vulnerability factor for the global economy is equal to 1. This normalization ensures that the vulnerability factors remain consistent with the aggregate macroeconomic dynamics generated via NiGEM.[29] In the end, the transition factors will reflect embodied CO_2 emissions needed to generate value-added of an industry. Using these vulnerability factors implies that an industry that needs, say, twice as much CO_2 in its

[28] Information is available at https://www.exiobase.eu/index.php/about-exiobase. URL last accessed on 19 January 2019.
[29] This implicitly assumes that the industry composition of the global stock market index is the same as that of the global economy.

production process, i.e. with an vulnerability factor equal to 2, will be hit twice as much by energy transition shocks.[30] [31]

Figure 4 illustrates the impact of using transition vulnerability factors. The figure plots equity index declines for several industries under a scenario with a policy shock (horizontal axis) and a scenario with a technology shock (vertical axis). These equity index changes are obtained by multiplying aggregate equity declines generated by NiGEM (under both scenarios) with scenario-and-industry-specific vulnerability factors. In the scenario with a policy shock, the global stock market index would drop, on impact, by 5 percentage points; in the technology scenario, this decline would be 3 percentage points. These aggregate declines are denoted by the dotted lines. As the figure indicates, the industry-specific equity declines could be much larger. In particular, the utilities sector would be severely hit under both scenarios, while the mining industry would take a strong hit (of close to -40% compared to the baseline level) in the technology scenario.

[insert Figure 4 around here]

3.4 Methods for calculating financial risks

The last step in the analytical framework (block IV in Figure 2) relies on standard approaches to stress testing. The focus is on two main categories: credit risk and market risk. To quantify credit risks for the corporate loan book under the four stress scenarios, we partly

[30] The vulnerability factors also differ across the four transition scenarios, as some industries may be even more sensitive to technology shocks than to climate policy shocks.

[31] Interestingly, even though most of the 14 sectors that were deemed *a priori* to be carbon-intensive indeed turn out to have a high transition vulnerability factor, there are a few exceptions. For instance, the NACE category H53 (‘Postal and courier activities’) has a vulnerability factor of 0.2. This illustrates the difference made by taking a value-chain perspective. Even so, industries with low vulnerability factors will still be subject to stress generated by changing macroeconomic outcomes, as Section 4 will discuss.

rely on a top-down stress test model for banks (see Daniëls et al. (2017) for a detailed exposition). This model is also used for regular stress-test exercises. The model was adjusted to account for the industry classification of the loans. In addition, we construct small-scale models to quantify market risks. These models calculate price shocks for bonds and stocks. For stocks, we compute changes based on the results for equity indices according to NiGEM, which are then adjusted for the sector-specific transition vulnerability factor. For bonds, we first calculate price changes caused by changes in risk-free interest rates. This is captured by the duration of a bond. Furthermore, based on bonds' credit ratings and ratings transition matrices, we also calculate the price changes caused by a deterioration in bond risk premia, where again we utilize the TVFs, this time to account for the carbon-intensity of the industry of the bond issuer.

In closing, we note that we compute all risk measures on impact, i.e. in the first year of the scenario. For market risk, that is, in fact, a standard approach in stress-testing exercises, such as those of the European Banking Authority (EBA). For credit risk, stress-tests usually consider horizons of up to three years. We calculate additional losses in each scenario relative to the losses in the baseline scenario over a five-year horizon, but we then aggregate these to effects on impact. In doing so, we essentially assume a discount rate of zero, and thus present a worst-case outcome for credit risks. It also implicitly assumes that banks need to provision for all future credit losses caused by the scenario at once. Doing so again provides us with an upper-bound estimate, but the approach is consistent with IFRS 9 regulations, under which banks need to provision for lifetime losses on assets with a material increase in credit risk.

