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Transition risk of a petroleum currency[☆]

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ABSTRACT

The Norwegian krone has been persistently weak since 2017. This is not well explained by data in a standard model where the exchange rate depends on relative interest rates and prices. We extend the standard model by including a risk premium consisting of non-traditional explanatory variables, including the importance of petroleum exports, foreign direct investments and a petroleum related equity index. These variables reflect risks associated with the expected transition of the Norwegian economy which is linked to fading petroleum revenues and the green shift. The model is estimated on quarterly data from 2001, when a monetary policy of inflation targeting was implemented, up to and including 2019. We find that the weak Norwegian krone can be attributed to a higher risk premium. The risk premium is driven by oil prices and improves the model's explanatory power.

1. Introduction

From 2013 and into 2016, the Norwegian krone (NOK) weakened to levels not seen earlier in this century. Since 2017, the krone has not been in line with fundamentals and has not regained its previous strength. This paper investigates factors that may have caused the prolonged period of a weak krone.

As in most oil-exporting countries, there is reason to believe that the domestic petroleum sector and the oil price are important to the Norwegian exchange rate, not least because oil price fluctuations constitute important exogenous terms-of-trade shocks. Higher (lower) oil prices and revenues can thus contribute to real appreciation (depreciation); see e.g. Holden (2013) and Benedictow et al. (2013). Akram and Mumtaz (2016) find an increasing correlation between oil prices and nominal exchange rates in the Norwegian economy, especially after the turn of the millennium. The Norwegian strategy to mitigate appreciation of the NOK in order to protect the traditional export industries has been twofold:

First, oil revenue was phased into the economy gradually. This was accomplished quite successfully by establishing the Government Pension Fund Global, in which all petroleum revenue is placed, and since 2001 applying a fiscal rule of not spending more than the expected real return of the fund, see Holden (2013) and Benedictow and Boug (2017). This arrangement also counteracts the effects of fluctuations in the value of the fund on public spending, and thus on the economy and the exchange rate. The first krone was transferred to the fund in the late 1990s and the fund increased rapidly from the early 2000s.[1]

Second, an inflation targeting monetary policy was introduced at about the same time, in 2001. The inflation target was set at 2.5 per cent, somewhat higher than the European norm of 2 per cent, with a view to absorbing some appreciation internally through higher domestic inflation and thus dampening nominal (external) appreciation. In 2018, the inflation target was adjusted to 2 per cent, in line with the euro area. This was partly justified by the authorities with the assumption that the era of phasing in oil revenues was coming to an end.

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[1] By 2019 the fund's value had increased to 300 per cent of Mainland GDP.

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Standard economic models hold that exchange rates are influenced by fundamental variables such as relative prices and interest rates, see e.g. Williamson (2009) for a survey of theoretical literature. The evidence from a large number of empirical studies is mixed; see e.g. Meese and Rogoff (1988), Sarno and Taylor (2003) and Engel et al. (2007). Nevertheless, many studies have found empirical support for such fundamentals-based models. Kurita and James (2022) find evidence that macroeconomic variables are the core elements determining the Canadian-US dollar exchange rate. Bergvall (2004) investigates the Nordic countries' exchange rates and finds that terms of trade is the most important determinant of long-run movements in the real krone exchange rate. Akram (2006) and Drine and Rault (2008) find support for purchasing power parity (PPP) for Norway and a number of OECD countries. Koijen and Yogo (2020) find that macroeconomic and policy variables explain more than 50 percent of exchange rate variation.

In our model of the NOK-EUR exchange rate, we take as our starting point the classical hypotheses of purchasing power parity (PPP) and uncovered interest parity (UIP) - or rather deviations from UIP - the latter in terms of a foreign exchange risk premium; see for example Fama (1984), Johansen and Juselius (1992), Miyakoshi (2003), Rashid (2009), Engel (2016), Avdjiev et al. (2019) and Bak and Park (2022). The risk premium may help explain the weak NOK of recent years, and includes several relevant variables.

First, like Akram (2006), Bjørnland and Hungnes (2006), Bjørnstad and Jansen (2007) and Akram (2020), we account for effects of oil prices on the krone exchange rate. Empirical studies find support for including commodity prices in exchange rate models for a number of commodity-exporting countries; see e.g. Chen and Rogoff (2003), Bodart et al. (2012), Benedictow et al. (2013), Nusair and Kisswani (2015), Kohlscheen et al. (2017), Poncela et al. (2017) and Kurita and James (2022). Inspired by Kilian (2009), we also use data from the Federal Reserve Bank of New York[2] that breaks down a shock to the Brent oil price into supply, demand and a residual shock. We do not find that the effect on the NOK of shocks to the oil price depends on the origin of the shock.

Second, in order to better capture the existence of an exchange rate premium, and in this context also take into account potential effects related to market dynamics and microstructure, we also include a number of additional variables in our information set. This selection of variables has been inspired by several claims to insights made by market participants and also has a theoretical rationale. First, we include the value of Norwegian oil and gas exports as a share of total Norwegian exports as an indicator of the importance of the petroleum sector to the Norwegian economy. To capture the effects of different types of investor behaviour and market sentiment, we include a petroleum-related equity index and the difference between foreign direct investment in the euro area and Norway, both as a percentage of GDP. Finally, we also include in the analysis four indices reflecting market uncertainty and volatility from the Federal Reserve Economic Database and the S&P500 US stock market volatility index (VIX).

We argue that the variables defining the risk premium may be related to the risk associated with the expected transition of the Norwegian economy heading towards fading petroleum income and the transition to a low carbon intensity economy (the green shift). Economic theory predicts that reduced revenue from natural resources will lead to lower domestic demand and a flow of capital and labour towards the traded sector; see for example (Corden, 1984)'s paper on the Dutch disease. This transformation is facilitated by a depreciation of the exchange rate. A transition away from petroleum revenue could be attributable to a permanent fall in commodity prices or to lower activity in the commodity extracting sector, either way reducing resource revenue as a share of GDP, see e.g. Bjørnland and Thorsrud (2016), Bjørnland et al. (2019). This implies that increased transition risk and structural changes away from oil and commodity production, or expectations thereof, should lead to depreciation.

