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Climate-Related Stress Testing: Transition Risks in Norway

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Climate-Related Stress Testing: The Transmission of Transition Risks in Norway[1]

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Abstract

This paper explores three possible transmission channels for transition risk shocks to the financial system in Norway. First, we estimate the direct firm-level impact of a substantial increase in domestic carbon prices under severe assumptions. Second, we map the impact of a drastic increase in global carbon prices on the domestic economy via the Norwegian oil sector. Third, we model the impact of a forced reduction in Norwegian oil firms' output on shareholder portfolios. Results show that such a sharp increase in carbon prices would have a significant but manageable impact on banks. Finally, the paper discusses ways to advance the still evolving field of transition risk stress testing.

JEL Classification Numbers: G21, G32, H23, Q3, Q54, Q58

Keywords: Climate change, transition risk, carbon emissions, carbon price, environmental policy, asset pricing, financial stability

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CONTENTS

I. INTRODUCTION

"Transition risks" of climate change are the risks stemming from the transition to a "low-carbon economy" – that is, an economy that emits fewer greenhouse gases (GHG).[2] Transition risks can be driven by changes in policy, advances in technology, or a combination of both, as suggested by Vermeulen et al. (2018). Transition risks can also be driven by a shift in market sentiment caused, in turn, by a changing public opinion (TCFD, 2017). A policy shock could be a top-down decision to significantly reduce GHG emissions, for example through the imposition of a carbon tax, on either unilateral or global basis.[3] Technological advances, on the other hand, are likely to reduce the cost of alternative sources of energy, potentially leaving fossil fuels and other GHG-emitting assets as stranded. Depending on the nature of policy shocks and technological advances, feedback loops between them could either reinforce or offset their effects.

The existing literature treats these "transition risks" as distinct from "physical risks", with the latter being the immediate risk to assets stemming, directly or indirectly, from rising temperatures and natural disasters.[4] While physical risk analysis has been an integral part of previous Fund stress tests (see, e.g. Bahamas FSAP), the aim of this paper is to complement the IMF's climate-related stress testing framework with the introduction of transition risk analysis. The integration of climate-related risks in its risk analysis toolkit remains high on the IMF's agenda also in a post-COVID world, as, after the pandemic, climate change is "another huge challenge we face as human race" (Georgieva, 2020).

[2] See Annex for a description of the main greenhouse gases.

[3] Among other climate policies that could trigger transition risks, contributions in the literature have looked, for example, at Green Supporting Factors (see Dunz, Naqvi and Monasterolo, 2018).

[4] Extreme weather events (such as hurricanes and typhoons) can damage assets directly, but they can also affect them via their impact on the economy at large. Apart from this 'acute' forms of physical risks, the economy can also be affected by physical risks of more 'chronic' kind, such as progressive increase in global temperatures (determining, for example, lower productivity in agriculture or the increase of costs for air conditioning in manufacturing) and significant changes in precipitation patterns (more frequent and/or more severe droughts/floods); see TCFD (2017).

The analysis of transition risks in Norway, an oil exporting country that is potentially vulnerable to transition risks, focuses on channels that represent a policy-driven transition.[5] In doing so, the analysis focuses on the financial stability implications of such transition risks by answering two main questions. First, how does a substantial increase in domestic carbon pricing impact banks' credit exposures, such as loans, by affecting corporates' operating costs and profitability under severe assumptions? And, second, how does a drastic increase in global carbon taxes affect banks' loan losses through a fall in the revenues of domestic oil producers? In addition, we investigate how a reduction in the production of domestic oil firms would affect their share price and, in turn, the net wealth of domestic shareholders (such as households or financial and non-financial corporates). To keep the exercise tractable, the sensitivity tests are conducted in partial equilibrium and cover only a few of the many channels at play. For example, they do not account for the use of revenues from higher carbon taxes or gains from the expansion of clean energy sectors.[6,7]

The analysis proceeds as follows. Section II reviews the literature on the topic and lays out the intended contribution of this working paper to the existing literature. Section III describes the current situation of carbon pricing in Norway. Sections IV, V and VI in turn approach the above questions by giving an overview of the methodologies, data and results. Section VII concludes.

II. Literature Review

While several academics and think-tanks had been investigating for some time the risks for the financial sector stemming from climate change, the September 2015 speech by Mark Carney, then Governor of the Bank of England and Chair of the Financial Stability Board, at

[5] The analysis was part of the overall analysis of risks and vulnerabilities in the Norwegian financial system, conducted within the IMF Financial Sector Assessment Program of Norway in 2020 (IMF, 2020).

[6] While our analysis is limited to a small set of climate mitigation policies, a successful climate policy mix is likely to include a much larger variety of policies, as outlined, for example in IMF (2019) Fiscal Monitor: How to Mitigate Climate Change.

[7] Other channels that might play a role in general equilibrium could include feedback effects from the financial sector to the real economy (e.g. a reduction in lending), or macro-financial effects such as changes in the exchange rate, which has historically been closely tied to the oil price in Norway.

Lloyd's in London, was the first time these ideas were brought to the attention of the industry as top-of-the-agenda issues. The speech introduced a taxonomy of climate-related risks (between physical and transition risks, with a mention also for litigation risks) that has since become a standard way of classifying climate-related risks. It also introduced to a broader audience concepts like 'stranded assets' and 'unburnable reserves'[8] and indicated stress testing as an adequate technology to shed light "on the future implications of environmental exposures embedded in a wide range of firms and investments" (Carney, 2015).

In 2017 the Task Force for Climate-related Financial Disclosures (TCFD), created in 2015 by the Financial Stability Board (FSB), published its final recommendations, advocating, inter alia, the use, by every type of organization, of scenario-based assessments of climate-related risks and their potential financial implications. These should contribute to "better information to support informed investment, lending, and insurance underwriting decisions and improve understanding and analysis of climate-related risks and opportunities" (TCFD, 2017).

The interactions between climate and economic systems have been studied for decades, especially within Integrated Assessment Models (IAM), such as William Nordhaus's DICE model (Nordhaus, 1992 and Nordhaus, 1994). However, the analysis of the financial stability implications of the transition to a low-carbon economy has only recently gained momentum.

One of the first studies on the financial stability implications of the transition to a low-carbon economy is the report by Weyzig et al. (2014). It analyzes the exposure to fossil fuel producing firms of 20 banks and 23 pension funds among the largest in the European Union and estimates their potential losses under a variety of assumptions. While the sets of assumptions are presented as 'scenarios', the exercise actually represents a sensitivity (or 'what-if') analysis. The analysis is based on shocks calibrated judgmentally by the authors and on the calculation of the direct impact of those shocks on the banks' and pension funds' exposures. The sets of assumptions range from the extreme of a rapid and decisive transition to a low-carbon economy ('Low-carbon Breakthrough') to the opposite extreme of a complete roll back of climate measures ('Carbon Renaissance'). In a 'Low-carbon

[8] First introduced by the think tank Carbon Tracker Initiative, together with the concept of 'carbon bubble'. See CTI (2011) and CTI (2013).

Breakthrough' world, banks would experience losses equal to 0.4 percent of their total assets—much less than pension funds, owing to the shorter average maturity of their exposures.

The report by the University of Cambridge Institute for Sustainability Leadership (2015) on 'unhedgeable risk' presents a scenarios analysis over a 5-year risk horizon. It reconciles such a short-to-medium risk horizon with the typically long-term effects of climate change (and of climate policies) by emphasizing the role of market sentiment and confidence shocks in bringing forward the financial implications of each scenario. For that aim, it identifies potential 'scenario triggers'. These could generate 'financial tipping points' that would accelerate the unfolding of each scenario. Under a 'Two Degrees' scenario—characterized by high, well-coordinated and timely global cooperation—the trigger could be, for example, the announcement of a global agreement to limit GHG with a tax or a cap (the scenario specifically assumes that a carbon tax of $100/ton CO2 be agreed internationally). The transmission of the shocks to the economy is simulated via the Oxford Economics' General Equilibrium Model. The model output (interest rates, credit spreads, equity indices, exchange rates) is used to re-evaluate four representative investment portfolios. The report finds that three of the four portfolios would experience positive returns over the risk horizon under the 'Two Degrees' scenario, while a 'High Fixed-Income Portfolio', mimicking the investment strategies of insurance companies, would suffer a loss of a few percentage points.

Battiston et al. (2016) use a network-based approach to estimate losses from exposures beyond the fossil fuel sector and to capture second-round effects. Firms are reclassified into expressly-defined 'climate-policy-relevant' sectors ('CPRs': fossil fuel, utilities, energy-intensive, transport and housing) and the equity exposures of aggregate financial actors to those sectors are calculated. The paper then investigates the exposures of the top 50 listed European banks to the CPRs and to each other, simulating first-round losses (i.e. direct losses from the equity holdings in firms belonging to the CPRs) and second-round ones (i.e. indirect losses due to the devaluation of counterparties' debt obligations on the interbank credit market). The initial shocks are first calibrated at 100 percent (i.e. all equity being wiped out) in one or more CPRs; then, the realism of the exercise is improved by approximating the shocks with the changes in market shares of the fossil fuel, fossil-fuel-based utility, and

renewable-based utility sectors, as projected by the LIMITS Integrated Assessment Models up to 2050.[9] The study underscores the importance of not neglecting second-round losses, that are found to be, on average, larger than first-round losses.[10]

A similar approach is applied to the sovereign bond portfolios of European insurers, with the added consideration of the impact of a climate policy shock on sovereign fiscal assets (Battiston et al. 2019); and to central banks' portfolios (Battiston and Monasterolo, 2018).