4. Results for energy transition risks

Applying our multi-step framework to the Dutch financial sector suggests that disruptive energy transition paths may result in substantial levels of financial stress. In the most extreme case, we estimate a potential loss of 11% of assets. Figure 5 provides an overview of the quantitative findings. For the three types of financial institutions in our sample, the figure shows percentage losses under the four scenarios. These losses are shown as percentage of total assets for each type of financial institution. The losses are the sum total of those generated by credit risk and market risk. The bars also indicate the source of the losses, i.e. whether losses on asset positions stem from increases in risk-free interest rates (shown in light gray), exposures to carbon-intensive industries (shown in black), or exposures to the other NACE industries (shown in dark gray).

[insert Figure 5 around here]

The percentage losses on asset positions differ strongly across the three types of financial institutions. For banks, we find that losses on asset positions range between 1% and 3%. These losses are mainly due to direct exposures to carbon-intensive and other industries within the loan and bond portfolio. In addition, credit losses are related to the deteriorating macroeconomic conditions in the four transition scenarios. For insurance companies, the potential losses are much larger, with the top end of the estimates lying at 11%. To a large extent, these losses are not so much due to direct exposures, but rather stem from changes in macroeconomic conditions. In particular, the increase in interest rates has a direct negative effect on the value of bond portfolios, which are characterized by a high duration. For pension funds, estimated losses range between 3% and 10%. Though to a smaller extent than for insurers, the pension sector is also directly affected by rising interest rates. In addition, pension funds would incur losses on bond and equity positions, both from carbon intensive as well as other industries.

Much of the debate focuses on the choices that financial firms make in terms of asset holdings. For those holdings, financial institutions have to decide to what extent they would like to factor in climate-relevant information. However, an important insight from Figure 5 is the observation that in certain scenarios, a large fraction of losses can arise in exposures to industries which are traditionally not seen as carbon intensive. This is the case because macroeconomic developments will affect all exposures, which shows that a binary classification into 'green' and 'brown' exposures will not show all relevant risks.

While asset positions form a natural starting point for the analysis, it is important to note that the total effect on financial firms will depend on the overall composition of the balance sheet, i.e. liabilities matter. For instance, rising interest rates will lower the present value of liabilities of pension funds and insurance companies. Generally, the insurers in our sample also hedge virtually all interest rate risk, while pension funds also hedge a significant share of this type of risk.

To somewhat broaden the discussion, therefore, we close by briefly highlighting effects on supervisory ratios. Although the primary focus of this stress test is on the asset side of the balance sheet, financial institutions and supervisors will be ultimately concerned with the impact on supervisory ratios. It should be noted, however, that this analysis requires making a range of additional assumptions. For instance, we assume that the Risk Exposure Amount (REA) remains constant when calculating CET1-ratios after stress. Also, we abstract from potentially mitigating factors, such as reduced tax payments or the fact that banks would often be allowed to gradually build up capital required to cover an increase in expected future losses on corporate loans.

Under this set of assumptions, we confirm the notion that a disruptive energy transition can have material effects for Dutch financial institutions. For instance, we find that the average CET1 ratios of Dutch banks could decline by as much as four percentage points from its current level of close to 16%. This degree of capital decline is somewhat larger than the average delta for Dutch banks under the adverse scenario of the recent 2018 EBA stress test. For insurers, the regulatory solvency ratio could decrease by up to 16 percentage points, while the coverage ratio for pension funds could decline by up to 6 percentage points.

5. Conclusions

This paper proposes a multi-step stress test framework for assessing risks for the financial sector stemming from the energy transition. To illustrate the stress test methodology, we use granular information for portfolios of more than 80 Dutch financial institutions with a total value of EUR 2.3 trillion. The granularity is such that we can classify exposures on 56 industries on the basis of the carbon-intensity of value added. Overall, our methodology suggests that financial stress under disruptive energy transition scenarios could well be sizeable for the Dutch financial sector, further underlining the need to give close and timely attention to climate-transition risks from a financial stability perspective. Using the words of Philip Lane (2019), all this "… calls for ongoing monitoring of climate risks, together with the development of climate-driven scenario analyses and stress tests."

