A contingent claims approach to climate stress testing

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A growing body of literature attempts to understand the impact of climate policies on the value of financial sector assets, such as equity and debt instruments. However, most of these studies look primarily at losses on equities, while for banks the majority of their exposures is debt (e.g., in the Eurozone loans and bonds represent 85% of total assets). This paper uses the Merton contingent claims methodology to assess the impact of adverse asset valuation shocks on the market value of loans and bonds, including corporate debt and residential mortgages. We then proceed by performing a climate stress test, based on detailed exposure data on the Dutch banking sector. Our estimates for a EUR 100 carbon tax scenario show that combined losses on debt and equity instruments lead to a decline in the market value of banks' assets that is equivalent to 22-39% of their core capital.

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1. Introduction

In light of the Paris Agreement on Climate Change of 2015, there is an increasing realisation amongst central banks, financial supervisors and financial institutions that policies to reduce greenhouse gas emissions may potentially become much more stringent over time. This realisation stems from the substantial gap between emission paths that would result from currently implemented climate policies and emission paths that are consistent with the aim to keep global warming well below two degrees Celsius (Rogelj, McCollum, Reisinger, Meinshausen, and Riahi, 2013). A rich body of academic research has emerged that studies climate change and climate adaptation from an economic growth perspective. For instance, the costs and benefits of reducing greenhouse gas emissions and a changing climate have been integrated into growth models, which aim to inform discussions on the timing and pace of greenhouse gas emissions reduction (Acemoglu, Aghion, Bursztyn, and Hemous, 2012; Nordhaus, 1992).

From a financial perspective, a literature is emerging to understand climate-related financial risks. Depending on distributional choices made, costs of a transition to a low-carbon economy may fall onto the owners of financial assets, such as banks, insurance companies, and pension funds. For example, higher taxes on carbon emissions can lead to the more rapid write-off of capital investments in carbon-intensive sectors, reducing market value and increasing credit risk (Campiglio et al., 2018; Leaton, 2011). Moreover, short-term costs may be substantial and range across a wide variety of sectors (Monasterolo and Raberto, 2019).

Some first attempts have been made to quantify the potential effects of climate policies on the balance sheets of financial institutions. In an innovative paper, Battiston et al. (2017) perform a climate stress test for Eurozone banks, looking at the impact of climate policies on the equity exposures of European banks and allowing for second-round effects (resulting from exposures between financial institutions). Recently, Vermeulen et al. (2019) have set out a framework for analysing climate-related financial stress that builds on the traditional macro-economic stress test literature. Furthermore, a range of papers have investigated the effects of carbon pricing on firm profitability and stock market valuation, however without explicit consideration of the impact on the balance sheets of financial institutions (e.g., Rothe, 2009; Scholtens and Van Der Goot, 2014; Smale, Hartley, Hepburn, Ward, and Grubb, 2006).

A large part of the existing research related to financial variables focuses on the impact that climate policies can have on the value of equity instruments. For banks, however, the majority of assets are debt instruments – such as bonds and loans. For example, in the euro area, at least 85% of all banking assets consist of debt, while only 2% is equity (see table 1). Not including the debt valuation channel in financial sector stress tests could hence lead to a substantial underestimation of potential losses. Moreover, specifically concerning climate policy shocks, one may expect a relatively large share of losses to be absorbed by senior instruments since the effects of the policies are non-evenly distributed across firms and industries (i.e., some firms experience a much more significant impact of a climate policy shock than others). We show in this paper that losses to senior instruments increase exponentially with the size of the valuation shock.

This paper contributes to the literature by setting out an approach to link scenario variables and financial variables that is based on well-established finance theory. We do this in two steps. First, we model the impact of scenario variables on the cash flows of representative firms in different sectors of the economy, which leads to valuation shocks per sector. Then, we calibrate a Merton contingent claims model to allocate these losses to junior (equity-like) and more senior (debt like) claimholders of the firm. Senior claims, such as bonds and loans, will only stop paying out promised cash flows when a counterparty defaults (or sometimes as a result of pre-default restructuring).[4] The outcome of this two-step process is the market value losses per euro exposure for different asset classes and per sector (industries and real-estate).

To illustrate the potential impact of severe energy transition scenarios on the balance sheet of banks through the valuation channel, we apply the model to detailed exposure data of the Dutch Central Bank. Data on mortgages are available on loan-level, while aggregate loan exposures are used for corporate loan and bond exposures to climate-sensitive industries (based on two-digit NACE codes). We set up a tractable scenario, based on the abrupt (overnight) introduction of a carbon tax of EUR 100 per tonne CO2e of emissions.[5] Such a policy shock would be severe and unlikely – but not entirely implausible. It will hence serve the purpose of investigating an extreme policy scenario. We relax the assumption of an abrupt application as part of the sensitivity analysis.

1.1 Related literature

Our paper relates to but uses a different approach than the traditional macro-economic stress test literature. Stress tests of financial institutions' balance sheets have gained much in popularity since the financial crisis that originated in 2007. The primary aim of stress tests is to test the resilience of either individual financial institutions or the financial system as a whole to plausible but severe future scenarios (Henry and Kok, 2013). In contrast to many other risk management practices in the financial sector, stress testing is a forward-looking tool that allows one to investigate the potential impact of future adverse developments in the financial sector.

Next to the literature on traditional macro-financial stress testing, a strand of research is developing on stress tests that are specifically tailored to investigating climate-related financial risks (Battiston, Mandel, Monasterolo, Schütze, and Visentin, 2017; Vermeulen, Schets, Lohuis, Kölbl, and

[4] Note that, from a market value perspective, adverse asset valuation shocks can affect the market value of debt even without default or restructuring.

[5] We base ourselves on the Eurostat air emissions accounts for air pollutants that have global warming potential (greenhouse gases). This includes CO2, N2O and CH4. Whenever we refer to a carbon tax or carbon price we refer to a tax that is applied to the emission of these three gasses, expressed in CO2-equivalents (CO2e).