Kapfhammer et al. (2020) point out that increased climate transition risk may be associated with lower oil prices. Accordingly, we argue that the variables defining the risk premium may also be related to climate transition risk and steps towards a green shift. Kapfhammer et al. (2020) introduce a news media-based measure of climate transition risk. They find that when such risk is high, several major commodity currencies experience persistent depreciation, and also that the relationship between commodity price fluctuations and currencies tends to become weaker. In a survey on climate risk perceptions, Krueger et al. (2020) find that institutional investors believe climate risk has financial implications for their firm portfolios, and that such risks have begun to materialize. Bua et al. (2022) examine the existence of climate transition risk in euro area equity markets. Their results suggest that climate risk premia have increased since the time of the Paris Agreement of 2015. Gu and Hale (2023) use a data set developed by Sautner et al. (2023) that explores whether multinational firms react to Climate-related risks by altering their presence in countries that are more affected. Overall they do not find consistent statistical evidence of climate transition risks on FDI. However, firm-level evidence suggests that firms that are more exposed to climate risks react more negatively to physical climate risk following the Paris Agreement. Sautner et al. (2023)'s data indicates that climate change risk increases from 2013 and the increase is accentuated from 2017, since when the NOK has not been in line with fundamentals.

Our data span from 2001, when the Norwegian exchange rate was floated, up to and including 2019. We find evidence that the weak krone since 2017 is related to the factors included in the risk premium: the declining importance of oil and gas in the Norwegian economy, negative developments in the relative flow of foreign direct investment in Norway relative to the euro area and a fall in an equity index related to petroleum production in Norway. The long-term structure of the model indicates that these factors are all driven by lower oil prices. To the extent that our risk premium variables capture climate transition risk, our results corroborate the findings in Kapfhammer et al. (2020). We also find a depreciating effect on the NOK of an increase in the VIX index. Our main findings are summarized in Table 1.

The theoretical background is explained in Section 2, where we argue for including variables that capture a foreign exchange premium in the empirical analysis. Section 3 presents data and identifies possible long-term relationships among a set of different variables in our data set. Finally, Section 4 presents the results of the empirical analysis, including simulations aimed at illustrating the model's in-sample prediction and ex ante forecast properties. Section 5 summarizes the results and Section 6 provides a conclusion.

2. Theoretical background

The starting points of our empirical analysis are the hypotheses of purchasing power parity (PPP) and uncovered interest parity (UIP).

PPP in its most restrictive form is based on the law of one price, which states that (in the long run, or in equilibrium) the cost of a commodity or a commodity group is the same regardless of the currency (or country) in which you pay; see for example (Sarno and Taylor, 2002). There is little empirical support for PPP in the short term, but several studies employing long time series find support for it in the long term. In his global macroeconometric model, Fair (2004) finds support for PPP in 8 out of 22 countries with time series covering more than 50 years. Akram (2006) finds support for PPP for Norway using long time series.

Uncovered interest parity (UIP) states that the interest rate differential between two countries will be equal to the expected change in the bilateral exchange rate between the countries. UIP applies in an efficient market, and then the choice of country in which one invests in

[2] See https://www.newyorkfed.org/research/policy/oil_price_dynamics_report.

Table 1
Main insights.

What is new?	How do we know?	Why should we care?
–We extend a traditional exchange rate model with a risk premium, including new variables inspired by claims to insights made by market participants –These variables reflect risks associated with the expected transition of the Norwegian economy which is linked to fading petroleum revenues and the green shift –The risk premium is driven by the oil price –The new variables increase the explanatory power of the model –The weak Norwegian krone from 2017 can be attributed to a higher risk premium	–We use data spanning from 2001, when the krone was floated, until the end of 2019 –The risk premium includes new variables, reflecting the importance of petroleum for the Norwegian economy, including foreign direct investments in Norway and a petroleum-related equity index –We develop a conditional dynamic model for the euro-krone exchange rate which is based on a fully simultaneous understanding of the underlying long-term structure in the data	–Exchange rates affect economic activity, inflation, trade, the balance of payments and more –Thus, exchange rates affect individuals, businesses and governments, and their decisions –To understand exchange rate dynamics and perform efficient macroeconomic policies in a globalized economy, empirical evidence of exchange rate determination is key –The results are relevant to other commodity currencies that have experienced the same kind of depreciation as the NOK

interest-bearing securities has no effect on the return, since an interest rate difference between two countries will be offset by a change in the bilateral exchange rate in the same period. The hypothesis of efficient markets is consistent with risk-neutral market participants with rational expectations; see e.g. Sarno (2005). There is little empirical support for UIP, see Bak and Park (2022) for a recent overview. They found that extending UIP by an estimated risk premium may improve fit and short-run predictability of exchange rates.

As shown in Appendix C, by combining PPP and UIP we can express the nominal bilateral exchange rate as a function of the current relative prices of the two countries, the expected long-term real exchange rate and the expected future real interest rate differential. However, in our set-up we will also include a risk premium. In addition to account for the possibility of inefficient markets this opens up for including a set of additional variables related to risk. We have included variables that may capture risks associated with the expected transition of the Norwegian economy linked to fading petroleum revenues and the green shift, as explained in Section 1. The theoretical justification for this can also be found in the introductory section, where we use theory related to the Dutch disease to argue for a possible link between climate transition risk and exchange rate fluctuations. In particular, this theory predicts that reduced revenue from natural resources, or expectations thereof, will lead to a flow of resources away from the domestic sector towards the traded sector that is facilitated through a depreciation of the exchange rate. The variables are described in Section 3 and the empirical methodology is explained in Section 4.

3. Data

Following the formal introduction of inflation targeting in Norway in 2001, there are three distinct periods during which there was a marked weakening of the krone exchange rate. The krone quickly regained its strength following the first two, but it has not recovered from the third to this very day; see Fig. 1.

In 2001–2002, the krone strengthened markedly, which can probably largely be attributed to an increased interest rate differential between Norway and other countries; see for example (Naug, 2003). The following weakening probably overshot, after which the krone reverted to around its previous level, more in line with a closing of the interest rate differential.