Stress-testing, already a fundamental ingredient in the toolkit for the analysis of financial stability, is increasingly used by central banks and financial regulators to assess financial institutions' exposure to climate change, including in terms of transition risk. In 2020, the Network for Greening the Financial System (NGFS), a group of 66 central banks and financial supervisors and 12 observers from across the globe, published a Guide on Scenario Analysis to provide "some practical elements of guidance on climate-related scenario analysis for financial risk assessment" (NGFS, 2020).

One of the most advanced scenario-based stress testing frameworks has been developed at the Dutch central bank to capture the financial stability risks posed by a disruptive energy transition (Vermeulen et al., 2018; 2019). To account for the significant uncertainty surrounding climate developments and the transition to a low-carbon economy, the framework rests on four scenarios, which are designed as the combination of the absence/presence of technological breakthroughs to lower CO2 emissions with an assumed public policy stance to mitigate the adverse impact of climate change (active—with abrupt implementation of stringent policy measures—vs passive—causing a negative confidence shock for economic agents). The aim is to assess tail risks, reflected in losses incurred by financial institutions in a worst-case scenario. A multi-country macroeconometric model is used to translate each scenario into macroeconomic outcomes, ensuring that the sets of macroeconomic outcomes simulated by the model are mutually consistent. It also allows to account for the potential global impacts of energy transition risks and for the fact that

[9] https://tntcat.iiasa.ac.at/LIMITSPUBLICDB/dsd?Action=htmlpage&page=about.

[10] See also Battiston and Martinez-Jaramillo (2018).

financial firms are exposed to both foreign and domestic risks. Carbon exposures are estimated for the bond and equity portfolios of banks, insurance companies and pensions funds, as well as the corporate loan portfolio of major banks. The transmission of the shocks to the productive sectors (grouped into 56 industries) is approximated via "transition vulnerability factors", which aim to capture the typical GHG emission intensity along the whole value chain (i.e. not only the GHGs directly emitted by the average firm in each sector, but also those embedded in the inputs into their production processes). An interest-rate channel for asset prices is also included for each scenario.

A stress test run by the California Insurance Commission in 2018 was specifically focused on the future alignment of Californian insurers' investment portfolios, over a 5-year risk horizon, to an economic transition consistent with limiting global warming to (less than) 2°C above pre-industrial levels.[11] Conducted with the help of the 2° Investing Initiative, an international think tank, the analysis is based on the evolution of the production and assets in the fossil fuel, power generation, and automotive sectors. It analyses the insurers' equity and fixed income investments in companies belonging to those sectors, by comparing the companies' current planned production with future production levels defined in a 'below 2°C' global warming scenario (2° Investing Initiative, 2018).

The Insurance Stress Test exercise launched by the Bank of England in 2019[12] includes climate change scenarios for life and general insurers. It explicitly covers transition risks, via a 'sudden and disorderly transition' scenario covering a short risk horizon (up to 2022) and a 'long-term orderly' scenario over a long risk horizon (up to 2050). The shocks apply only to the asset side of insurers' balance sheets and cover their exposures to the following sectors: fuel extraction, power generation, transport, energy intensive industries, agriculture and food security, and real estate assets (the latter only under a 'sudden' transition scenario).

The present study aims to contribute to this stream of literature by focusing, in particular, on the transmission channels of transition risk to the economy at large and to financial

[11] See https://interactive.web.insurance.ca.gov/apex_extprd/f?p=250:70.

[12] https://www.bankofengland.co.uk/prudential-regulation/letter/2019/insurance-stress-test-2019

institutions. There are two situations where a country's financial system can be particularly vulnerable to transition risks: when financial institutions are considerably exposed to carbon-intensive corporate borrowers—whose production costs can be significantly increased by a shift towards more stringent climate policies—and when the economy in which the financial institutions operate is highly reliant on the production and export of carbon-intensive products, especially fossil fuels, that are extremely dependent on external demand conditions.

The following sections analyze the transmission of a climate policy shock—in the form of a carbon price shock—to the financial sector via the two above mentioned channels: corporate costs of emissions and external oil demand. In focusing specifically on the transmission channels of transition risks, the analysis adopts a number of simplifying assumptions, from the partial equilibrium setup to the absence of feedback and second-round effects.[13]

III. CARBON PRICING IN NORWAY

In international comparison, carbon pricing in Norway is advanced, complex and evolving. As described in OECD (2018), only Switzerland and Luxembourg are estimated to have a smaller "carbon pricing gap" (i.e. the shortfall in carbon pricing compared to an OECD benchmark value) than Norway. According to data collected by Statistics Norway, the average price payed per ton of CO2-equivalents in 2019 was NOK 419 (about USD 45). This is well above the global average of USD 2, but it still stops short of the USD 50-100 range considered necessary by the IMF to achieve the targets set out in the Paris Agreement (IMF, 2019).

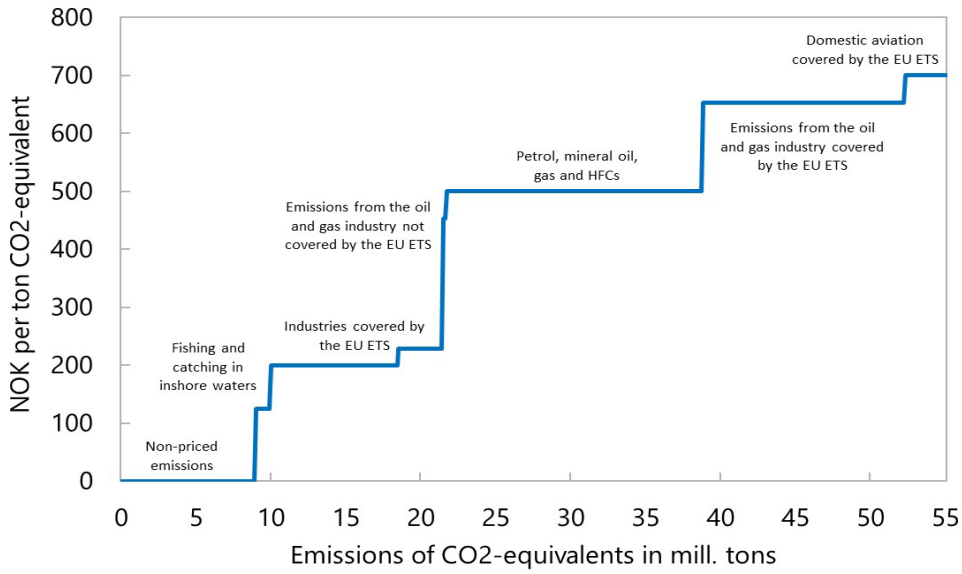
Current carbon pricing in Norway is complex, as rates differ substantially across industries along two dimensions. First, some industries are covered only by national emissions charges, while others are covered by both domestic emissions charges as well as the EU Emissions

[13] The assumptions are also different between the two channels: for the analysis of the costs of emission for corporates, we assume neither pass-through nor any adjustment of supply and demand in the different economic sectors, with the impact of the carbon price shock borne entirely by each firm according to its GHG scope 1 emissions; in the analysis of the external oil demand channel, instead, oil supply and demand are assumed to adjust to clear the market, based on the new carbon price.

Trading System (EU ETS).[14] Moreover, nationally imposed emission charges vary in size depending on the sector. Figure 1 shows a simplified breakdown of emissions charges across the Norwegian economy, with charges ranging from zero up to NOK 750 (about USD 85) per ton of CO2-equivalents for domestic aviation.

In the following sections, we will refer to both carbon taxes and the EU-ETS as "carbon prices".

Figure 1: Marginal Cost of GHG Emissions in Norway 2019



Sources: Ministry of Finance, Norwegian Environment Agency and Statistics Norway

Note: Marginal cost of GHG emissions across sectors. The tax-rates are shown in NOK per ton CO2-equivalents in 2019 and with an EU ETS price of 200 NOK. Recorded emissions from 2017.

Moreover, the state of carbon pricing in Norway is constantly evolving with emissions charges generally increasing during annual reviews conducted by the Norwegian Parliament. In January 2020, for example, the government removed carbon tax exemptions that had

[14] In the context of the "European Green Deal", the European Commission recently announced a number of additional climate policy initiatives, including more ambitious emissions goals and a border carbon adjustment. These initiatives are expected to spill over to Norway due to the close regulatory alignment of Norway with the EU.

previously been granted to the fishing sector, bringing the industry more in line with other sectors in the economy.

In summary, the current system puts Norway among the world's leading jurisdictions when it comes to setting a level of carbon prices aligned with Paris climate goals. In a transition risk stress-testing context, this reduces, but does not eliminate, the risks associated with a rapid transition to a low-carbon economy.