Jansen, 2019). One of the key differences between traditional macro-financial stress testing and climate-related stress testing is the importance of sectoral shocks: in many scenarios, there is a specific set of industries or other groups of economic actors that are most affected. This is, for example, the case in the debate surrounding ‘stranded assets’, where some carbon-intensive industries (such as oil and coal producers) are thought to lose a substantial share of their value when externalities from fossil fuel combustion are priced in. These differences lead to new challenges, specifically in understanding how changes in the valuation of certain real economy assets have an impact on financial institutions’ balance sheet. Approaches in the literature and by practitioners so far have either made direct assumptions on fractions of industry equity value to be lost (Battiston et al., 2017) or made assumptions on the impact of climate scenarios on macro-economic variables, such as economic growth, and then use existing models to understand the impact on financial sector assets (Vermeulen et al., 2019). The financial channel from asset valuation (e.g., firms and real-estate) to financial asset value has to our knowledge not been explored so far in the context of climate stress testing.

To investigate the financial channel based on asset valuation, this paper builds on the structural credit risk modelling literature. Specifically, we make use of the ideas as developed by Merton (1974), who models equity as a call option on the value of the firm’s assets where the payoff is either zero (in case of default) or the value of assets minus the face value of the debt. Conversely, the debt holder has a risk free bond and is short a put option of the firm’s assets. This implies that a negative asset valuation shock will affect the value of both equity and debt in a non-trivial way. The standard Merton model assumes that default occurs when at maturity the value assets V lies below the face value of debt L. For corporates, this is likely a valid approximation, although some extensions have been proposed to relax this assumption. For example, Black and Cox (1976) look at the case where restructuring already occurs before V falls below L. However for mortgages, which represent an important asset class for banks, default is more complicated since these types of loans often have additional safeguards build in for the lender. Especially in the euro area, mortgages are common that do not only have recourse to the underlying real-estate, but also to the wealth and income of the borrower. This implies that, in a Merton setting, we need to adjust the default trigger for residential mortgages (Sy, 2014). Therefore, for mortgages, we take an approach where default is conditional on both insolvency (i.e. the value of the house falling below the value of the mortgage) and delinquency (i.e. not having sufficient liquidity to make the periodical payment on a loan).

2. Financial vulnerability modelling

This section describes the vulnerability model that underlies our stress test. We also discuss assumptions and possible extensions, amongst others for later use in the sensitivity analysis. The primary goal of our modelling is to determine the impact of stress scenarios on the value of debt and equity portfolios of banks. This will allow us to estimate stress test coefficients $\vartheta_{E,k}$ that can be applied to equity portfolios and stress test coefficients $\vartheta_{D,k}$ that can be applied to debt portfolios respectively as:

$$\vartheta_{E,k} = \frac{MV_{E,k}^{*}}{MV_{E,k}} \text{ and } \vartheta_{D,k} = \frac{MV_{D,k}^{*}}{MV_{D,k}} \tag{1}$$

In the above formula MV_k represents the market value of portfolio *k*, and an asterisk is used to denote the market value after the scenario shock has been applied. Using this definition gives us the fraction of the market value of the portfolio that remains after the stress scenario is applied. Hence, the expected market value loss per unit of exposure can be written as $1 - \vartheta$.[6]

We develop the vulnerability model in two sections. In section 2.1 we put forward a stylized discounted cash flow model to determine a valuation shock ξ_k per sector. We model ξ_k such that it ranges between zero (no losses) and one (full loss of sector value). This can be viewed as the 'real economy' or 'left' side of the balance sheet, representing the value of a physical bundle of assets. We take ξ_k to be a function of the scenario variable τ_t, which represents the euro value of a carbon tax over time, and a set of vulnerability parameters $\Omega_{k,t}$ which we differentiate per sector *k* and that may vary over time *t*. Finally, we use a sector specific discount rate r_k.

$$\xi_k = f(\tau_t, \Omega_{k,t}, r_k)$$

Section 2.2 provides the modelling of $\vartheta_{D,k}$ and $\vartheta_{E,k}$ as functions of a set of model parameters Θ_k and an asset valuation shock ξ_k. For this we use the Merton (1974) structural credit risk model, which we extend to take into account more complicated default conditions that are characteristic of European mortgages with double recourse. The basic idea is to distribute the asset valuation shock ξ_k to holders of equity (E) and debt (D).

$$\vartheta_{E,k}, \vartheta_{D,k} = f_{Merton}(\xi_k, \Theta_k)$$

[6] Since we are interested in the consequences for the market value of the bank balance sheet we will estimate the expected loss in risk-neutral terms (i.e. the probability of default is adjusted to reflect market participants' risk preferences).

2.1 Economic vulnerability

To determine the valuation shock due to this carbon tax, we take the yearly emissions per sector and multiply this by the carbon price. The total valuation impact of the tax is then determined by discounting these cash flows, some of which will occur in the future, into a net present value using an appropriate discount rate per industry. Without any response from any of the actors involved (such as adjustments in the production process, the quantity produced or the price of products), a shock in carbon tax would lead to a reduction in EBIT given by the present value of the additional future (negative) cash flow. Assuming that there are no net tax and funding cost effects, the impact on the net present value of an industry of the tax shock can be formalised as follows:

$$NPV_{tax} = \sum_{t=0}^{T} (1 - r_k)^t * \gamma_k(-\tau_t) \quad (13)$$

Where γ are the total carbon emissions of the industry, τ_t the carbon tax per unit of emission in year *t*, and *r* the applicable discount rate.