During the acute phase of the international financial crisis in the autumn of 2008, the krone weakened sharply as a result of a flight to large, safe haven currencies such as the US dollar and the Swiss franc, before it regained its previous strength through 2009 and into 2010.

From 2013 and into 2016, the Norwegian krone weakened sharply against the euro, first due to a general strengthening of the euro, which may have been attributable to improved prospects for the European economy, but, especially from the summer of 2014, as a result of the steep fall in oil prices; see Fig. 1. The figure also shows that the krone-euro exchange rate is well aligned with the krone nominal effective exchange rate, and that the weakening of the krone relative to the euro mainly reflects a general weakening of the krone against a broader basket of currencies (NOKne) and not a general strengthening of the euro, which would be reflected in the euro nominal effective exchange rate (EURne).

In this paper we model the krone-euro exchange rate. The euro is by far the most important currency for Norwegian trade. In 2019, close to 35 per cent of Norwegian exports of traditional goods and services went to the euro area. An advantage of studying a bilateral exchange rate is that corresponding prices, interest rates etc. are easily available. The model is estimated on quarterly data. The estimation period runs from 2001, when an inflation target for monetary policy was first introduced, up to and including 2019.

Fig. 2 depicts simple bivariate correlation patterns between some of the most important variables in our information set, where the variables have been scaled to match by means and ranges (Doornik, 2015). First, panel a indicates a strong relationship between the logarithm of the nominal krone-euro exchange rate, s, and the logarithm of the relative consumer price ratio between Norway and the euro area, $p - p^{*}$, a relationship that seems to be particularly pertinent from 2014 onwards when the krone started to weaken in earnest. However, looking at panel b, which depicts the real exchange rate, $s - (p - p^{*})$, together with the value of oil and gas as a share of total exports, v, the relationship between the nominal exchange rate and relative prices does not seem to be one-to-one in the sense of generating a stationary real exchange rate. Thus, this opens up for the possibility of other variables informing the real exchange rate in the long run. A key candidate in that respect – and as suggested by panel b – is the value of oil and gas as a share of total exports. Panels c and d introduce two other candidates: the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway, I, and a petroleum-related equity index, a. Both variables demonstrate some capacity for capturing certain aspects of the non-stationary nature of the real exchange rate. Fig. 2 also demonstrates the Norwegian economy's degree of oil dependence more generally, as all the variables mentioned above seem to be strongly linked to the USD oil price, op, in one way or another. This applies not only to the value of oil and gas as a share of total exports, as illustrated in panel g, but also to the petroleum-related equity index, (a), and the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway (I). The last panel, h, shows the real interest rate differential between Norway and the euro area, $r - r^{*}$, and clearly demonstrates its high degree of stationarity, a stylized fact that will later form the basis for the co-integration analysis to come.[3]

Our analysis was initially conditional on four indices reflecting market uncertainty and volatility, including a world uncertainty index (WUI), a world trade uncertainty index ($WTUI$), an uncertainty index pertaining to advanced economies (AUI) – all from the Federal Reserve Economic Database (FRED) – and the S&P500 volatility index (VIX).

[3] For a more formal testing of the stationarity properties of the variables included in our information set, we refer to the stationarity tests in Appendix A. They indicate that the real exchange rate, the nominal interest rate differential and all of our individual time series variables are I(1).

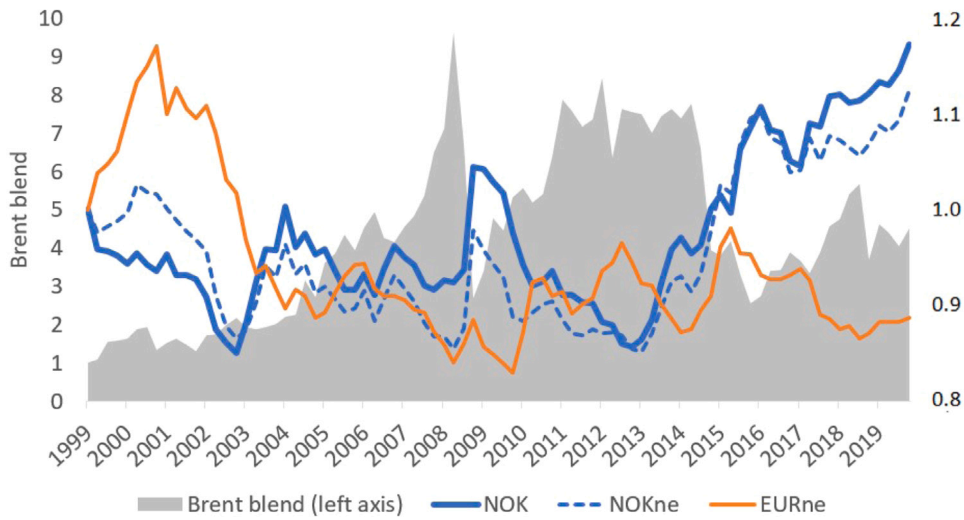

Fig. 1. Krone per euro (NOK), krone nominal effective exchange rate (NOKne), euro nominal effective exchange rate (EURne) and oil price per barrel (Brent blend) in US dollar. 1999=1.
Source: Macrobond.