IV. MEASURING THE IMPACT OF HIGHER DOMESTIC CARBON PRICES: THE "CORPORATE COST OF EMISSIONS" CHANNEL

To analyze the impact of higher domestic carbon prices on financial stability, this chapter follows a firm-level balance sheet approach.[15] In summary, we aim to estimate whether the additional cost from higher carbon prices implies difficulties for firms to service their debt, thereby affecting their lenders' financial health and, eventually, the stability of the financial sector. The output of this analysis is given by the change in debt at risk for each bank operating in Norway.

Throughout our analysis, we follow four hypothetical scenarios for carbon taxes, with the scenarios differing along two dimensions: the average level of the carbon price and the differentiation of carbon price levels across sectors.

Regarding the average level of the carbon price, we analyze two calibrations. In the first case, we assume an increase of the carbon price to an average of $75 per ton CO2-equivalent. This value corresponds to the mid-point of the range estimated by the High-Level Commission on Carbon Prices (2017) as necessary to achieve Paris climate targets and supported by the IMF. In the second, we assume a more severe increase of carbon taxes to an average of $150 per ton CO2-equivalent, a value presented in the literature as supporting a more rapid transition to a low-carbon society.[16]

[15] However, due to data limitations, GHG emissions per unit of output and the share of bank loans are both calculated at sector level.

[16] See, for example, Kent et al. (2019).

When it comes to the differentiation of carbon price levels across sectors, we also look at two specifications. In our baseline specification, the carbon price level is assumed to rise to a uniform level across all sectors. In an alternative specification, we preserve the current differentiation of carbon prices across sectors and induce a parallel shift of the price curve up to an average of either $75 or $150 per ton CO2-equivalent. In doing so, we consider the immediate impact of the policy change, with no consideration for a specific time horizon or dynamic effects.

Calculating the effect of higher carbon prices on firm profitability in practice requires making assumptions about the pass-through of such increase. As a result of the higher carbon prices, firms in reality would likely adjust both the quantities and prices of their output—as well the relative weight of their production factors—thereby dampening the effect of higher carbon taxes on profitability. Except for extreme cases, the decision on how much of the increase in carbon price to pass through to customers would result in a change of revenues. Any price adjustment would in turn likely lead to substitution effects for firms downstream, i.e. those using the affected products as input in their own production processes.

Outside of a general equilibrium framework, it is difficult to track the adjustments in demand and production processes along the various value chains in the economy. We hence adopt a 'no-pass-through' assumption, i.e. that firms fully absorb the increased costs, adjusting neither price nor quantity of their output, and that they do not change inputs to their production either. A no-pass-through assumption in principle corresponds to the assumption of perfectly elastic demand, completely inelastic supply, or both, under perfect competition and with profit-maximizing agents. In reality, demand and supply curves are likely to be neither perfectly elastic nor perfectly inelastic, such that some pass-through occurs, allowing each firm to mitigate the impact of the carbon tax. In general, the results under the no-pass-through assumption can thus be considered as an upper bound of the earnings loss for each firm.

Moreover, we assume that individual firms are representative of the sectors they operate in. This allows us to switch between sector- and firm-level data in our analysis.

A. Calculating greenhouse gas emissions by firm

We start our analysis by estimating greenhouse gas emissions for all firms in the scope of our analysis. As firm-level emissions data only exists for a restricted number of companies (generally listed ones) and their quality and comparability are still quite limited, we resort to approximating firm-level emissions with emissions of the sectors that firms operate in.

Using input-output tables from Exiobase,[17] we calculate CO2-equivelent GHG emissions per NOK of output, for 163 sectors, in 2016. In doing so, we calculate only "scope 1" emissions, i.e. GHGs emitted by the sectors themselves, while disregarding emissions generated either upstream (during the production of the energy used) or further downstream. Doing so brings our analysis in line with the current administration of carbon taxes and is consistent with our 'no-pass-through' assumption (i.e. increases in carbon prices stay within each firm, without propagating through the value chains).[18]

For firm-level analysis, we use 2017 Orbis data with NACE 2 sectoral breakdown. To match sector emissions to the firm-level data, we consequently convert the industry breakdown of Exiobase (with 163 sectors) to NACE 2 (with 85 sectors).

In our analysis, we need to take into account the fact that various industries in the Norwegian economy are currently subject to different carbon prices, as highlighted in Section III. This implies that an increase of carbon prices to, e.g., $75 per ton CO2-equivalent has a very different effect on a sector that already pays close to $75, compared to a sector that currently pays $10. While we do not have an exact breakdown of the current carbon tax price per sector (including tax rates and, where relevant, the cost of EU-ETS allowances), we estimate carbon taxes by crossing data on actual taxes paid by each sector with data on actual emissions in the corresponding sector in previous years.

[17] Exiobase is a database containing a Multi-Regional Environmentally Extended Supply-Use Table (MR-SUT) and an Input-Output Table (MR-IOT) covering 44 countries and 163 industries. See https://www.exiobase.eu/.

[18] Scope 1 emissions by sector are closely correlated to emissions normalized by value added. For this reason, emissions themselves are indicative of the burden of higher carbon prices even when value added is not taken into account.

Once current tax rates are established, it is then straightforward to calculate the additional cost faced by each firm, under the 'no-pass-through' assumption, as the difference between new and old carbon price per NOK of output, multiplied by the output of a firm. As stated above, we make the simplifying assumption that all firms in each sector have the same GHG emissions intensity.

In what follows, we calculate firm profits before and after the increase in costs. Comparing these profits to a firm's (unchanged) interest expense gives the "interest coverage ratio" (ICR), a frequently used signifier of the financial health of a company. Algebraically:

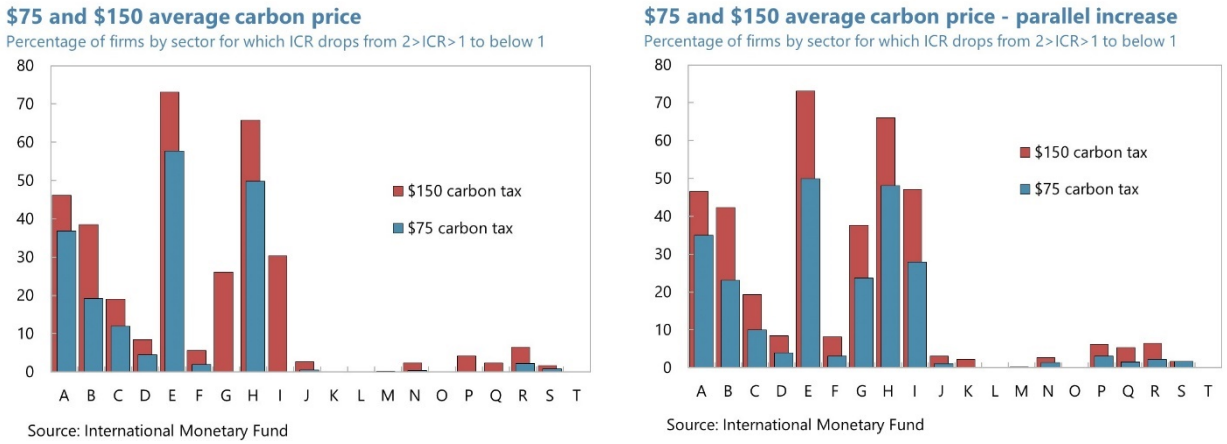
$$ICR = \frac{EBIT}{Interest\ Expense},$$

where EBIT is earnings before interest and taxes.

Aggregating results to the sector level, ICR metrics indicate which sectors are most exposed to financial difficulties following an increase in carbon taxes. As a simple indicator, we look at the (unweighted) share of companies within each sector for which the ICR drops from between one and two—an area of increased risk—to below one, where a company is no longer able to cover interest expenses with its earnings.

Figure 2: Share of firms per sector with debt at risk following increase in carbon price

Agriculture, waste management and transportation… *…are most affected under all scenarios*



Note: A = Agriculture, forestry and fishing; B = Mining and quarrying; C = Manufacturing; D = Electricity, gas, steam and air conditioning supply; E = Water supply; sewerage, waste management and remediation activities; F = Construction; G = Wholesale and retail trade; repair of motor vehicles and motorcycles; H = Transportation and storage; I = Accommodation and food service activities; J = Information and communication; K = Financial and insurance activities; L = Real estate activities; M = Professional, scientific and technical activities; N = Administrative and support service activities; O = Public administration and defence; compulsory social security; P = Education; Q = Human health and social work activities; R = Arts, entertainment and recreation; S = Other service activities; T = Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use.

Figure 2 shows the impact following an increase of carbon prices to $75 or $150 per ton CO2-equivalent for both a uniform carbon price (panel 1), as well as for a parallel shift up to an average carbon price of either $75 or $150 (panel 2). Standing out among the sectors are A – Agriculture, forestry and fishing, E – water supply, sewerage, waste management and remediation activities, and H – transportation and storage. This is due to a combination of a currently very low carbon price in some of these sectors (industries such as waste management currently enjoy significant exemptions from emissions charges) as well as a high carbon-intensity of the sectors. The small impact on sector D – Electricity, gas, steam and air conditioning supply is explained by the high share of renewable energy in Norwegian electricity production.