Of course, it can be expected that firms will adjust their business model in an attempt to offset the potential loss in their value after a carbon tax is announced. One response that is well-documented in the literature is the pass-through of increasing costs (in this case the carbon tax) into product prices (e.g., Fabra and Reguant, 2013). This increase in price could partially offset the initial tax burden on producers. However, for most goods, an increasing price reduces the size of the market which potentially leads to firms exiting the market or lowering their production volumes.[7] We allow within the model the possibility that the amount of the tax that is passed on to consumer prices is a function over time, e.g., due to contract renewals after certain periods. Also, our model takes into account the possibility that firms adjust their business models over time, by substituting their inputs (e.g., green for brown electricity) and production processes (e.g., introduce technology that avoids atmospheric emissions such as carbon filters).

$$NPV_{tax,k} = \sum_{t=0}^{T} (1 - r_k)^t * \gamma_{k,t}(1 - \varphi_{k,t})(-\tau_t) \quad (14)$$

In this equation $\varphi_{k,t}$ is the fraction of the tax that can be passed on to customers by increasing prices, which can change over time. $\gamma_{k,t}$ is the sector specific carbon intensity, which we allow to vary over time as a result of business model adjustment. We hence add a subscript *t*. Finally we relate the net

[7] Note that this could not only lead to *stranded assets* (e.g. oil reserves and specialized capital goods) as often referred to in the literature, but also *stranded business* (i.e. future earnings that are priced into firm value but are not expected under the new climate policy regime).

present value of the tax shock to the total asset value within the sector, which gives us the fraction of the total asset value that is lost due to the carbon tax:

$$\xi_k = \frac{NPV_{tax,k}}{Total\ asset\ value} \tag{14}$$

2.2 Financial vulnerability

A typical firm is funded with equity (e.g. shares) and debt (e.g. bonds and loans) which can in turn be held by financial institutions and other investors. In a seminal paper, Merton (1974) investigates the structural factors that determine the credit risk component of debt and thereby affect the value of the debt. A key insight in this paper is that equity can be viewed as a residual claim on assets after debt has been repaid. This implies that the equity holder has a call option on the value of the firm's assets, where the payoff is either zero (in case of default) or the value of assets minus the face value of the debt. Conversely, the debt holder has a risk free bond and is short a put option of the firm's assets. Hence a negative asset valuation shock will affect the value of both equity and debt in a non-trivial way.

In a standard Merton structural debt framework, the market value of debt MV_D can be written as its risk free value minus the risk-neutral expected loss (the latter being equivalent to a put option on the value of the assets). Following the notation of Giesecke (2002):

$$MV_D = Le^{-r(T-t)} - Le^{-r(T-t)}\big(N(-d_2)\big) - V_t N(-d_1) \tag{2}$$

with

$$d_1 = \frac{\ln(\frac{V_t}{L}) + (r + \frac{\sigma_V{}^2}{2})(T-t)}{\sigma_V\sqrt{T-t}}$$

$$d_2 = \frac{\ln(\frac{V_t}{L}) + (r - \frac{\sigma_V{}^2}{2})(T-t)}{\sigma_V\sqrt{T-t}}$$

Where N is the probability of the standard normal density function below *d*. Hence MV_D can be expressed as a function of asset value *V*, contracted repayment *L*, time to maturity *T-t*, the standard deviation of asset value σ_V and the risk free interest rate *r*. Furthermore, under the Merton model's assumptions of geometric Brownian motion, the volatilities of the firm and its equity are given by:

$$\sigma_E = \frac{V}{E} N(d_1)\sigma_V \tag{3}$$

A typical problem that can be solved using these equations is to determine the unobserved value of the firm *V* and the standard deviation of the firm's assets σ_V. For our purposes, however, we will assume an instantaneous shock ξ on asset value such that immediately after the shock asset value V* is given as follows:

$$V^* = (1-\xi)V \tag{4}$$

Which gives the market value of debt after the shock as:

$$MV_D{}^* = Le^{-r(T-t)} - Le^{-r(T-t)}\big(N(-d_2^*)\big) - V_t^* N(-d_1^*) \tag{5}$$

Replacing V^* with $(1-\xi)V$, defining the ratio of contracted repayment to asset value (leverage ratio) as $R = L / V$ and dividing by the discounted exposure $Le^{-r(T-t)}$ we find that:

$$MV_D{}^* = 1 - \big(N(-d_2^*)\big) - ((1-\xi)/Re^{-r(T-t)})N(-d_1^*) \tag{6}$$

with

$$d_1^* = \frac{\ln(\frac{(1-\xi)}{R}) + (r + \frac{\sigma_V{}^2}{2})(T-t)}{\sigma_V\sqrt{(T-t)}}$$

$$d_2^* = \frac{\ln(\frac{(1-\xi)}{R}) + (r - \frac{\sigma_V{}^2}{2})(T-t)}{\sigma_V\sqrt{(T-t)}}$$

Hence,

$$\vartheta_D = \frac{MV_D{}^*}{MV_D} = \frac{1-\big(N(-d_2^*)\big)-((1-\xi)/Re^{-r(T-t)})N(-d_1^*)}{1-\big(N(-d_2)\big)-(1/Re^{-r(T-t)})N(-d_1)} \tag{7}$$

Thus, given a risk-free interest rate r, ϑ_D is a function of the asset valuation shock ξ, the leverage ratio *R*, asset value volatility σ_V and the time to maturity *T-t*. Moreover, equations 2 and 5 can be solved simultaneously in order to determine V and σ_V from E and σ_E.