Going forward, it would be particularly interesting to see whether similar conclusions on the magnitude of transition risks would apply to other jurisdictions. As we have argued, the stress test framework can be readily used by financial institutions or by prudential supervisors. The four scenarios can be taken as a starting point, and an econometric model could be used to generate country-specific macroeconomic contexts. To take heterogeneity across industries into account, future work could use the vulnerability factors described in this paper.

Beyond these possible short-term steps, we see several important avenues for future research. A first point for future work relates to integrating both physical and transition risks in one analytical framework. Since both risks can materialize simultaneously, there is a large value-added of analyses in this direction. Second, developing a more integrated modeling framework, which could map the interactions between climate change, economic conditions, and financial risks at an industry-level, would improve the consistency of the analysis. Third, in line with this, it would be important to have an agreed-upon methodology for determining the degree to which a particular industry is vulnerable to transition risks. Fourth, it would be important that financial institutions integrate such a taxonomy into their data-warehousing, so that future analyses can readily build on this. Fifth, it would be instructive to have further discussions on appropriate climate-stress scenarios within the financial stability domain, both for physical and transition risks.

This paper focused on running a complete stress test for energy-transition risks, in the process accepting individual elements of the framework could still be further developed. As a result, this paper was able to provide an estimate of the financial stability risks of a disruptive energy transition under different scenarios for the Dutch financial sector. We look forward to future work on these important issues.

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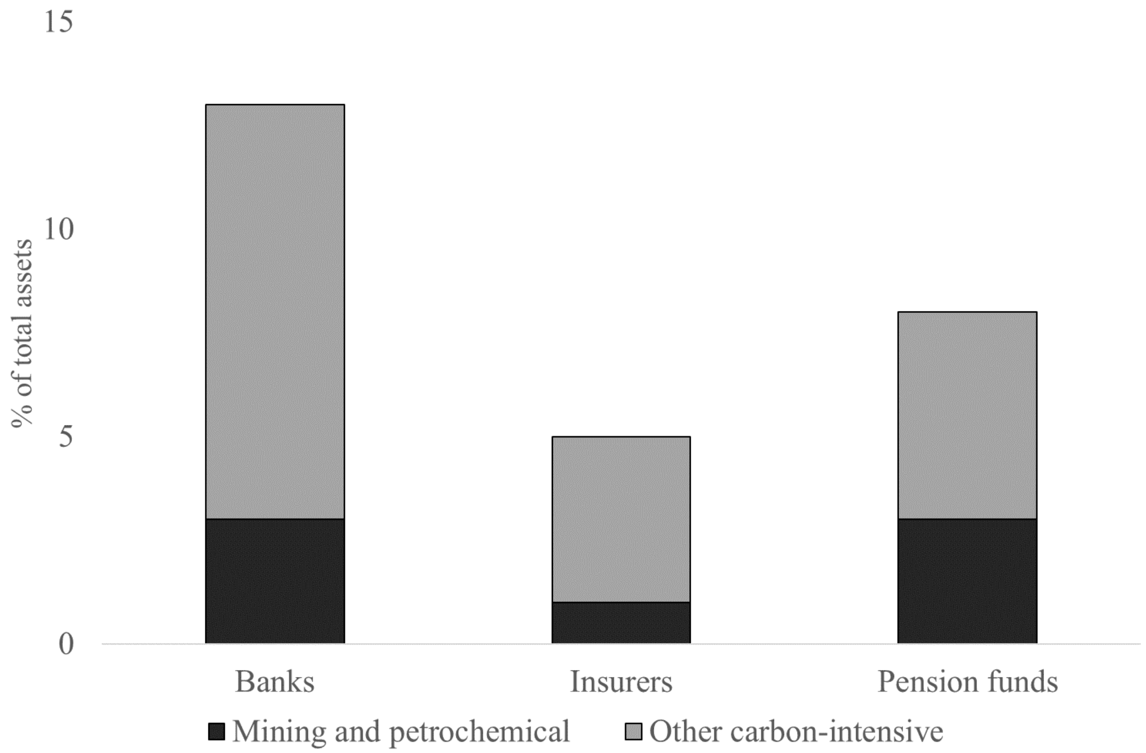
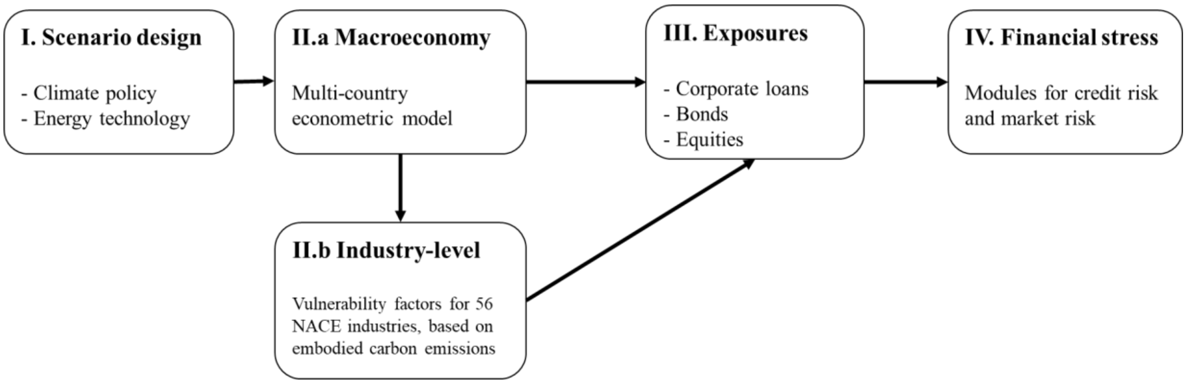
Fig. 1. Exposures of Dutch financial institutions to carbon-intensive industries