When assuming a carbon price of $150, additional sectors also become at risk as shown in Figure 2: G – wholesale and retail trade, repair of motor vehicles and motorcycles, and I – accommodation and food service activities. In particular, under a uniform carbon price, emissions-intensive sectors that already face a high carbon price are subject to a noticeable increase only at $150 (while imposing a $75 carbon tax in these sectors did not imply a significant change compared to current carbon prices). Under a parallel increase of carbon prices, this mechanism does not play out, as every sector sees increases in carbon prices already under the $75 regime, no matter how high a sector's carbon price is before the increase.[19, 20]

Generating a link to the financial sector through supervisory data, it is possible to gauge bank exposures to sectors at risk.[21] Concretely, we calculate banks' exposure at risk as the share of total sectoral exposure for which ICRs drop below a threshold value. Table 1 shows various

[19] Of all the firms with an ICR between 1 and 2 before the increase, 7.3 percent of firms see their ICR fall below 1.

[20] In order to provide a sense of how the results depend on assumptions for pass-through, we also calculate the vulnerability of firms when allowing for a partial passing-on of the burden from the carbon price increase. When allowing for 50 percent of the burden to be passed on, 4.8 percent of firms with initial ICR between 1 and 2 fall below ICR 1. When allowing for 70 percent of the burden to be passed on, only 3.4 percent of firms fall below the threshold. Note that this calculation still does not take into account general equilibrium effects such as input substitution triggered by changes in prices.

[21] As said, banks' exposures to firms were available only at sector level.

configurations, assuming uniform and parallel carbon price hikes to $75 or $150, as well as ICR thresholds of 2 and 1.

Table 1: Banks' corporate debt at risk from higher carbon prices

uniform carbon price of	**$75**		**$150**	
	drop below ICR 2	drop below ICR 1	drop below ICR 2	drop below ICR 1
all banks	2.3%	2.2%	4.0%	4.0%
most exposed bank	9.0%	9.1%	15.9%	15.8%
parallel increase of price to	**$75 average**		**$150 average**	
	drop below ICR 2	drop below ICR 1	drop below ICR 2	drop below ICR 1
all banks	2.2%	2.2%	4.3%	4.3%
most exposed bank	8.1%	8.1%	16.0%	16.1%

Following a uniform carbon price hike to $150, for example, about 4 percent of all corporate bank exposures see their ICR drop below the threshold value. The exposure at risk can be significantly higher for individual banks. Indeed, the most affected bank in our sample sees around 16 percent of corporate exposures with the ICR dropping below the threshold, following a carbon price hike to $150.

More generally, banks that concentrate lending to sectors that are highly affected see more of their exposure at risk compared to banks that have a more diversified lending portfolio across sectors. Notably, results are little changed under a parallel increase of carbon prices compared to a uniform increase. Likewise, results are very similar when looking at an ICR threshold of 2 compared to a threshold of 1.

It is important to highlight once again that, given data availability, our approach relies on the assumption that the firms a bank is exposed to are representative of the sectors they operate in. We assume, for example, that the manufacturing firms on a bank's lending portfolio are affected in the same way by a carbon price shock as the manufacturing sector overall. This assumption could be violated, for example, when a bank systematically lends to companies that are more progressive on emissions reductions than their peers. While this discrepancy is important to consider when looking at an individual bank, the analysis retains its general validity when considering the Norwegian financial sector as a whole.

V. THE IMPACT OF HIGHER GLOBAL CARBON PRICES THROUGH THE EXTERNAL DEMAND CHANNEL

While the previous section looked at an increase in domestic carbon prices—which may or may not go hand in hand with a global increase—this section focuses on the implications of a sudden increase in global carbon prices.[22]

The Norwegian economy is heavily reliant on oil and gas. In 2019, the oil sector made up around 14 percent of GDP, 19 percent of total investments, 21 percent of state revenues and 36 percent of total exports. As most of the extracted oil is exported abroad, changes in external demand are likely to play a major role for the Norwegian economy, with potential implications for financial stability.

To better understand these dynamics, we pose the following questions. Given an exogenously imposed increase in global carbon prices, what is the likely reduction in global equilibrium producer prices and demand for oil? What is the likely change in revenues for Norwegian oil producers in the new equilibrium? And what would be the impact to Norwegian financial stability following the fallout in oil sector revenues? To answer these questions, we first model supply and demand curves for both global and Norwegian oil markets. In the next step, we conduct a comparative statics analysis, by modeling the impact of lower oil sector revenues on the Norwegian economy as a whole, focusing in particular on the impact on bank loan losses.[23]

The imposition of large global carbon taxes in effect places a wedge between the consumer and producer prices of oil, with global consumers facing a higher price, while global producers face a lower price. The exact distribution of the tax burden is then determined by

[22] In this context, higher *global* carbon taxes should not necessarily be understood as higher carbon taxes in every jurisdiction, but rather a selection of jurisdictions that together are large enough to significantly alter the playing field for the majority of carbon emitters.

[23] As in the previous section, we assume an instantaneous change in carbon and oil prices. Naturally, this approach abstracts from a number of effects than may play a role in a more dynamic set-up, such as an increase in extraction in the near future, driven by expectations of even lower oil prices in the medium to long run (as popularized, for example, by Hans-Werner Sinn (2012) *The Green Paradox*).

the elasticities for demand and supply. On a global level, our analysis accounts for the change in both consumer and producer behavior.

When looking at the Norwegian economy, however, we focus solely on the producer side, while assuming that consumer behavior is unchanged. The latter is justified by two circumstances. Firstly, as highlighted in the introduction, Norwegian consumers already face a high carbon tax on fossil fuels, implying that—at least for lower levels of global carbon prices—an increase in global prices would not significantly change the tax burden on consumers in Norway. Secondly, Norwegian consumers' reliance on fossil fuels for their energy needs is relatively low, in the international comparison, given the large share of domestic energy stemming from hydropower and the high penetration of electric vehicles for private transport.[24]

We use Rystad Energy data for global oil supply in 2018, based on breakeven cost curves, for both global and Norwegian producers. For global oil demand, we adopt a price elasticity of -0.24, which represents a median of price elasticities in the empirical literature (Caldara et al. 2016). We calculate the tax per barrel of oil based on a minimum CO2 content of 0.43 ton/barrel and given an average word-wide carbon tax of currently $2.

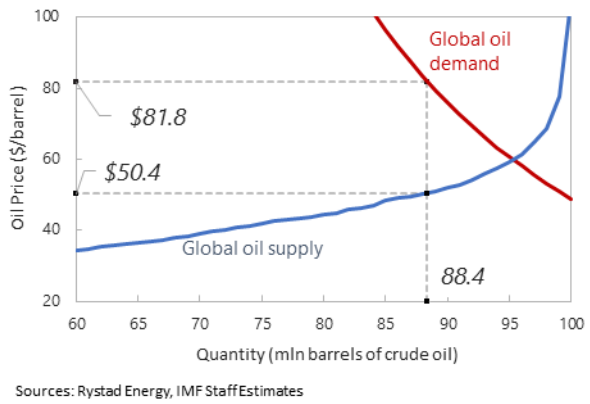
Starting at an oil price of $60, we find that the imposition of a global carbon price of $75 per ton of CO2-equivalent would correspond to a tax of $31.4 per barrel of oil.[25] This would reduce the equilibrium quantity by roughly 7 percent (see Figure 3). At the same time, the consumer price would increase by about 36 percent, while the producer price would fall by about 16 percent. Global producers would face a 26.5 percent drop in revenues.

[24] Norway has the highest number of electrical vehicle owners per capita in the world, with the sales of electric and hybrid cars overtaking those of internal combustion engine vehicles in 2019.

[25] For this calculation, we assume an embedded CO2 content of 0.43 ton per barrel of oil. The new equilibrium quantity is then found at the point where the wedge between the supply and demand curves equals the tax.