In a similar fashion, the Merton equation for equity is given by

$$MV_E = V_t N(d_1) - Le^{-r(T-t)}N(d_2) \tag{8}$$

And following the same line of reasoning as for debt, we find that:

$$\vartheta_E = \frac{MV_E{}^*}{MV_E} = \frac{(1-\xi)N(d_1^*) - Re^{-r(T-t)}N(d_2^*)}{N(d_1) - Re^{-r(T-t)}N(d_2)} \tag{9}$$

2.2.1 Merton extensions

The Merton (1974) model is based on several assumptions[8], some of which have been challenged in subsequent research. An important assumption is that asset value follows a geometric Brownian motion, which implies that in a short interval of time, asset value can only change by a small amount (Merton, 1976). Several authors have noted that this is inconsistent with empirical observation, namely that in a short interval of time there are sometimes large changes in stock prices or "jumps" (e.g., Cai and Kou, 2011). Moreover, in most industries, there are substantial costs associated with default. Hence some approaches explicitly introduce recovery values to account for these costs (e.g., Benos and Papanastasopoulos, 2007; Longstaff and Schwartz, 1995). Both of these assumptions lead to potentially higher losses as a result of an asset valuation shock and are considered explicitly in the sensitivity analysis.

Specifically for mortgages, the Merton model may overestimate losses due to the recourse nature of most European mortgages. Recourse entitles the creditor to other household assets besides the value of the secured real-estate, including future income. In contrast to American mortgages, this implies that households are less prone to default on their mortgages in the face of asset valuation losses, even if the value of the real-estate is lower than the value of the mortgage.[9] To account for recourse we model a more stringent default condition, rewriting equation 1 by dividing by the discounted exposure $Le^{-r(T-t)}$ and multiplying its last term by $N(-d_2)/\,N(-d_2)$:

$$MV_D/Le^{-r(T-t)} = 1 - N(-d_2)(1 - \frac{V_t}{Le^{-r(T-t)}} * \frac{N(-d_1)}{N(-d_2)}) \tag{10}$$

In this equation $N(-d_2)$ is the risk-neutral probability of default and $N(-d_1)/\,N(-d_2)$ is the expected discounted recovery rate. For residential mortgages, we can then introduce a more strict default trigger by replacing the Merton probability of default $N(-d_2)$, which could be thought of as representing insolvency, by a more broad probability of default that is a multiplication of $N(-d_2)$ and the probability that a household will not have sufficient wealth and/or income to pay their instalment *P(delinquent)*. If default is triggered by combined insolvency and delinquency, while assuming that there is no correlation between $N(-d_2)$ and *P(delinquent),* equation (10) can be rewritten as:

$$\frac{MV_D}{Le^{-r(T-t)}} = 1 - N(-d_2) * P(delinquent) * (1 - \frac{V_t}{Le^{-r(T-t)}} * \frac{N(-d_1)}{N(-d_2)}) \tag{11}$$

[8] For a full list of assumptions, see Merton (1974).

[9] We note here that although a mortgage may legally be full-recourse, in practice this full-recourse is not always (fully) applicable. An example is the case of Ireland where in the aftermath of a housing crisis the central bank implemented regulations that severely restricted the ability of banks to contact or harass delinquent borrowers, making the Irish residential mortgages *de facto* limited recourse contracts (Connor and Flavin, 2015).

Which leads to

$$\vartheta_{D,M} = \frac{{MV_D}^*}{MV_D} = \frac{1-N(-d_2^*)*P(delinquent)^* * (1-(1-\xi)/Re^{-r(T-t)} * N(-d_1^*)/N(-d_2^*))}{1-N(-d_2)*P(delinquent)*(1-1/Re^{-r(T-t)} * N(-d_1)/N(-d_2))} \tag{12}$$

3. Data and calibration

This section describes our data and calibration methods. We use two different approaches to obtain and estimate the required parameters for the Merton model, respectively for corporate exposures and real-estate exposures. The reason for this is that the structure of the data differs substantially for the two types of portfolios. In our analysis, we take the risk-free interest rate to be constant at 3% and we have remaining maturity buckets available for banks' portfolios (for which we will assume no correlation with the other parameters, which implies a distribution of loan characteristics that is constant over time). We hence still need to obtain parameter values for the standard deviation of asset value σ_V and the leverage ratio R for individual firms and real-estate. A summary of the obtained estimates is provided in table 2.

3.1 Corporate exposures

To investigate the vulnerability of the Dutch banking sector to an abrupt energy transition scenario we use a 2017 dataset on the sectorial classification of the asset holdings of Dutch banks. This dataset was obtained as part of a climate exposure survey and included the three largest banks in the Netherlands, which together hold 76% of total assets. Exposures are available for a list of transition-sensitive industries according to the NACE classification (see the list of industries in Appendix II). Included asset classes are stocks, corporate bonds, sovereign bonds, loans, and trade commodity finance. Loans are furthermore classified according to their remaining maturity (less than one year, 1-5 years and more than five years). Based on this data, Dutch banks have EUR 209 billion worth of assets in transition-sensitive industries (excluding real-estate, which we treat as a separate asset class), which equals 12.6% of total assets.

For corporate exposures, we do not have loan-level portfolio data that provide the variables to calibrate the Merton model. We hence base ourselves on the Orbis database by Bureau van Dijk, which provides balance sheet data of most listed and non-listed firms including those in the euro area. Using this data we construct a representative corporate loan portfolio for each industry at the two-digit NACE industry classification level. For listed firms, we then combine the Orbis data with Thomson Reuters Datastream using ISIN-codes to link our data at the firm level in both databases. We use stock prices, obtained from Datastream, to estimate the standard deviation of stock returns which, combined with the leverage ratio, is sufficient to determine the standard deviation of asset value using the Merton model. For non-listed firms, we calibrate the standard deviation of asset value using OLS regression based on a subset of listed firms.

To determine the leverage ratio, we start with the sample of all active companies in the Orbis database for 15 countries of the European Union.[10] We then select only those companies that have a non-zero gearing metric, implying they are funded using both equity and debt. Finally, we label the firms using the NACE Rev. 2 classification in order to be able to calculate average leverage ratios per industry, weighted by the firm's total assets. To calculate the leverage ratio we use the relationship between leverage ratio and gearing which is defined as leverage ratio = gearing/gearing + 100%. By employing this procedure we end up with 374.701 observations in transition sensitive industries.