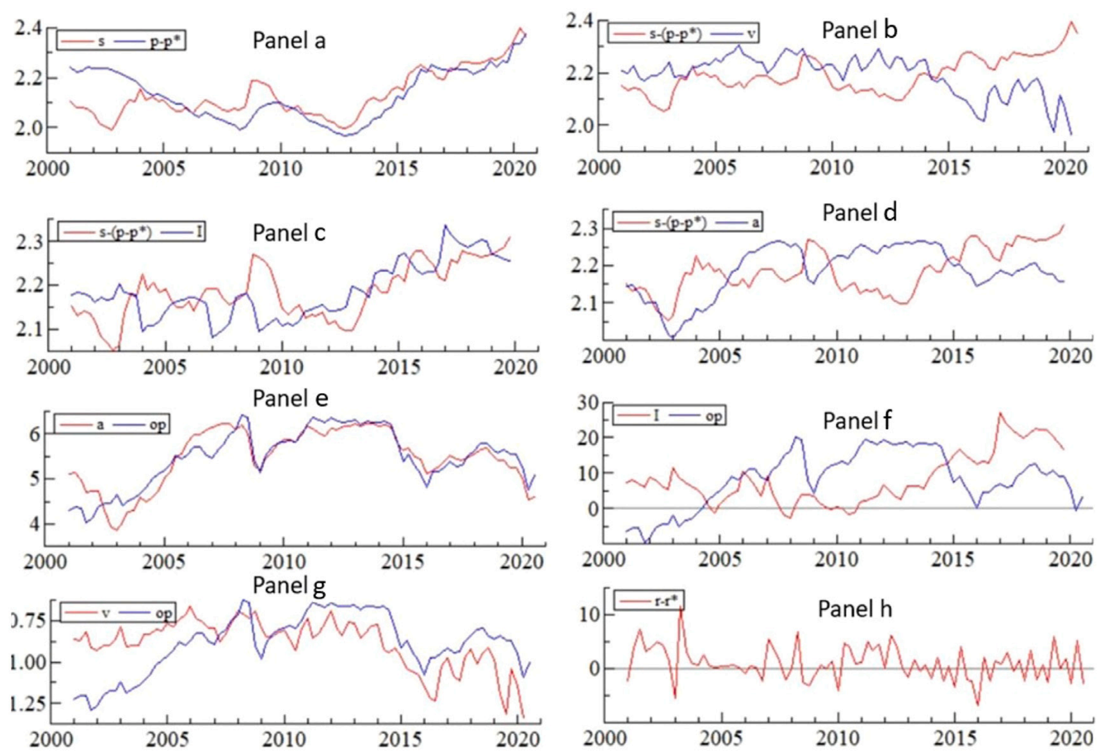

Fig. 2. Data.
Note: s and $s-(p-p^{*})$ are the logarithms of the nominal and the real exchange rate, respectively, $p-p^{*}$ is the logarithm of relative consumer prices between Norway and the euro area, v is the logarithm of the ratio of the value of oil and gas exports to the value of total Norwegian exports, a is the logarithm of an equity index pertaining to the Norwegian petroleum industry, I is the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway, op is the logarithm of the oil price in USD and $(r-r^{*})$ is the real interest rate differential between Norway and the euro area. The variables have been scaled to match by means and ranges (Doornik, 2015).
Source: Norges Bank, Macrobond, Statistics Norway.

This was done to capture a possible flight to safe haven currencies as a result of international market turmoil. With the exception of the VIX index, these indices proved to add little explanatory power to the analysis. See Appendix B for a detailed data description.

4. Econometric analysis

As our point of departure we chose the vector equilibrium correction model (VECM) in reduced form. In the general case this can be given the following representation:

$$\Delta X_t = \Pi Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i \Delta X_{t-i} + \Phi D_t + \epsilon_t, \tag{1}$$

where X_t represents a $p \times 1$ vector of endogenous variables, $Y_t = (X_t', Z_t')'$ a $(p+q) \times 1$ vector where Z_t is a $q \times 1$ vector of exogenous variables and k the order of the VECM. D_t is a vector composed of contemporaneous and lagged differences of the model's exogenous variables, Z_t, deterministic variables such as dummies,[4] a trend and a constant. ϵ_t is a Gaussian white noise vector with an unrestricted covariance matrix. The rank of the Π matrix gives us information about the cointegration properties of the model, and in the case where the rank, r, is less than full, i.e. less than p, the Π matrix may be written as the product of a $p \times r$ matrix, α, and a $(p+q) \times r$ matrix, β, with full column rank equal to $r < p$. The level term in Eq. (1) can then be written as $\Pi Y_{t-1} = \alpha\beta' Y_{t-1}$ where $\beta' Y_{t-1}$ represents the r cointegrating linear combinations of the variables while the α matrix has the interpretation of a coefficient matrix with equilibrium correction coefficients or loadings.

The cointegration analysis in connection with the preparation of the "structural" equilibrium correction model of the krone-euro exchange rate[5] is based on a five-dimensional conditional VECM of order 2, for the simultaneous determination of the real exchange rate, $q = s-(p-p*)$, the real interest rate differential vis-à-vis the euro area, $\tilde{r} = r - r^*$, a Norwegian petroleum-related equity index, a, the ratio of the value of oil and gas exports to the total value of Norwegian exports, υ, and the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway, I.[6] In addition to a constant and some dummies for structural breaks, the model is contingent on the Brent blend crude oil price measured in US dollars, op, the S&P volatility index, VIX and the world uncertainty index of the FRED database, WUI, being exogenous processes. With the exception of interest rates, lower case letters indicate logarithmic transformations.

We have chosen to base the cointegration analysis on the assumption of a full pass-through of relative price changes to the nominal exchange rate in the long run. This restriction receives broad support from preliminary analyses where such a restriction was not imposed a priori, and is later dissolved when we proceed with the dynamic design of our contingent model for the krone-euro exchange rate.

4.1. Long-run analysis

Starting with the reduced form analysis and identification of the model's long-run structure, the results, as reproduced in Tables 2 and 3, provide support for the possible existence of as many as five cointegrating vectors. As can be seen from the significance probabilities of the tests for the number of cointegrating vectors, with the exception of the last one, they are all significant at a level very close to or significantly below 1 percent.[7] We refer the reader to footnote 8 for a more detailed explanation of the identification process, and content ourselves here with confirming that the system is robust to several ways of exactly identifying the system: the over-identified structure in the upper part of Table 3 associates a long-run cointegration relationship with each of the individual variables treated as endogenous in our five dimensional VECM.[8]

In particular, the first two cointegrating relationships pertain to the real krone-euro exchange rate and the real interest rate differential, respectively, the latter implying that the variable constitutes a stationary relationship in itself. The three other relationships can be said to represent the degree of dependence on oil of the Norwegian economy, as measured by two different kinds of investor behaviour and the relative contribution of oil and gas exports to the total value of Norwegian exports.