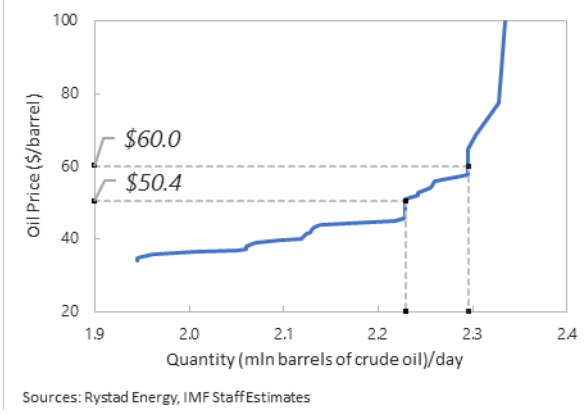
Figure 3: Global equilibrium quantities and prices following increase of carbon price

Higher carbon prices would drive a wedge…



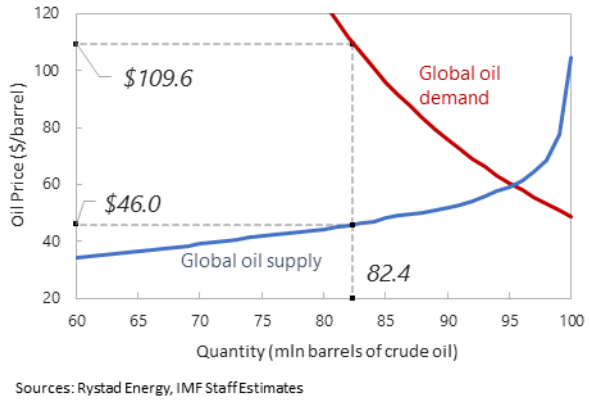
Sources: Rystad Energy, IMF Staff Estimates

…between consumer and producer prices



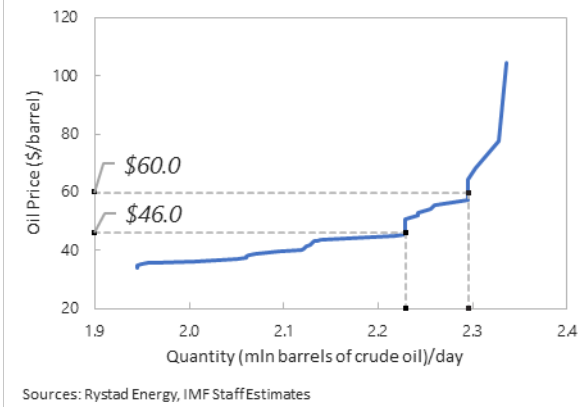
Sources: Rystad Energy, IMF Staff Estimates

Norwegian producers take prices from global market…



Sources: Rystad Energy, IMF Staff Estimates

…and adjust supply according to break-even prices



Sources: Rystad Energy, IMF Staff Estimates

Note: Supply curves are based on break-even prices for global oil production sites as provided by Rystad Energy. Demand curves are based on median prices elasticity of oil demand from estimates in the literature.

Under a global carbon tax of $150, equilibrium quantities would fall by over 13.5 percent, with an increase in consumer prices by more than 80 percent and a decrease in producer prices of 23.4 percent (see Figure 3). Given this reduction in price and quantity, global oil producers would face a reduction of revenues by more than 38 percent.[26]

[26] The measures adopted worldwide since the first quarter of 2020 to reduce the spread of the SARS-COV-2 virus have determined a marked shift of the global oil demand curve to the left, with a consequent drastic oil price drop. The present analysis, being based on comparative statics, remains pertinent: it still provides an estimate of the potential decrease in oil revenues as a result of a carbon price shock. Assuming an initial oil price of $40 per barrel (close to the mid-2020 price for Brent oil), the reduction of producers' revenues at global

To find out how these changes on the global oil market affect Norway, we look at the specific breakeven cost curve for Norwegian producers. In this context, it is noteworthy that Norwegian producers managed to significantly reduce their operating costs during the 2014-16 downturn in oil prices.[27] But while lower breakeven prices would keep Norwegian producers competitive even after a further reduction in oil prices, revenues would still see a significant decline, much more pronounced than in 2014-16.

We estimate that the changes in global oil markets following a $75 carbon tax would lead to a reduction in Norwegian oil revenues of 26.5 percent. A $150 carbon tax would lead to a reduction in Norwegian oil revenues by more than 38 percent. [28] To put these numbers into context, during the 2014-16 drop in oil prices, Norwegian oil revenues fell by about 43 percent.

When comparing these numbers, a degree of caution is necessary, given different assumptions about the persistence of the shock. During 2014-16, the oil price was expected to recover to some degree, buffering investment responses. A carbon price hike, however, is likely to be seen as permanent by economic agents, leading to larger responses in consumption and investment.

In what follows, we introduce oil sector revenues into a structural vector-autoregression (SVAR) to better understand the interaction between the oil sector and the rest of the Norwegian economy. In particular, we are interested in the extent to which losses of banks and mortgage corporations are affected by a drop in oil sector revenues.

In the SVAR setup, a negative shock to oil sector revenues is meant to represent the introduction of a carbon tax. It would be preferable, of course, to use carbon tax data itself, rather than a proxy, but the lack of consistent data with a sufficiently long history makes this

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level would be smaller, but comparable: 21 percent with a $75/ton CO2 carbon price and 33 percent with $150 carbon price.

[27]Also, Norwegian oil producers already exploited most opportunities for cost-cutting during the downturn of 2014-16, leaving little room for further adjustments in case of a new material drop in oil prices.

[28] Assuming an initial oil price of $40/barrel, Norwegian oil revenues would fall by 22.8 and 36.4 percent with a carbon price of $75 and $150, respectively.

impossible. Using the oil price itself, meanwhile, is not feasible, given that the introduction of a carbon tax drives a wedge between consumer and producer prices. Using a single oil price would therefore fail to capture the dynamics following a carbon tax shock.

To some extent, this criticism also applies to a model that uses oil sector revenues. In our time series, the largest variation in oil sector revenues stems from the 2014-16 period of low oil prices, during which both the consumer and producer prices fell. Looking at the data more closely, however, we find little reason to believe that results are significantly skewed. In effect, the low reliance of Norwegian consumers on fossil fuels implies that, according to our calculations, an increase of carbon prices to $150 would reduce Norwegian households' income by only 2.1 percent.

A. Data and Methodology

For the SVAR, we use quarterly data from Q1 2010 to Q2 2019, sourced from Statistics Norway and the IMF World Economic Outlook database. In the baseline specification, we include oil sector revenues, real GDP, bank loan losses, the Norwegian Regional Network Survey,[29] and the NOK/USD exchange rate, as well as four lags of each of variable. This ordering is also used for the Cholesky decomposition in the baseline model. Oil sector revenues and bank loan losses are included to provide a link between the oil sector and financial stability—the main interest of the analysis. The Regional Network Survey, meanwhile, is not of interest per se, but is included to improve the dynamics in the estimated model. How oil firms adjust their business and investment decisions to a drop in revenues is expected to crucially depend on the outlook for the future of the industry. It is the information contained in these expectations that we bring to the SVAR through the inclusion of the survey variable.[30] Based on the results of unit root tests, we apply first differences to

[29] The Regional Network Survey summarizes views of executives from over 300 Norwegian enterprises and organizations on recent economic developments and the outlook ahead. It is conducted by Norges Bank on a quarterly basis. In our analysis, we include the survey's subcategory relating to the export-oriented oil sector. As this series does not go all the way back to 2010, we combine it with the overall oil-sector series during the early years of our sample.

[30] In a similar vein, Sims (1992) found that the prize puzzle in a standard VAR largely disappears when commodity prices are included, as such an "information variable" can give indications of future inflation, thereby helping to avoid misspecification of the VAR model.

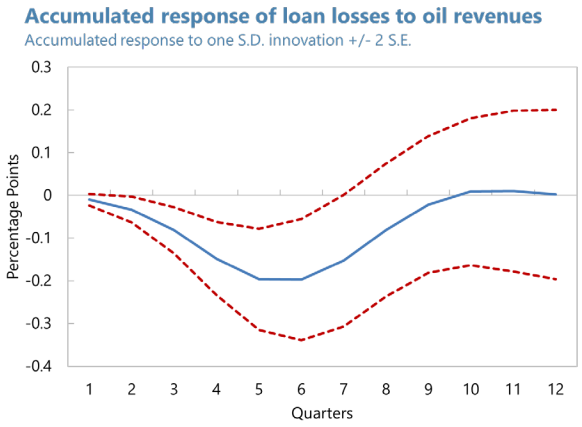
oil revenues and GDP to induce stationarity, while loan loss rates, survey results, and the exchange rate are included in levels.

B. Results

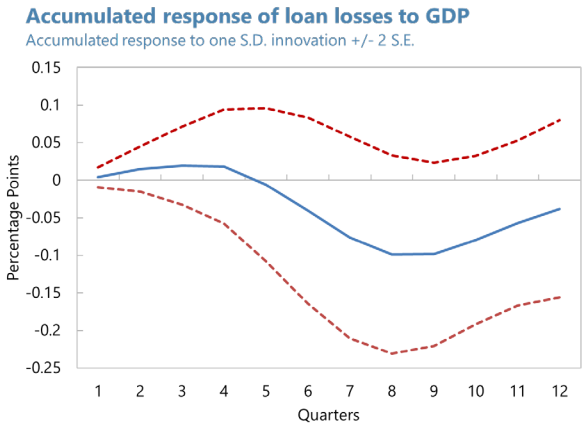
Figure 4 shows impulse response functions of the endogenous variables to a 1 standard-deviation shock in oil revenues, with the horizonal axis showing time periods in quarters. Looking at our variables of interest, we find that loan losses of banks and mortgage corporations show a significant reaction to shocks in oil revenues. By construction, the model is symmetric, implying that a drop in oil revenues leads to an increase in loan losses.