For the standard deviation of asset value, we first look at the historical returns on traded shares of a subset of firms in the Orbis sample using Thomson Reuters Datastream. For all firms with an ISIN-code, we calculate the monthly standard deviation of the total return index (RI)[11] as provided by Datastream for the 12 years from 2006 to 2017. We exclude time-series that have more than two missing observations. This procedure yields 973 observations for which a complete time-series is available. Then, based on the leverage ratio and the standard deviation of equity returns we use the Merton equations (2) and (3) and solve them simultaneously to obtain the asset value volatility.

For the remainder of the firms for which asset and equity volatility cannot be observed, we estimate an OLS regression model that is based on the subset of 973 firms for which we have this data available. We set the standard deviation of asset value as the dependent variable, controlling for firm size (total assets) and industry (two-digit NACE classification). We use the resulting model to obtain estimates for the unknown asset value standard deviations of the full set of firms as obtained from Orbis. The regression model is provided in table 3.

3.2 Real-estate exposures

For real estate, we base ourselves on loan-level mortgage data available at the Dutch Central Bank. These include maturity and loan-to-value (LTV) statistics on individual mortgage loans of banks in the Netherlands. These are summarised in table 4. We combine them with data from Eurostat and the Netherlands Enterprise Agency to estimate asset value volatility and the vulnerability to asset valuation shocks respectively.

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[10] AT, BE, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, NL, PT, SE

[11] The return index (RI) provides the theoretical growth in value of a shareholding over a specified period, assuming that dividends are re-invested to purchase additional units of an equity. This provides a better metric for our purposes compared to the price index (PI) which does not correct equity value for dividend payments.

We obtain historical house price data for the Netherlands from Eurostat to estimate the volatility of asset value. Since the time series provided are only available at the national level, we can only directly determine the volatility of the aggregated residential real-estate portfolio, which based on a sample of the last 12 years is equal to 5% (see table 5). To account for the difference between aggregated portfolio volatility and the volatility of individual homes, we apply a factor (x2) based on the similar (but observable) difference between equity indices and individual stocks.

Since Dutch mortgages are based on the principle of double recourse, we will introduce the additional constraint on default that the homeowner is both insolvent and delinquent. We approximate the fraction of home-owners that become delinquent during the two years by the yearly probability that a homeowner becomes unemployed and/or divorces, where we assume all homeowners to have a job and 50% of homeowners to be married (or living together in a legal form equivalent to marriage). This leads to a combined probability of becoming unemployed and becoming divorced in the next two years of 11.6% (see table 5 for underlying statistics).

Finally, we obtain information on the energy label distribution for Dutch residential real estate from the Netherlands Enterprise Agency as provided in table 6.

3.3 Carbon tax valuation shocks

To estimate the effect of a carbon tax shock on the asset value of firms, we use the air emissions intensity per euro value added to obtain a measure of the cost of a carbon tax relative to firm value. To this end, we obtain the air emissions intensity per euro value added by NACE Rev. 2 activity as provided by Eurostat in 2017. This metric covers the emissions that are relevant for a carbon tax, including CO2, N2O, and CH4 in CO2 equivalent (CO2e). We furthermore classify the industries into five categories concerning their expected ability to pass through the tax to their customers and their ability to cost-effectively adapt their production processes to reduce their CO2e air emissions. For each category we define pass-through (φ_t) and adaptation (γ_t) functions (see appendix I, table C). Finally, we use a cost-of-debt of 5.5% as the relevant discount rate in net present value calculations since assumed certain negative cash flows as a result of the carbon tax apply only as long as the firm has active operations (and hence the cash flow is not risk-free).

4. Climate stress test of the Dutch banking sector

In this section, we define the stress scenarios which we use to determine total market value losses for Dutch banks on their corporate debt and equity portfolios as well as on their mortgage portfolios.

We define two baseline stress scenarios, assuming an overnight introduction of a EUR 100 carbon tax. The two scenarios differ in the extent to which corporates can pass the carbon tax onto consumers by increasing prices. In the first scenario, we assume that there is no pass-through of taxes to consumers, which could, for example, be caused by the limited geographical application of the tax whereby domestic firms cannot increase prices due to international competitive pressures. In the second scenario, we assume that most firms can pass-through 50% of taxes to consumers with exceptions for industries that provide either luxury products or have strong competition from renewable substitutes. This scenario reflects the situation in which a carbon tax is applied globally, and hence a level playing field is maintained. The asset valuation shocks per industry are provided in table 7, and underlying assumptions and intermediary model outcomes in Appendix I.

Results are shown in table 8. Scenario 1 (no pass-through) leads to market value losses of EUR 23.6 billion for the three largest Dutch banks. Extrapolated to the total market this equals EUR 28.2 billion for the whole Dutch banking sector, which is equal to 1.7% of total assets and 38.7% of Core Equity Tier 1 (CET1) capital. For scenario 2 (including pass-through) market value losses of EUR 13.0 billion for the largest three banks and EUR 15.8 billion for the sector as a whole, which is equal to 0.9% of total assets and 21.7% of CET1 capital.

We perform sensitivity analyses (to be completed) on several of the key assumptions that were made in the process. A first check that we complete regard two assumptions within the Merton model, which are that firm valuation follows Brownian motion over time and no bankruptcy costs. For the former, we run the model with an alternative specification based on the jump-diffusion model (Cai and Kou, 2011), while for the latter we run the model while allowing for an additional (and one-off) cost at bankruptcy that is equal to a fraction of the remaining value. A second check that we complete regards our methodological choices and specifically the approach of using representative households and firms. We challenge this approach by allowing for variation in the parameters of the model.