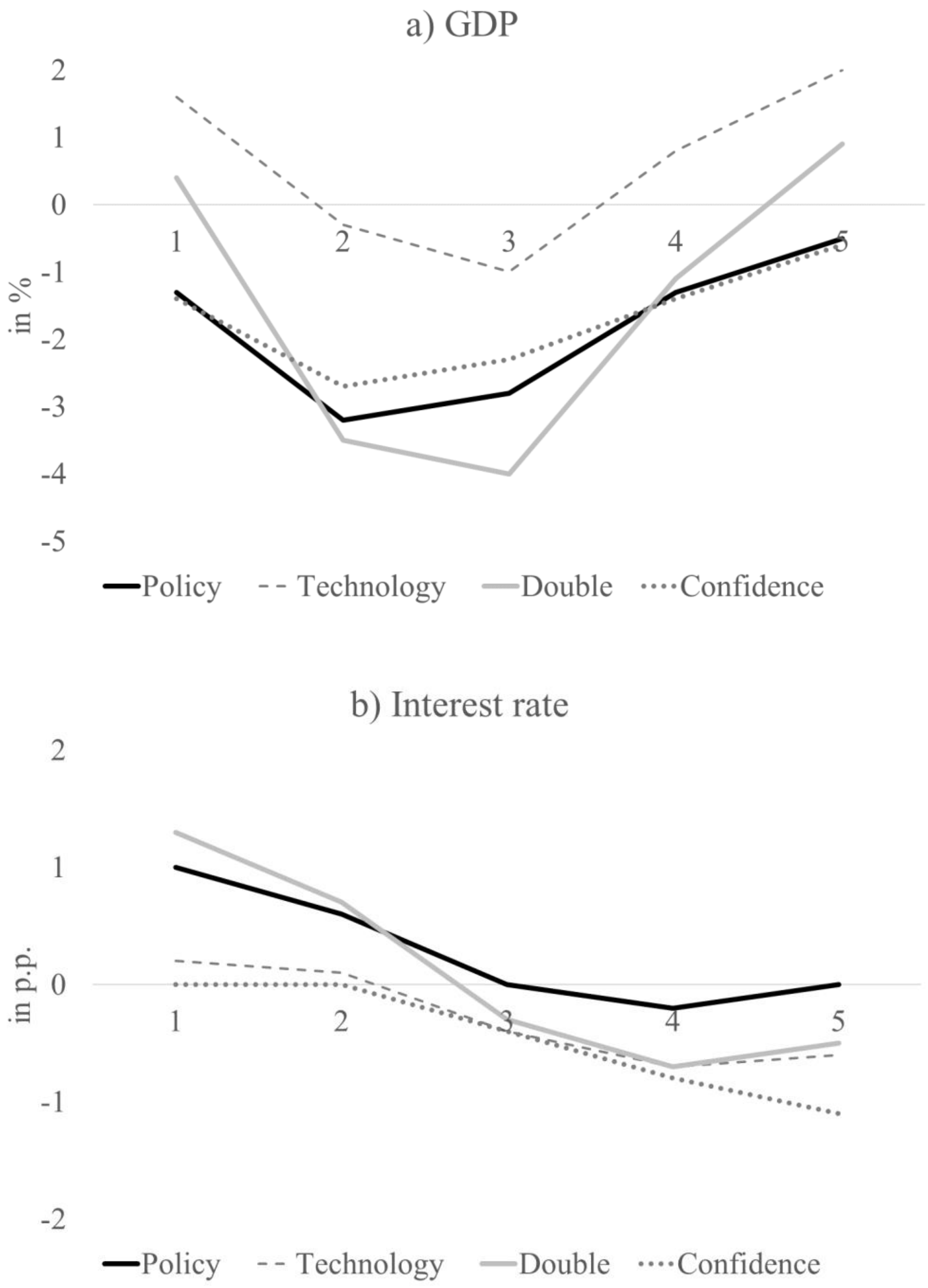
Note: This figure reports the percentages of assets in financial portfolios of Dutch financial institutions that were exposed to two sets of industries: First, companies active in mining and petrochemical industry; second, companies active in other carbon-intensive industries, such as utilities or transport. This classification follows Schotten et al (2016). The portfolios were held by three Dutch banks, 29 insurers, and 50 pension funds at ultimo 2017. The assets in the portfolios were corporate loans, bonds, and equity. See also footnote 12 in the main text for the NACE codes corresponding to these two sets of industries.