Figure 4: Impulse response functions for loan losses in SVAR

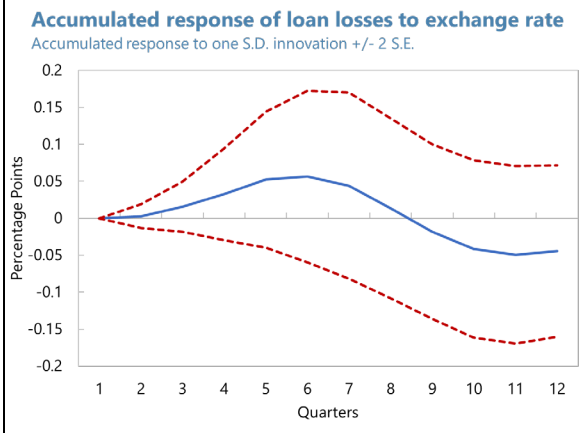
Loan losses fall (increase) when oil revenues rise (fall)...



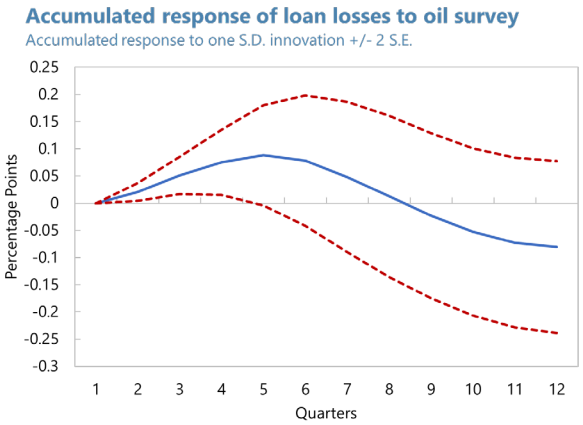
...while GDP shocks have no significant impact on losses.



The reaction to exchange rate shocks is insignificant...



...and shocks to the oil survey have a small positive impact.



Note: Note: Impulse response functions are calculated with a structural vector-autoregression (SVAR) using quarterly data from 2010 to 2019. Variables are transformed to induce stationarity and we include 4 lags. Identification is achieved through a Cholesky decomposition with the following ordering: Oil sector revenues, Regional Network Survey (export-oriented oil sector category), GDP, bank loan losses, NOK/USD exchange rate.

The maximum reaction occurs after 6 quarters and has an average size of 0.2 percentage points. For a drop in oil revenues following a $75 carbon price, this result would imply an increase in loan losses of around 0.6 percentage points (0.5 percentage points assuming an initial oil price of $40/barrel). With carbon prices rising to $150, results suggest an increase in loan losses of 0.9 percentage points (0.8 percentage points assuming an initial oil price of $40/barrel). This compares with an average loss rate of 0.35 percent in 2019 for the whole banking system and of 0.88 percent in Q4 2016, at the height of the problems caused by the drop in the oil price between 2014 and 2016.

To test for the robustness of our results and allow for richer dynamics, we re-run the SVAR in a specification that includes both investment and consumption while removing GDP. The results are depicted in Appendix II. Overall, the results are very similar, with loan losses increasing after a fall in oil sector revenues. Compared to the baseline, this effect is somewhat larger in magnitude, with a maximum reaction of the point estimate of 0.26 percentage points.

For further robustness analysis we also ran both of the above SVARs with different orderings of the endogenous variables, which did not change results for loss rates in either a qualitative or quantitative way.

VI. CLIMATE POLICY-ENFORCED OUTPUT REDUCTION: THE PORTFOLIO CHANNEL

While Norwegian oil producers are among the world's most advanced in terms of abatement of the emissions generated during extraction (so-called scope 1 and scope 2 emissions), high emissions are produced downstream as global consumers burn off the fossil fuels (so-called scope 3 emissions). It is possible to envisage a scenario where climate policy, possibly coordinated at global level, forces a reduction of these scope 3 emissions by reducing the overall output generated by the oil sector[31]. To achieve emissions that are consistent with

[31] This could be achieved via a mix of policies, including a higher carbon tax and supply-side measures (e.g. nationally determined limits to domestic production of fossil fuels).

Paris targets, the Carbon Tracker Initiative (2019) estimates that a company such as Equinor, for example, has to reduce its overall output by about 45 percent before 2040.[32]

Table 2: Estimated emissions reduction required for oil majors to stay within B2DS

NPS capex outside B2DS to 2030 for both sanctioned and unsanctioned projects, zero year minimum production reductions and carbon emissions reductions required to stay within B2DS company carbon budgets

Company	Capex Outside B2DS to 2030	Zero Year (Linear)	Minimum Production Reduction to 2040
ExxonMobil	60%-70%	Post 2040	55%
Shell	30%-40%	Post 2040	10%
Chevron	30%-40%	Post 2040	35%
BP	20%-30%	Post 2040	25%
Total	30%-40%	Post 2040	35%
Eni	30%-40%	Post 2040	40%
ConocoPhillips	40%-50%	Post 2040	85%
Petrobras	30%-40%	Post 2040	65%
Equinor	30%-40%	Post 2040	45%

Source: Carbon Tracker Initiative
Note: Production calculated in million barrels of oil equivalent. The table includes the top 9 companies (by enterprise value) in the Carbon Tracker Initiative universe. "NPS capex outside B2DS" is defined as the amount of potential future capex (for both sanctioned and unsanctioned projects) for projects that fit within the IEA's New Policies Scenario (NPS) that is not required under the IEA's Below 2 Degrees Scenario (B2DS) over the period 2019-2030, expressed as a percentage. Reductions to 2040 are rounded to the nearest 5 percent. Linear decline assumed for production reductions to 2040. "Zero Year" is the year in which a given company's absolute emissions would reach zero on a linear projection.

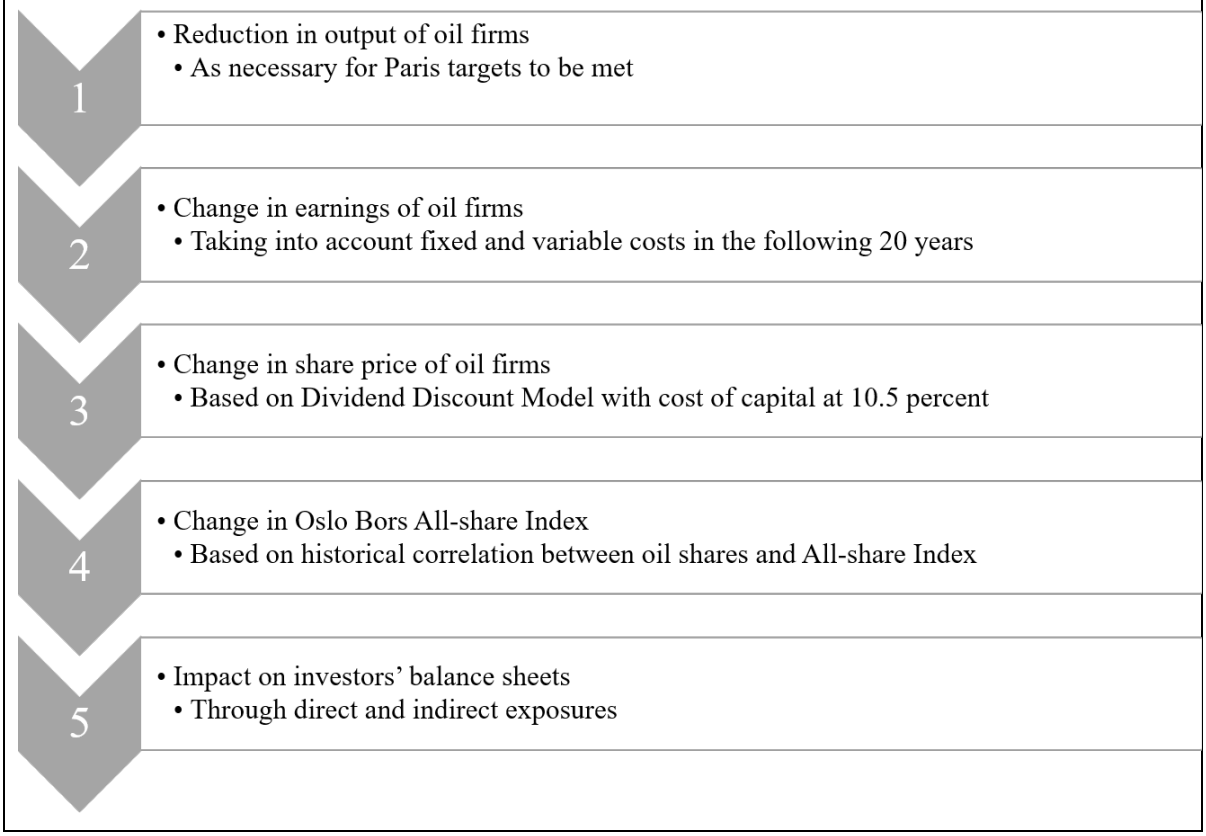
In this section, we try to make a first pass at estimating the impact of such reductions on oil majors' stock prices and, in turn, on stock portfolios held by Norwegian households. From a stress-tester's perspective, the interest lies in the implications for financial stability of a shock to households' financial wealth following such a change in valuations. The analysis is of particular interest as it extends beyond the typical risk-management horizon, taking into account the possibility of longer-term changes.