5. Conclusion and discussion

Current trajectories of carbon emissions lead to a global warming scenario of three to four degree Celsius. That is well beyond the safe boundary of keeping global warming below two degree Celsius. A sudden tightening of climate policies is therefore possible. Using the Merton methodology to assess the impact of an abrupt carbon tax of EUR 100 per tonne CO2e of emissions on equity- and debt-type assets allow us to calculate the impact on bank assets. Current studies of climate stress tests look primarily at losses on equities and thus underestimate carbon risk.

Our findings indicate that about one to two fifths (22% to 39%) of the available Common Equity Tier 1 capital of the Dutch banking system is wiped out in first round losses following an abrupt implementation of a sizeable carbon tax of EUR 100. This can be seen as a lower bound, as second-round effects could lead to further losses. These findings suggest that climate policies pose a systemic risk to the financial sector. To mitigate the impact of climate policies, banks may wish to reduce the carbon intensity of their equity and debt portfolio and central banks may include regular carbon stress tests in their macroprudential toolbox (Schoenmaker and Van Tilburg, 2016).

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Table 1 Aggregate assets in the euro area banking sector

	EUR trillion	Percentage of total
Equity exposures	0.5	2%
Corporate loans and debt	5.1	23%
Residential mortgages	3.8	17%
Consumer loans (non-mortgage household loans)	1.9	8%
Government loans and debt	2.8	13%
Financial corporate loans and debt	3.4	15%
Central bank loans and debt	1.8	8%
Other	2.9	13%
Total	22.3	100%

Source: ECB Statistical Data Warehouse

Table 2 Standard deviation of equity

NACE category	Standard deviation of equity (σ_E)			
	Mean	Standard deviation	Asset weighted mean	N
Growing of non-perennial crops	0.37	0.14	0.31	16
Animal production	0.37	0.30	0.20	3
Support activities to agriculture and post-harvest crop activities	0.34	0.15	0.35	11
Forestry and logging	0.16	0.08	0.28	4
Mining of coal and lignite	0.66	0.39	0.37	9
Extraction of crude petroleum and natural gas	0.63	0.47	0.19	30
Mining of metal ores	1.00	0.69	0.54	34
Other mining and quarrying	0.57	0.46	0.62	29
Mining support service activities	0.84	0.82	0.43	55
Manufacture of paper and paper products	0.47	0.27	0.43	49
Manufacture of coke and refined petroleum products	0.34	0.13	0.20	10
Manufacture of chemicals and chemical products	0.41	0.29	0.27	107
Manufacture of rubber and plastic products	0.35	0.17	0.47	47
Manufacture of other non-metallic mineral products	0.36	0.25	0.30	71
Manufacture of basic metals	0.57	0.36	0.55	98
Electric power generation, transmission and distribution	0.31	0.23	0.31	86
Manufacture of gas; distribution of gaseous fuels through mains	0.28	0.18	0.20	11
Land transport and transport via pipelines	0.29	0.17	0.24	27
Water transport	0.44	0.39	0.34	26
Air transport	0.47	0.23	0.41	17
Warehousing and support activities for transportation	0.34	0.20	0.30	51

Source: Bureau van Dijk Orbis and Thomson Reuters Datastream

Table 3 Leverage ratio

NACE category	Leverage ratio (*R*)			
	Mean	Standard deviation	Asset weighted mean	N
Growing of non-perennial crops	0.37	0.21	0.27	16
Animal production	0.44	0.17	0.57	3
Support activities to agriculture and post-harvest crop activities	0.41	0.23	0.50	11
Forestry and logging	0.30	0.26	0.61	4
Mining of coal and lignite	0.31	0.22	0.40	9
Extraction of crude petroleum and natural gas	0.29	0.25	0.42	30
Mining of metal ores	0.27	0.20	0.36	34
Other mining and quarrying	0.31	0.22	0.48	29
Mining support service activities	0.34	0.26	0.48	55
Manufacture of paper and paper products	0.38	0.19	0.41	49
Manufacture of coke and refined petroleum products	0.44	0.17	0.52	10
Manufacture of chemicals and chemical products	0.33	0.22	0.43	107
Manufacture of rubber and plastic products	0.36	0.19	0.39	47
Manufacture of other non-metallic mineral products	0.40	0.19	0.42	71
Manufacture of basic metals	0.34	0.23	0.50	98
Electric power generation, transmission and distribution	0.52	0.24	0.66	86
Manufacture of gas; distribution of gaseous fuels through mains	0.47	0.27	0.61	11
Land transport and transport via pipelines	0.48	0.24	0.59	27
Water transport	0.48	0.21	0.34	26
Air transport	0.52	0.22	0.55	17
Warehousing and support activities for transportation	0.43	0.21	0.51	51

Source: Bureau van Dijk Orbis

Table 4 Debt by LTV bucket for Dutch residential mortgages in the first quarter of 2017

LTV bucket	EUR billion
<50%	87.36
50-60%	43.36
60-70%	54.56
70-80%	59.06
80-90%	79.27
90-100%	86.22
100-110%	54.34
110-120%	23.44
120-130%	9.04
>130%	11.23
Unknown	2.82

Source: Dutch Central Bank

Table 5 Eurostat statistics for the Netherlands

Variable	Average	Standard deviation	Available period
Annual crude divorce rate (% of married)	2	0.06	2005-2016
Quarterly transition employment – unemployment (% of employed)	1.2 (4.8 annualized)	0.28	2010Q2-2018Q2
Annual rate of change of the house price index (%)	1.1	5.00	2006Q1-2018Q2

Source: Eurostat

Table 6 Energy-label distribution of real estate in the Netherlands and natural gas usage, per 1 January 2016, and calculation of the asset value shock based on a EUR 100 / tonne CO2e carbon tax

Label	Percentage of total	Natural gas usage (m3/m2)	Asset value shock (ξ)
A	8.7%	9.3	0.028
B	16.2%	9.6	0.029
C	30.6%	10.1	0.030
D	22.5%	10.7	0.032
E	12.1%	11	0.033
F	6.7%	11.4	0.034
G	3.3%	11.5	0.034

Source: Netherlands Enterprise Agency and Netherlands Statistics

Note: based on an average house size of 100m2, an average value of EUR 300,000, carbon emissions per burned m3 of natural gas of 1.9 kg, and a discounting of future cash flows at 2% over 50 years.