Fig. 2. Overview of the stress test framework



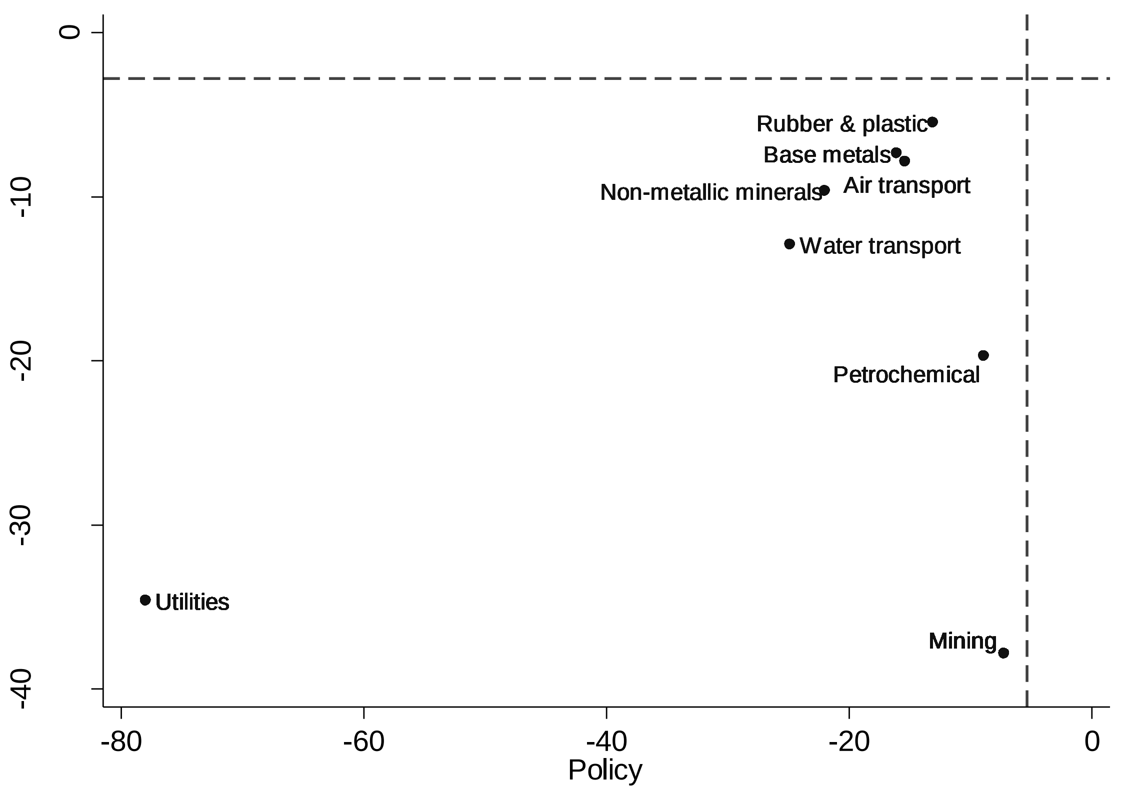
Note: This figure describes a multi-step stress-test framework for measuring financial risks related to the energy transition. Step I entails the construction of severe but plausible transition narratives. Step II entails generating macroeconomic contexts (II.a) and industry-level impacts (II.b). Step III is the collection of data on financial exposures at a level of granularity that can first be connected with steps II and then used in step IV, which is the phase were standard stress test modules are used to compute consequences for credit risk and market risk.