[32] McGlade and Ekins (2015) find that, globally, a third of oil reserves, half of gas reserves, and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of a global warming of no more than 2°C above pre-industrial level.

Our analysis proceeds in three steps. First, we calculate the impact on earnings for Norwegian oil majors given the reduction in output which is deemed necessary by the Carbon Tracker Initiative to reach Paris targets. In doing so, we take into account fixed and variable costs in the oil sector, but assume no other behavioral change in the operation of oil corporations. Next, we use a dividend discount model to estimate the change in firms' share prices, assuming that current market pricing reflects fair value. Finally, we estimate the impact on Norwegian households' and other institutions' balance sheets under the assumption that they hold a portfolio that is representative of the Oslo Børs All-share Index.[33]

Within this framework, we assess three scenarios. In the first scenario, Norwegian oil majors' output is assumed to drop by 45 percent as a result of an unspecified mix of policy measures

Figure 5: Overview of the Portfolio Channel



[33] The related question on whether asset prices already reflect transition risks has been investigated, among others, by Bolton and Kacperczyk (2020), who find that carbon emission risk seems to be priced in the cross section of stocks, and Monasterolo and de Angelis (2020), who find that after the Paris Agreement the

that do not entail a change in oil prices. In the remaining two scenarios, the output reduction is assumed to be partly achieved by increasing the global carbon price to US$75 or US$150.

In our analysis, we explicitly calculate results for the largest Norwegian oil, Equinor, and extrapolate results to other oil firms operating on the Norwegian Continental Shelf.[34] All in all, these firms make up roughly one third of the Oslo Børs Benchmark Index.

Based on the example of Equinor, we estimate that a reduction in production by 45 percent would still leave the company profitable, but with a drop in net operating income of up to 80 percent. The imposition of a carbon price of US$75-150 could further decrease output, by approximately 8-12 percent. Distributing the reduction in production linearly between 2020 and 2040, and adjusting income and dividends accordingly, we estimate a change in the share price of up to -50 percent. A degree of uncertainty is attached to the result stemming from different assumptions about the cost of capital and the growth rate of the company after the output reduction phase.

The fall in oil-related shares can spill over to other Norwegian shares. Using historical time-series of the Oslo Børs All-share Index and its components, we find that other equities tend to correlate on average one-to-one with the oil sector over time horizons up to one year.[35] As a rule of thumb, this implies that a fall in oil shares could lead to an equally large drop in other Norwegian shares.

In 2018, Norwegian households on average held about 22 percent of their financial assets directly in domestic equity, and another 3 percent indirectly via their pension claims, life insurance policies, and holdings of investment fund shares. Assuming that equity holdings

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correlation among low-carbon and carbon-intensive equity indices dropped and that the overall systematic risk of low-carbon indices decreased.

[34] For robustness, we check results also when calculating dividend discount models for other large oil producers such as Aker BP. Across the oil sector as a whole, results are not significantly different.

[35] In the past 10 years, the correlation of the daily returns of the Oslo Børs Benchmark Index with those of the energy sector index over a 1-year horizon has averaged 90 percent and has never been lower than 84 percent. This high correlation can be largely explained by the structure of the Norwegian economy, which is not only dominated by the oil sector, but also features many industries that service the oil sector and are consequently closely tied to it.

are representative of the Oslo Børs All-share Index, the above reduction in oil production would lower the value of households' financial assets by about 11 to 12 percent.[36]

Table 3: Portfolio effects of reduction in oil production

Scenario	Change in output of oil companies	Change in share price of oil companies	Impact on assets of Norwegian households	Impact on assets of Norwegian insurers and pension funds	Impact on assets of Norwegian non-money-market investment funds
Output reduction only	-45%	-43%	-11%	-5%	-5%
Output reduction and $75 carbon price	-53%	-47%	-12%	-5%	-5%
Output reduction and $150 carbon price	-57%	-49%	-12%	-5%	-6%

The same calculation for insurers and pension funds (which collectively hold 10.6 percent of their financial assets as domestic equity) would lead to a drop in the value of their portfolios of around 5 percent, while for non-money-market investment funds (who hold 11.7 percent of their portfolios in domestic equity), the potential drop would be between 5 and 6 percent.

For Norwegian banks and mortgage corporations, the direct holdings of domestic equity are much smaller (2.6 percent of their financial assets in 2018). However, the indirect effect via the impact on the wealth of their borrowers (households, but also non-financial corporations)

[36] As in the previous sections, the analysis is of static nature: it investigates the immediate impact of the shock, assumed to occur suddenly and, consequently, with no room for adaptation by the economic agents (who, in reality, would likely try to mitigate the impact of the shock, for example by changing the composition of their equity portfolios).

could be non-negligible, for example, in terms of increased default rates and/or lower recovery rates. They could also be affected by the difficulties faced by other entities in the banking groups, such as direct losses (e.g. for insurers) or redemption surges (for asset managers).

The analysis of portfolio effects remains preliminary and is conditional on a number of assumptions. While the dynamics of oil firm valuations under a scenario of output reduction are likely to impact the balance sheets of Norwegian households and asset managers, results are to be treated as preliminary at this stage. Further work is necessary to integrate a number of side-effects into the analysis that could both weaken or strengthen the overall results.

VII. CONCLUSIONS

This paper provides a framework for analyzing the financial stability implications of climate-related transition risk by focusing, in particular, on a subset of its propagation channels. Doing so in the context of Norway, the paper focuses on channels that represent a policy-driven transition such as an increase in carbon prices. The analysis tries to answer two main questions. First, how does an increase in domestic carbon pricing impact banks' credit exposures, such as loans? And, second, how does an increase in global carbon taxes affect banks' loan losses through a fall in revenues of domestic oil producers? In addition, we investigate how a reduction in the production of domestic oil firms would affect their share price and, in turn, the net wealth of domestic shareholders (such as households or financial and non-financial corporates).

The analysis yields three main results. First, a domestic increase in carbon prices could result in inability to service debt for firms with higher emissions, especially when profits are low compared to interest expenses. At a carbon price of $75 per ton CO2 equivalent, the sectors most at risk are agriculture, forestry and fishing; water supply, sewerage, waste management and remediation activities; as well as transportation and storage. Banks' debt at risk from an increase in carbon prices is small on average but can be significant when lending is concentrated to sectors at high risk.

Second, a global increase in carbon prices could lead to a fall in oil sector revenues that implies a significant increase in banks' loan losses. The fall in revenues stemming from a

carbon price of US$75 is estimated to increase loan loss rates by about 0.6 percentage points. With carbon prices rising to $150, results suggest an increase in loan losses of 0.9 percentage points. This compares with a loss rate of 0.88 percent in Q4 2016, at the height of the problems caused by the drop in the oil price between 2014 and 2016.

Third, we find in a preliminary analysis that climate policy to curb the oil sector's total output could reduce valuations of oil producers, implying portfolio effects for Norwegian households and asset managers.

While the presented analysis relies on some strong assumptions and simplifications, , the proposed frameworks offer some valuable insights into climate-related transition risks—a relatively new and underdeveloped area in the field of financial stability analysis.

A stress test exercise specifically focusing on climate-related transition risks raises a number of issues with respect to at least three of the four typical constituent elements of an 'ordinary' (i.e. non-climate-related) financial stress test:[37] the identification of the risk exposures subject to stress; the definition of a scenario comprised of exogenous shocks that stress those exposures; and the identification and estimation/calibration of the propagation channels that translate those shocks into impacts on financial institutions.[38]

As regards risk exposures, many analyses tend to focus on the obvious ones, those most likely to be directly impacted by the transition to a low-carbon economy and most at risk of turning into 'stranded assets': mainly exposures to the fossil fuel industry and to fossil-fuel-based utilities. Progress has been made in the literature to extend the view to other sectors that might still be affected by transition risks via their value chains (Vermeulen et al., 2018) and to second-round effects within the financial system that could amplify the initial, direct losses (Battiston et al., 2018). More remains to be done in order to capture other forms of

[37] See Borio et al. (2014), who list four elements always present in any financial stress test: risk exposures, scenario(s), models (to map shocks onto an impact), and outcome.

[38] The fourth element, the outcome of the exercise, does also represent a challenge when the risk horizon of the exercise is extended beyond the typical time span of financial stress tests (3 to 5 years) in order to capture the specificity of climate change and climate policies (i.e. that of carrying out their effects over very long periods, typically measured in decades, rather than years): the metrics generally employed in financial stress testing (losses, capital depletion, etc.) lose much of their meaning over such long horizons.

exposure that are affected less directly—but not necessarily less intensely—by the materialization of transition risks, such as the exposures to the real estate sector or to consumers, as well as the potential cross-border spillovers.