Table 7 Asset valuation shocks for corporate loans and bonds

NACE Rev. 2	Label	Scenario 1 asset value shock (ξ)	Scenario 2 asset value shock (ξ)
A.01.1	Growing of non-perennial crops	0.24	0.13
A.01.4	Animal production	0.24	0.13
A.01.5	Mixed farming	0.24	0.13
A.01.6	Support activities to agriculture and post-harvest crop activities	0.24	0.13
A.02	Forestry and logging	0.02	0.01
B.05	Mining of coal and lignite	0.27	1.00
B.06	Extraction of crude petroleum and natural gas	0.27	0.65
B.07	Mining of metal ores	0.27	0.35
B.08	Other mining and quarrying	0.27	0.35
B.09	Mining support service activities	0.27	0.45
B.09.1	Support activities for petroleum and natural gas extraction	0.27	0.65
C.17	Manufacture of paper and paper products	0.16	0.08
C.19	Manufacture of coke and refined petroleum products	0.62	0.58
C.20	Manufacture of chemicals and chemical products	0.22	0.12
C.22	Manufacture of rubber and plastic products	0.03	0.01
C.23	Manufacture of other non-metallic mineral products	0.73	0.39
C.24	Manufacture of basic metals	0.82	0.44
D.35.1	Electric power generation, transmission and distribution	0.58	0.44
D.35.2	Manufacture of gas; distribution of gaseous fuels through mains	0.58	0.61
H.49	Land transport and transport via pipelines	0.21	0.11
H.50	Water transport	0.93	0.50
H.51	Air transport	1.00	0.50
H.52	Warehousing and support activities for transportation	0.03	0.02

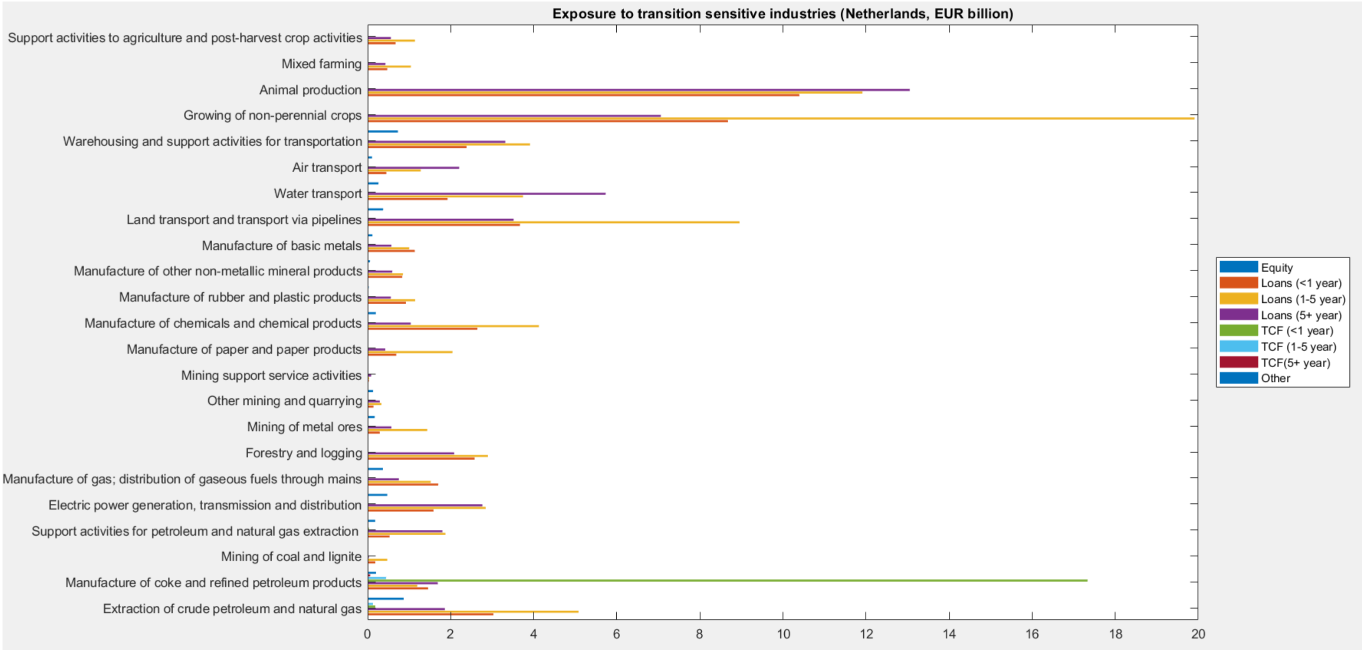
Scenario 1: EUR 100 carbon tax without pass-through

Scenario 2: EUR 100 carbon tax with pass-through

Table 8 Market value impact of a EUR 100 carbon tax on the Dutch banking sector

	Model I Standard Merton	
Asset class	Scenario 1 (EUR million)	Scenario 2 (EUR million)
Corporate debt	25,827	13,463
Corporate equity	2	1
Mortgages	2,334	2,334
Total	28,163	15,798
% of CET1 capital	38.7%	21.7%
% of total assets	1.7%	0.9%

Figure 1 Exposures of the Dutch banking sector to transition sensitive industries



Source: Dutch Central Bank

Appendix I Shock components and assumptions

Table A - Scenario 1 – EUR 100 local carbon tax (no pass-through)