The first cointegrating relationship, pertaining to the long-term real krone-euro exchange rate, provides support for four hypotheses that shed light on recent developments. To varying degrees, all can be related to the behaviour of forward-looking investors who envision a less oil-dependent Norwegian economy, a green shift and general uncertainty.

First, according to the first long-run relationship, the real exchange rate will weaken as oil and gas make up a smaller share of the Norwegian economy. A permanent 1 per cent fall in their export share is estimated to lead to a long-term weakening of the krone-euro exchange rate of approximately 0.23 per cent.

Second, a one per cent fall in the petroleum-related equity index will also lead to a real exchange rate depreciation, though the effect is estimated to be fairly weak. Third, a corresponding outflow of capital, represented by the difference between foreign direct investment in the euro area and in Norway expressed as a percentage of GDP, and fourth, an increase in the S&P volatility index denoted VIX also contribute to weakening the krone.

Individually, the estimated effects of changes in the last three variables are all relatively small. However, lasting changes in all these variables at the same time could apply a significant persistent negative long-term pressure on the krone in the absence of countervailing forces.

According to the cointegration analysis, the real interest rate differential is a stationary variable in itself. It will thus be included in the long-term solution both via the reduced form loading structure and, as a consequence of this, possibly also via the conditional equilibrium correction structure of the structural dynamic exchange rate equation.

[4] Including seasonal dummies.

[5] To distinguish the type of model developed in this paper from a reduced form model we use the term structural, being fully aware that a more correct term in this context would perhaps have been behavioural or relational, given the lack of a fully structural underpinning of its rationale.

[6] As shown in Appendix A.2 the VECM of order 2 amounts to a valid reduction of a data congruent VECM of order 6.

[7] If we allow for a somewhat higher level of significance, i.e. 6 per cent, the analysis confirms the results of an analysis carried out on a VECM of order 3 where the fifth cointegration vector is also significant at a level of around 1 percent. Fig. 5 in Appendix A, which provides a graphical representation of the overidentified cointegration structure, also shows that there is little reason to treat the fifth cointegrating vector differently from the third. Moreover, the same figure illustrates that all cointegration vectors show a clear tendency to converge towards a mean reverting time series, eventually.

[8] The starting point for exactly identifying a structure is that the order condition must be met. In the case of a five-dimensional structure this means that 4 linearly independent restrictions must be imposed on each of the structural equations. The over-identifying restrictions thus refer, both potentially and implicitly, to many ways of exactly identifying the long-term structure. However, what they all have in common in our case is that we had to impose zero restrictions on the coefficients pertaining to the direct effects of the interest rate differential, $r-r*$, the world uncertainty index, WUI, and the oil price in US dollars, po, in the equation pertaining to the real exchange rate. As a basis for the long-term analysis, we also condition on the FRED world uncertainty index (WUI). This was done to facilitate accurate identification of the starting point for the design of our final – and over-identified – long-term structure. For the system to be exactly identified we have imposed the structural effects of changes to I and VIX to be of equal magnitude. For the other equations, however, there are many ways to impose the required number of restrictions without compromising the rank condition. An example

Table 2
Johansen's test for the number of cointegrating vectors.

Trace Eigenvalue test:		
H_0	H_1	Values of test statistics
r = 0	r ≤ 5	127.87[0.00]***
r ≤ 1	r ≤ 5	76.92[0.00]***
r ≤ 2	r ≤ 5	37.07[0.01]***
r ≤ 3	r ≤ 5	18.73[0.01]***
r ≤ 4	r ≤ 5	3.52[0.06]*

VECM order: 2, unrestricted constant, ordinary and seasonal dummies and exogenous variables. Estimation period: 2001Q1 to 2019Q4.
Note: The values in square brackets are the respective tests' significance probabilities. *, ** and *** signify that the test is significant at levels of 10%, 5% and 1%, respectively.

The χ^2-test for the number of over-identifying restrictions in Table 3 shows that the final and over-identified system, consisting of five cointegrating relationships, constitutes a valid restriction on a corresponding exactly identified long-run structure.[9]

4.2. Dynamic design

Given the long-run structure in the upper part of Table 3, the next step is to specify a general unrestricted conditional "structural" model (GUM) of the krone-euro nominal exchange rate involving in principle all the cointegrating relationships and the variables in the VECM, and to reduce it to a parsimonious representation by a general-to-specific model reduction scheme; see e.g. Campos and Ericsson (2005), assisted by the Autometrics module in Doornik (2015).

The structural form or SEM representation of the reduced form is obtained by multiplying (1) by a contemporary response matrix B. This results in the simultaneous equation system:

$$B\Delta X_t = B\Pi Y_{t-1} + \sum_{i=1}^{k-1} B\Gamma_i \Delta X_{t-i} + B\Phi D_t + B\epsilon_t,$$

or after having set $B\Pi = B\alpha\beta' = \alpha^*\beta'$, $B\Gamma_i = \Gamma_i^*$, $B\Phi = \Phi^*$ and $B\epsilon_t = u_t$

$$B\Delta X_t = \alpha^*\beta' Y_{t-1} + \sum_{i=1}^{k-1} \Gamma_i^* \Delta X_{t-i} + \Phi^* D_t + u_t \tag{2}$$

Given the five previously estimated long-run relationships and the fact that the cointegration analysis could just as well have been undertaken on a VECM of order 3, (2) will imply the following conditional structural GUM representation for the nominal krone-euro exchange rate, s_t:

$$\Delta s_t = \alpha_s^*\beta' Y_{t-1} + \sum_{i=1}^{3-1} \gamma_{s,i}^* \Delta s_{t-i} + \sum_{i=0}^{3-1} \Gamma_{s,i}^* \Delta\tilde{X}_{t-i} + \Phi_s^* D_t + \tilde{u}_t \tag{3}$$

where the subscript s stands for the row pertaining to the exchange rate in (2) and $\tilde{X}$ represents the vector of all the endogenous variables in Eq. (1) that remain after having substituted the nominal exchange rate for the real exchange rate, relegated lagged and contemporaneous first differences of the relative price ratio to the container of exogenous variables and deterministic terms, the D_t variable, and, finally, substituted the nominal interest rate differential for the real interest rate differential.[10]