For the design of scenarios, the assumption of a (sharp) increase in carbon prices is a convenient, powerful, and relatively simple assumption that allows to effectively and parsimoniously characterize a decarbonization scenario. Carbon pricing is also widely considered the first-best option for climate change mitigation from a welfare perspective (IMF, 2019). It is not by chance that a carbon price shock is used extensively in the scenario design for transition risk (including in this study). That said, the increase in carbon prices is also a highly contentious policy that, when implemented, has often triggered vehement backlash from the local population (Hallegatte, 2019). There are second-best policy alternatives that, although less easy to model (for example, feed-in tariff programs and portfolio standards for renewables), are probably more realistic and plausible as ingredients of a transition risk scenario. Transition risks can also be triggered by other forms of shocks, such as major technological breakthrough and shifts in public opinion or market sentiment.[39]

The characterization of the transmission channels of transition risk at a granular level is an area requiring further investigation: the common understanding of how the initial shock propagates through the economy and to the financial institutions is still relatively limited. Both the micro- and macroeconomic perspective are extremely relevant and, at the same time, interwoven.

As a result of a carbon price shock, for example, a number of micro-adjustments are likely to unfold at individual firm level as a function of price and cross-price elasticities (like input substitution, revisions of output volumes and prices, etc.). These, in turn, could trigger further adjustments, along the whole value chain and at the level of final demand, that can be better captured within a general equilibrium setup.

[39] It is, however, difficult to imagine a transition risk scenario in which the policy component does not play an important role, even if just in response to a shock of different nature.

The shock eventually produces effects at macro level (consumption, income, inflation, etc.). If it is of global nature, the shock can also produce inward and outward spillovers that further amplify (or dampen) the initial impulse, especially when the production and/or export structure of the domestic economy is particularly exposed to transition risk, like for fossil fuel producing/exporting countries. Finally, the policy response triggered by the initial shock further compounds the direct impact on the economy and on financial institutions.

Accepting a certain degree of aggregation, these adjustment processes can be modeled, at least in part, via Computational General Equilibrium (CGE) models. These typically allow for a relatively granular specification of the economy (in comparison to most macroeconometric models) and can be used to assess the impact of a specific policy (NGFS, 2020). By modelling the linkages between the different sectors of an economy, CGE models can capture not only the direct impacts of a policy on one sector of the economy but trace its full (or general equilibrium) impact on the interdependent sectors of that economy and ultimately the impact on consumption (Nikas et al., 2019). They can also take into account trade relationships between countries and allow for an analysis of inward and outward spillovers, for example in terms of potential carbon leakage effects and carbon border adjustments (Molico, 2019).[40]

While based on simplistic assumptions, the partial equilibrium perspective adopted in this paper highlights some of the complex effects that can be triggered by a shock along a decarbonization path and that contribute to determine the size of its ultimate impact on financial institutions. Climate-related stress testing needs to adequately incorporate these transmission channels of transition risk, as much as it needs to rely on a satisfactory representation of the most important interdependencies within the economy that only richer models can provide. Combining these different perspectives appears to be a challenging, but potentially fruitful direction for further research.

[40] The interdependencies in the economy can also be captured via non-equilibrium models, which, by allowing the economy to start from a non-optimal configuration (e.g. with investment not necessarily matching savings or the economy operating away from the productivity frontier), make room for climate policies to address such imperfections, possibly improving efficiency in the process and leading to higher growth (NGFS, 2020).

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APPENDIX I: GREENHOUSE GASES

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as halocarbons and other chlorine- and bromine containing substances, dealt with under the Montreal Protocol. Beside CO2, N2O and CH4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). 41

GHGs differ from each other in terms, inter alia, of persistency in the atmosphere and global warming potential. For example, methane is a more potent greenhouse gas—in terms of global warming—than CO2, but it has a far shorter persistence in the atmosphere (around ten years) than CO2, which has an average atmospheric residence time of around 100 years.

A carbon dioxide equivalent or CO2 equivalent, abbreviated as CO2-eq, is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.42 The conversion is generally based on a 100-year horizon (sometimes a 20-year one) and CO2 is taken as a unit of measure, so that it has, by definition, a GWP of 1. For example, methane has a GWP of 96 over 20 years, but, due to its far shorter lifespan than CO2, of 32 over a 100-year horizon.

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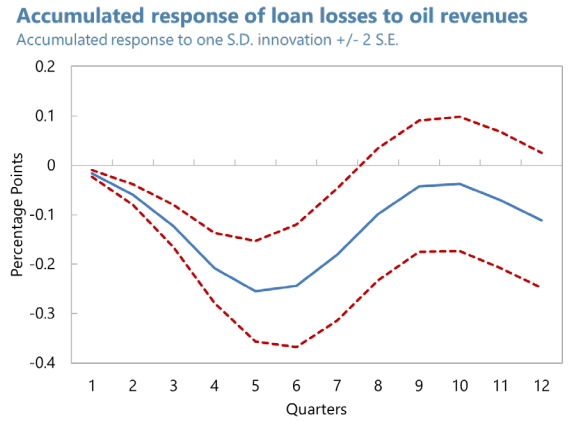
[41] IPCC, AR5 Climate Change 2013: The Physical Science Basis, Glossary, http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf

[42] Global-warming potential, abbreviated as GWP, is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. The global-warming potentials (GWPs) currently used are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Global-warming_potential_(GWP)

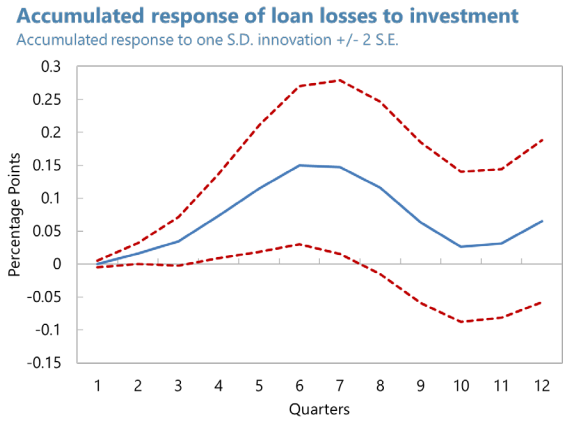
APPENDIX II: IMPULSE RESPONSE FUNCTIONS FOR ALTERNATIVE SVAR

Figure 6: Impulse response functions for loan losses in alternative SVAR

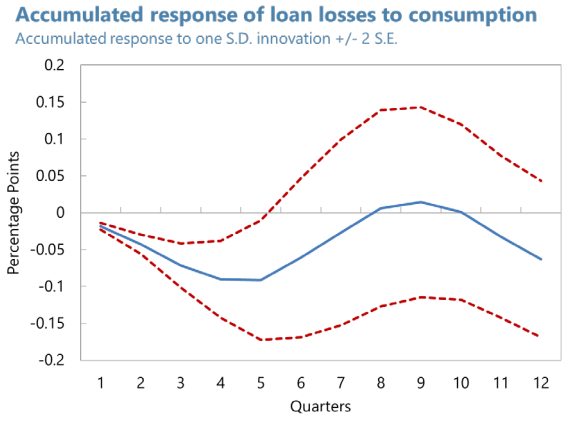
Shocks to oil revenues have a significant and economically meaningful impact on loan losses.



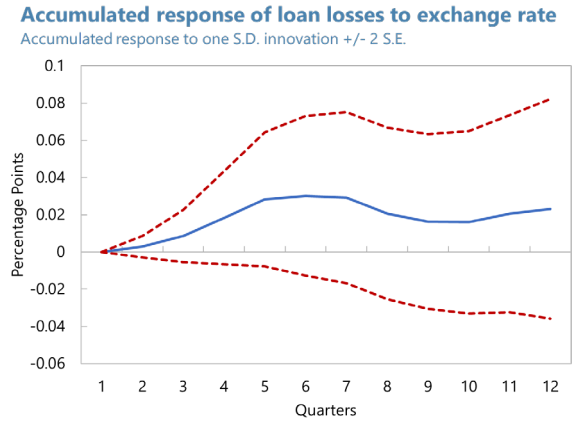
Shocks to investment have a small positive impact on loan losses…



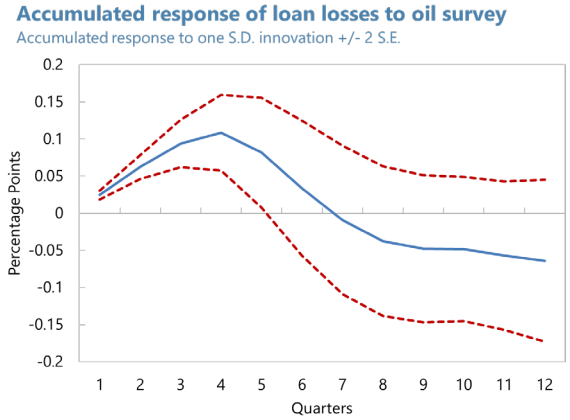
…while consumption shocks have a small negative impact



The reaction to FX shocks is insignificant.



A shock to the oil survey increases loan losses somewhat.



Note: Note: Impulse response functions are calculated with a structural vector-autoregression (SVAR) using quarterly data from 2010 to 2019. Variables are transformed to induce stationarity and we include 4 lags. Identification is achieved through a Cholesky decomposition with the following ordering: Oil sector revenues, Regional Network Survey (export-oriented oil sector category), investment, consumption, bank loan losses, NOK/USD exchange rate.