NACE Rev. 2	Industry	Scope 1 shock	Adaptation	Total shock
A.01.1	Growing of non-perennial crops	0.29	-0.05	0.24
A.01.4	Animal production	0.29	-0.05	0.24
A.01.5	Mixed farming	0.29	-0.05	0.24
A.01.6	Support activities to agriculture and post-harvest crop activities	0.29	-0.05	0.24
A.02	Forestry and logging	0.02	-0.00	0.02
B.05	Mining of coal and lignite	0.30	-0.03	0.27
B.06	Extraction of crude petroleum and natural gas	0.30	-0.03	0.27
B.07	Mining of metal ores	0.30	-0.03	0.27
B.08	Other mining and quarrying	0.30	-0.03	0.27
B.09	Mining support service activities	0.30	-0.03	0.27
B.09.1	Support activities for petroleum and natural gas extraction	0.30	-0.03	0.27
C.17	Manufacture of paper and paper products	0.17	-0.01	0.16
C.19	Manufacture of coke and refined petroleum products	0.68	-0.06	0.62
C.20	Manufacture of chemicals and chemical products	0.24	-0.02	0.22
C.22	Manufacture of rubber and plastic products	0.03	-0.00	0.03
C.23	Manufacture of other non-metallic mineral products	0.80	-0.07	0.73
C.24	Manufacture of basic metals	0.90	-0.08	0.82
D.35.1	Electric power generation, transmission and distribution	0.70	-0.12	0.58
D.35.2	Manufacture of gas; distribution of gaseous fuels through mains	0.70	-0.12	0.58
H.49	Land transport and transport via pipelines	0.25	-0.04	0.21
H.50	Water transport	1.13	-0.20	0.93
H.51	Air transport	1.48	-0.13	1.35
H.52	Warehousing and support activities for transportation	0.03	-0.00	0.03

Table B - Scenario 2 – EUR 100 carbon tax with pass-through

NACE Rev. 2	Industry	Scope 1 shock	Adaptation and price through	Scope 3 shock	Total shock
A.01.1	Growing of non-perennial crops	0.29	-0.16		0.13
A.01.4	Animal production	0.29	-0.16		0.13
A.01.5	Mixed farming	0.29	-0.16		0.13
A.01.6	Support activities to agriculture and post-harvest crop activities	0.29	-0.16		0.13
A.02	Forestry and logging	0.02	-0.01		0.01
B.05	Mining of coal and lignite	0.30	-0.15	0.90	1.00
B.06	Extraction of crude petroleum and natural gas	0.30	-0.15	0.50	0.65
B.07	Mining of metal ores	0.30	-0.15	0.20	0.35
B.08	Other mining and quarrying	0.30	-0.15	0.20	0.35
B.09	Mining support service activities	0.30	-0.15	0.30	0.45
B.09.1	Support activities for petroleum and natural gas extraction	0.30	-0.15	0.50	0.65
C.17	Manufacture of paper and paper products	0.17	-0.09		0.08
C.19	Manufacture of coke and refined petroleum products	0.68	-0.25	0.25	0.58
C.20	Manufacture of chemicals and chemical products	0.24	-0.12		0.12
C.22	Manufacture of rubber and plastic products	0.03	-0.02		0.01
C.23	Manufacture of other non-metallic mineral products	0.80	-0.41		0.39
C.24	Manufacture of basic metals	0.90	-0.46		0.44
D.35.1	Electric power generation, transmission and distribution	0.70	-0.26		0.44
D.35.2	Manufacture of gas; distribution of gaseous fuels through mains	0.70	-0.39	0.30	0.61
H.49	Land transport and transport via pipelines	0.25	-0.14		0.11
H.50	Water transport	1.13	-0.63		0.50
H.51	Air transport	1.48	-0.98		0.50
H.52	Warehousing and support activities for transportation	0.03	-0.01		0.02

Table C Assumed adaptation and pass-through functions

NACE Rev. 2	Industry	Pass-through (φ_t)	Adaptation (γ_t)
A.01.1	Growing of non-perennial crops	50% (after year 1)	20% (5 yr)
A.01.4	Animal production	50% (after year 1)	20% (5 yr)
A.01.5	Mixed farming	50% (after year 1)	20% (5 yr)
A.01.6	Support activities to agriculture and post-harvest crop activities	50% (after year 1)	20% (5 yr)
A.02	Forestry and logging	50% (after year 1)	10% (5 yr)
C.17	Manufacture of paper and paper products	50% (after year 1)	10% (5 yr)
C.19	Manufacture of coke and refined petroleum products	50% (after year 1)	10% (5 yr)
C.20	Manufacture of chemicals and chemical products	50% (after year 1)	10% (5 yr)
C.22	Manufacture of rubber and plastic products	50% (after year 1)	10% (5 yr)
C.23	Manufacture of other non-metallic mineral products	50% (after year 1)	10% (5 yr)
C.24	Manufacture of basic metals	50% (after year 1)	10% (5 yr)
D.35.1	Electric power generation, transmission and distribution	25% (after year 1)	20% (5 yr)
H.49	Land transport and transport via pipelines	50% (after year 1)	20% (5 yr)
H.50	Water transport	50% (after year 1)	20% (5 yr)
H.51	Air transport	25% (after year 1)	10% (5 yr)

Note: for pass-through, we take re-pricing to occur after year 1. In the pass-through scenario, we assume a 50% pass-through for all industries, unless an industry provides luxury products (air transport) or has strong competition from renewable players (electric power generation). In those cases, we cap pass-through at 25%. For adaptation, we take a linear reduction of carbon intensity per unit value added over a period of 5 years. We assume the maximum reduction to be 10% for all industries unless the industry has strong potential for electrification (land and water transport) or strong potential to capture emissions (agriculture and electric power generation). In those cases, we take adaptation potential to be 20%. For scope 3 industries, pass-through is not-applicable and adaptation potential is assumed to be zero.