Fig. 3. Macroeconomic consequences of four disruptive transition scenarios



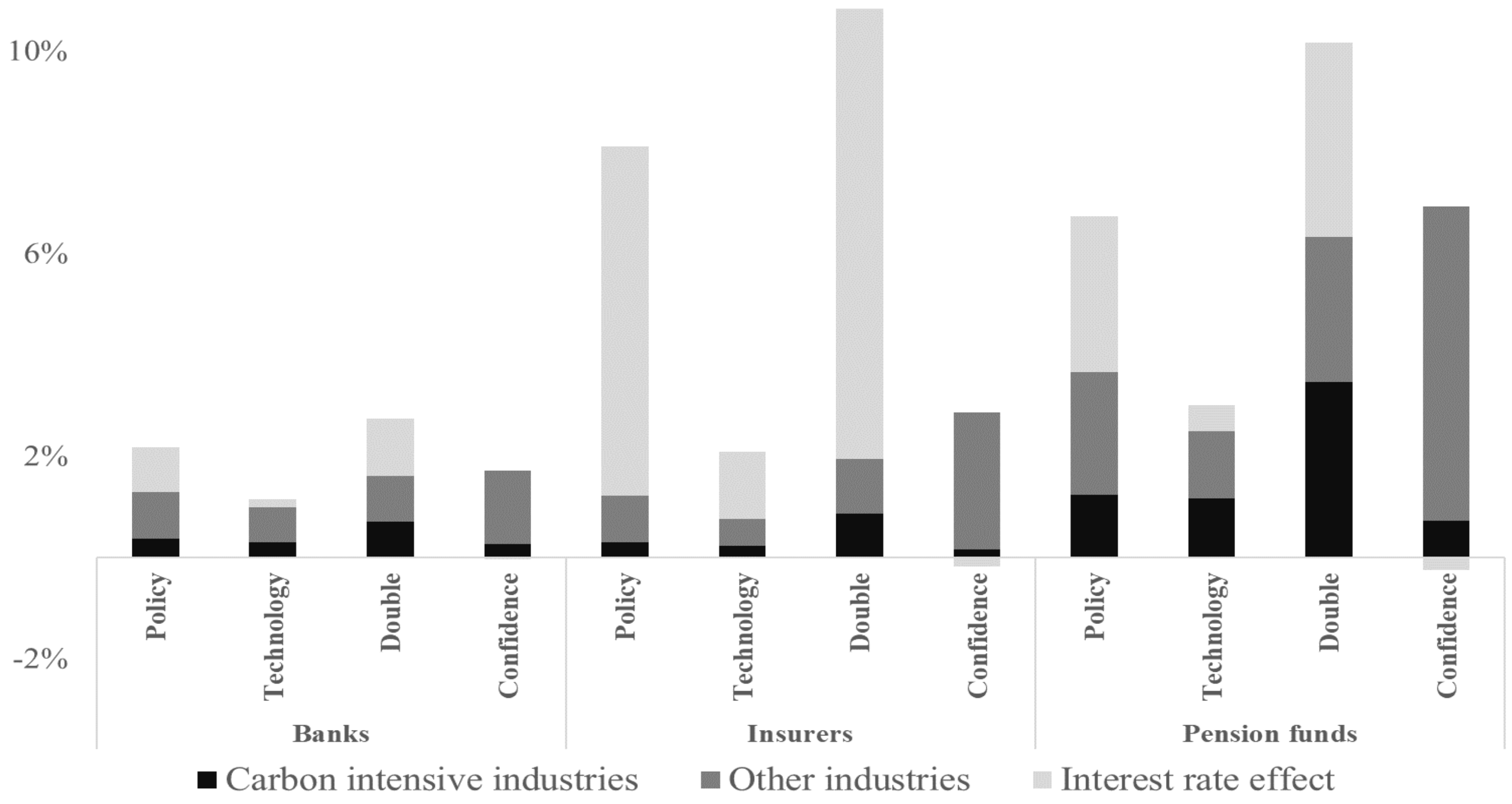
Note: This figure shows macroeconomic consequences for the Dutch economy under four scenarios of a disruptive energy transition. This corresponds to the modeling steps in part II.a of Figure 2. The simulations use NiGEM, a multi-country macroeconometric model. The top panel focuses on GDP, the bottom panel on ten-year interest rates. The numbers are percentage (for GDP) or percentage points (for interest rates) deviations from levels in a baseline projection. The four scenarios differ in assumptions regarding the stance of climate policy and occurrence of technological breakthroughs in the efficiency of renewable energy. Section 3.1 of the main text gives a detailed description of the scenario narratives.

Fig. 4. Industry-specific effects on equity indices under two disruptive transition scenarios



Note: This figure illustrates the impact of using transition vulnerability factors by showing effects on equity indices (in percentage deviations from baseline) for various industries under two disruptive energy transition scenarios. The x-axis shows deviations from baseline levels under a scenario with an active climate policy stance, while the y-axis shows deviations under a scenario with a sudden breakthrough in renewable energy technology. These numbers are obtained by multiplying results for aggregate equity indices according to a macroeconometric model (shown by the dotted lines) with industry-specific transition vulnerability factors. See sections 3.2 and 3.3 of the main text for details.

Fig. 5. Losses for financial institutions under four disruptive transition scenarios



Note: This figure reports financial losses as a percentage of total assets for Dutch banks, insurance companies and pension funds. For each of these three sectors, losses are reported for four possible disruptive energy transition scenarios. 'Policy' denotes a scenario with an active climate policy; 'Technology' denotes a scenario with a breakthrough in renewable energy; 'Double' denotes a scenario that combines these two shocks; 'Confidence' denotes a scenario where economic agents become more cautious in absence of clear steps forward in terms of policy or technology. The losses are the summation, at impact, for credit risk and market risk on corporate loan, bond, and equity portfolios. Losses are split in three sources: those on exposures to carbon-intensive industries (in black), those to other industries (dark gray), and those due to a change in the risk-free interest rate (light gray).

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