By reducing the model to a parsimonious representation, taking into account the possibility of a structural change both in the constant term and in the parameters governing the dynamic responses of the variables representing the effects of investor behaviour and market dynamics, the petroleum-related equity index and the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway, we get:[11]

$$\begin{aligned}
\Delta(s + p^* - p)_t &= \underset{(0.08)}{0.23} + \underset{(0.12)}{0.23}\Delta(s + p^* - p)_{t-1} + \underset{(0.09)}{0.32}\Delta(s + p^* - p)_{t-2} - \underset{(0.015)}{0.07}\,\Delta op_t \\
&+ \underset{(0.019)}{0.08}\,\Delta op_{t-1} - \underset{(0.009)}{0.065}\Delta(i - i^*)_t + \underset{(0.01)}{0.044}\Delta(i - i^*)_{t-1} + \underset{(0.001)}{0.004}\Delta(I * SD171)_{t-1} \\
&- \underset{(0.05)}{0.13}\Delta(a * SD171)_{t-1} + \underset{(0.0004)}{0.0009}\Delta\mathrm{VIX}_t - \underset{(0.013)}{0.041}(ID024 + ID031)_t \\
&- \underset{(0.04)}{0.12}((s_{t-1} + p_{t-1}^* - p_{t-1}) + 0.023a_{t-1} - 0.004I_{t-1} + 0.23v_{t-1} - 0.004VIX_{t-1}) \\
&- \underset{(0.0006)}{0.002}((i_{t-1} - \Delta p_{t-1}) - (i_{t-1}^* - \Delta p_{t-1}^*)) + \underset{(0.015)}{0.038}ID133_t + \epsilon_t^s
\end{aligned} \tag{4}$$

AR 1-5 test:	$F(5,57)$	=	0.78649[0.5637]
ARCH 1-4 test	$F(4,68)$	=	0.34840[0.8443]
Normality test:	$\chi^2(2)$	=	2.3016[0.3164]
Heterosc. test:	$F(41,33)$	=	1.1369[0.3548]
RESET23 test	$F(2,60)$	=	0.95941[0.3889]

In Eq. (4) $IDYYQ$ and $SDYYQ$ stand for, respectively, an impulse dummy that is equal to 1 in quarter Q of year 20YY, and a step-dummy equal to one from the Q'th quarter of 20YY and throughout the sample period. In both cases, YY denotes a combination of two individual numbers, where the first runs from 0 to 2 while the second runs from 0 to 9. The step dummy SD171 and the three impulse dummies $ID024$, $ID031$ and $ID133$ were detected by means of the step and impulse indicator saturation option of Autometrics during the design and reduction process of the modelling, see e.g. Castle et al. (2011). To avoid a problem related to imposing a deterministic quadratic trend on the model, the step dummy was implemented as a structural break to the dynamic responses of changes in the petroleum-related equity index and in the variable measuring the difference between FDI as a percentage of GDP in the euro area and in Norway in the first quarter of 2017.[12] A 1 percent increase in the petroleum-related equity index is estimated to lead to a strengthening of the nominal krone-euro exchange rate of just over 0.1 per cent in the quarter following the change. The two impulse dummies $ID024$ and $ID031$ probably capture asymmetric responses to changes in the interest rate differential, in that the first serves to reinforce the appreciation effect of the growing interest rate differential that developed in 2002, while the second contributes to dampening the effect of the fall in the same variable that followed at the beginning of 2003. The dummy for the third quarter of 2013 probably reflects prospects for a lack of budget discipline as a result of a new government coalition between the traditional conservative right

of how the structure can become exactly identified in this respect is relegated to Appendix D.

9 In order to arrive at the final over-identified system and to be able to generate estimated standard errors for the beta matrix, we had to calibrate the parameter that applies to the $(I + VIX)$ term after having decided to drop the WUI variable from the model altogether. This calibration is based on the estimate of this parameter made in the step prior to arriving at the final over-identified structure in Table 3.

10 In (3), α_s^* refers to a 1 x 5 parameter vector with equilibrium correction coefficients, β a $5 \times (p + q)$ matrix of cointegration parameters, while $\gamma_{s,i}^*$, $\Gamma_{s,i}^*$ and Φ_s^* stand for, respectively, a scalar, a 1×4 parameter vector and a vector containing all the parameters pertaining to the D_t variable vector. $\tilde{u}_t$ is a scalar residual.

11 The left-hand-side variable in Eq. (4) implies an imposed homogeneity restriction between the nominal exchange rate and relative prices that contributes to improve the model without leading to a discernible loss of information nor changes to the model's diagnostic properties. The equilibrium correction parameters are more precisely estimated, and the re-specification leaves out dummies that previously could not be accounted for. Eq. (4) can still be interpreted in nominal terms and is fully consistent with Eq. (3).

12 Note that this break is also consistent with the violation of normality discussed in Appendix A.2.

Table 3
The identified system of cointegrating linear combinations given r=5, the loading matrix and a test of overidentifying restrictions.

The identified long-run structure given 5 cointegrating relations:

$$\hat{\beta}'\begin{pmatrix} Y_t \\ X_t \end{pmatrix} = \begin{pmatrix} q_t + \underset{(0.013)}{0.023}\, a_t + \underset{(0.063)}{0.227}\, v_t - 0.004\,\{I+VIX\}_t \\ \{r-r^*\}_t \\ \{v-op\}_t \\ a_t + \underset{(0.014)}{0.043}\, VIX_t - op_t \\ I_t + 81.645\, op_t \end{pmatrix}$$

Equilibrium correction coefficient matrix:

$$\begin{array}{c} \Delta q \\ \Delta \tilde{r} \\ \Delta v \\ \Delta a \\ \Delta I \end{array} : \begin{pmatrix} \hat{\alpha}_{11} & \hat{\alpha}_{12} & \hat{\alpha}_{13} & \hat{\alpha}_{14} & \hat{\alpha}_{15} \\ \hat{\alpha}_{21} & \hat{\alpha}_{22} & \hat{\alpha}_{23} & \hat{\alpha}_{24} & \hat{\alpha}_{25} \\ \hat{\alpha}_{31} & \hat{\alpha}_{32} & \hat{\alpha}_{33} & \hat{\alpha}_{34} & \hat{\alpha}_{35} \\ \hat{\alpha}_{41} & \hat{\alpha}_{42} & \hat{\alpha}_{43} & \hat{\alpha}_{44} & \hat{\alpha}_{45} \\ \hat{\alpha}_{51} & \hat{\alpha}_{52} & \hat{\alpha}_{53} & \hat{\alpha}_{54} & \hat{\alpha}_{55} \end{pmatrix} = \begin{pmatrix} -0.15 & -0.002 & 0.05 & -0.18 & 0.0008 \\ (0.06) & (0.001) & (0.03) & (0.007) & (0.0004) \\ -22.492 & -0.96 & 3.92 & 1.17 & 0.05 \\ (7.52) & (0.16) & (3.38) & (0.85) & (0.04) \\ 0.51 & 0.000005 & 0.08 & -0.07 & 0.0006 \\ (0.30) & (0.006) & (0.136) & (0.034) & (0.0017) \\ -1.89 & -0.05 & -5.86 & -0.59 & -0.06 \\ (7.03) & (0.15) & (3.16) & (0.8) & (0.04) \\ -0.23 & 0.007 & -0.41 & 0.0015 & -0.005 \\ (0.20) & (0.004) & (0.09) & (0.023) & (0.001) \end{pmatrix}$$

LR test of overidentifying restrictions: $\chi^2(11) = 17.898$ [0.0840]

Note: The variables q_t, v_t, $\tilde{r}_t = (r-r^*)_t$, a_t, I_t and op_t are, respectively, the real exchange rate, the ratio of the value of oil and gas to the value of total exports, the real interest rate differential, an equity index pertaining to the Norwegian petroleum industry, the difference between foreign direct investment (FDI) as a percentage of GDP in the euro area and in Norway, and the oil price in US dollars. With the exception of interest rates, lower case letters denote logarithmic transformations of the original variables. r^i_t, where the index i is either a blank or an asterisk, are the two real interest rates. The vector to the left of the loading matrix and before the colon refers to the individual equations in the corresponding reduced form VECM representation. The Δ symbol stands for the first difference operator. The value in parentheses under each estimated coefficient is its standard error, while the value in parentheses following the test of over-identifying restrictions refers to the test's significance probability. Note that the test statistic of over-identifying restrictions refers to the restrictions that must be imposed on an exactly identified long-run structure in order to arrive at the final structure given by the cointegrated system's over-identified right hand side (See footnote 8 for further elaboration).

wing party (Høyre) and the populist Progress Party (FrP). Furthermore, we see that both the first and the second cointegrating vectors in the long-run structure of Table 3 enter significantly into Eq. (4), implying that a 1 percentage point increase in the real interest rate differential is estimated to lead to a real appreciation of approximately 1.7 per cent in the long run.[13] Compared to an estimated contemporaneous effect of about −6.5 per cent, this implies overshooting.[14],[15]

Given that the long-run relationship between the value share and the oil price is based on the third cointegrating relationship in Table 3, the effect of a 1 percent increase in the oil price would imply a long-term real appreciation of the krone-euro exchange rate of approximately 0.23 per cent. In addition to this long-run effect, the oil price also has clear dynamic effects according to Eq. (4). A 1 percent increase in the oil price is estimated to lead to an instantaneous appreciation of about 0.1 percent. This immediate effect is reversed in the next quarter, suggesting that in the very short-term the exchange rate is primarily affected by an acceleration in oil prices — and not just an oil price increase. Thereafter, the exchange rate appreciates in accordance with the estimated long-term relationship. This is an adaptation that takes place gradually via the model's equilibrium correction mechanism.

The outcomes of the statistical tests quoted under Eq. (4) suggest that the model is a congruent representation of an underlying DGP. Recursive tests demonstrate, moreover, that the model and its parameters are stable.[16]

Simulating the model dynamically from 2008 onwards by linking lagged values of the endogenous variable to the previously predicted ones also indicates that the in-sample prediction properties are fairly good, in the sense that there is no tendency for the simulated values to derail (see Fig. 8 in Appendix A).

We retain seven observations for use in making ex ante forecasts and use the model to dynamically forecast seven periods ahead. Unlike static one-step forecasts, where one uses actual data for all right-side variables – including the lagged values of the endogenous variable(s) – dynamic forecasts refer to forecasts made utilizing current and former forecasts of these values, including the lagged endogenous ones. The dynamic forecasts in Fig. 3 refer to a dynamic model for the simultaneous determination of the change in the real exchange rate, the level of the real and nominal exchange rates and the deviation from the first two long-term relationships. To achieve this, Eq. (4) has been equipped with the following identities:

$$CIa_t = \Delta(s + p^* - p)_t + CIa_{t-1} - 0.004(\Delta VIX_t + \Delta I_t) + 0.023\Delta a_t + 0.227\Delta v_t$$
$$CIb_t = CIb_{t-1} + \Delta\{r - r^*\}_t$$

[13] This follows by the fact that the long-run elasticity of the nominal exchange rate, $S = e^s$, with respect to the real interest differential, r-r*, is given by: $El_{(r-r^*)}S = -\frac{0.002}{0.12}(r-r^*) \approx -0.017(r-r^*)$. An increase in the interest differential of 100 basis points will thus lead to an appreciation of the exchange rate equal to $0.017(r-r^*)\frac{100}{(r-r*)} = 1.7$ per cent.

[14] Note that the interest and inflation rates in (4) are measured as annualized rates in percent. When discussing the effects of a quarterly change to these variables of 1 percentage point, we therefore have to multiply the coefficient by 4.

[15] As the domestic real interest rate can conceivably be assumed to be an endogenous variable it may not be legitimate to treat the contemporaneous nominal interest rate differential as a valid conditioning variable. However, the results based on IV estimation, reproduced in the last part of Appendix A, suggest that this does not represent a problem in our case.

[16] See Figs. 6 and 7 in Appendix A.

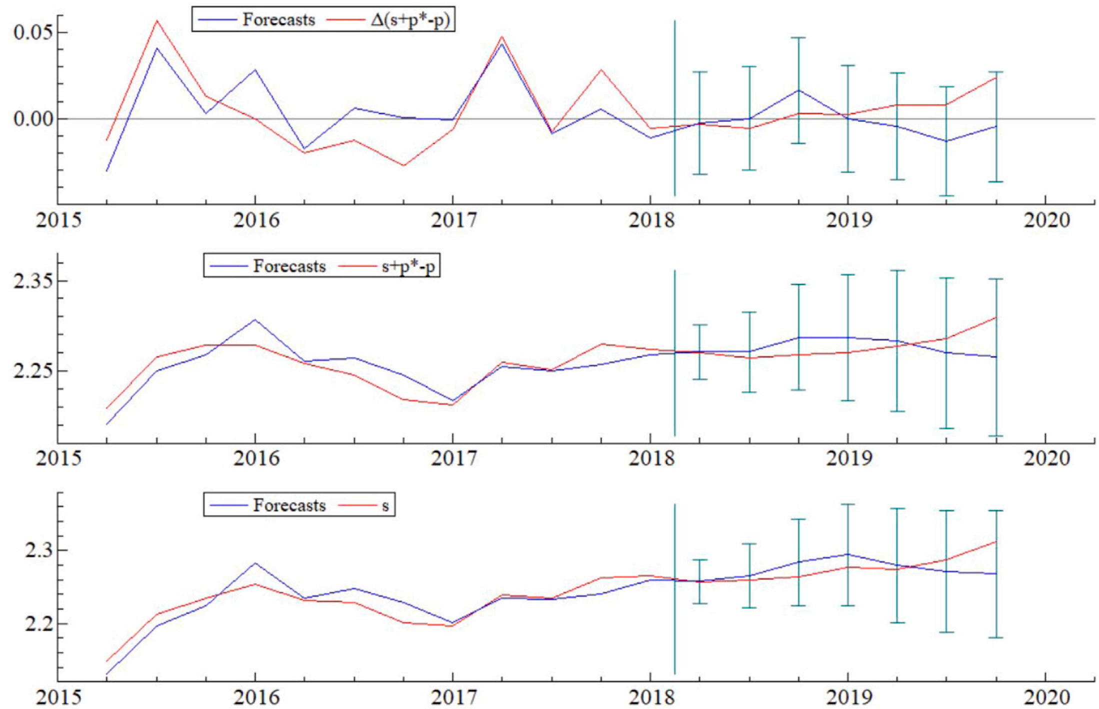

Fig. 3. Dynamic forecasts.
Note: Estimation period 2001q1 to 2018q1. Dynamic forecasts 7 periods ahead. s and $(s + p^* - p)$ are the nominal and real exchange rate, respectively, and Δ indicates change from the previous period.

$$(s + p^* - p)_t = \Delta(s + p^* - p)_t + (s + p^* - p)_{t-1}$$

$$s_t = (s + p^* - p)_t + p_t - p*_t,$$

where $CIa = (s + p^* - p)_t + 0.023a_t + 0.227v_t - 0.004\{I + VIX\}_t$ and $CIb = \{r - r^*\}_t$.

As born out by Fig. 3 the level forecasts are well within the 95 percent confidence interval for the whole period, although there are signs of a widening gap in the last two periods.

Although we estimate the long-run cointegration structure of our model by resorting to a fully simultaneous design process – involving all the variables perceived to be endogenous in the VECM – the design of the dynamic structural exchange rate equation per se has been constructed based on a one equation at-the-time design process where we condition on the variables previously treated as endogenous. We use the instrument variable method to test for the validity of conditioning on the nominal interest rate differential. An alternative approach would be to assume that the exchange rate is the outcome of a simultaneous causal dynamic interaction process, involving a set of interdependent endogenous variables also when designing the dynamic structure of the model. Such an approach could also benefit from a more structural theoretical understanding of the underlying process driving the Norwegian krone exchange rate and in this respect a more theory-based understanding of the expectation formation. However, we assess this to be outside the scope of the present paper and leave it for future research.

5. Results and discussion

In this paper, we find empirical evidence of a risk premium in the process driving the krone-euro exchange rate that contributes to explaining the weak NOK of recent years.

The risk premium is captured by a number of variables: the export value of oil and gas as a share of the total value of exports, the difference between inward FDI as a percentage of GDP in the euro area and in Norway, a petroleum-related equity index and a volatility index related to the US $S\&P500$ stock market index. These variables are driven by a common trend originating from the oil price. We argue that these variables can be related to the behaviour of investors envisaging a transition of the Norwegian economy linked to fading petroleum revenues and the green shift.

In our model, the NOK real exchange rate is estimated to weaken in the long run as oil and gas account for a smaller share of the Norwegian economy and as the export share of oil and gas falls. A fall in the petroleum-related equity index is also estimated to lead to a real weakening of the NOK in the long run, though the effect is relatively modest.

Combined with a net outflow of capital from Norway, represented by the difference between inward FDI as a percentage of GDP in the euro area and in Norway, and a rising $S\&P500$ volatility index, these effects will collectively contribute to exert a sustained negative pressure on the krone-euro exchange rate.

In the short term, the krone exchange rate is to a large degree driven by changes in the oil price and in interest rates, although some additional variables related to the risk premium and eigen-dynamics are found to be significant as well. However, the effect of these additional variables primarily apply from 2017 onwards.

The model passes a panoply of mis-specification tests, is stable and fulfil standard requirements for being a congruent representation of an underlying data-generating process.

In addition to the main analysis above, we investigate two sources of supplemental data, (1) a decomposition of the oil price and (2) a data set of climate transition risk.

First, we utilize data from the Oil Price Dynamics Report of the Federal Reserve Bank of New York[17] that breaks down a shock to the

[17] See https://www.newyorkfed.org/research/policy/oil_price_dynamics_report.

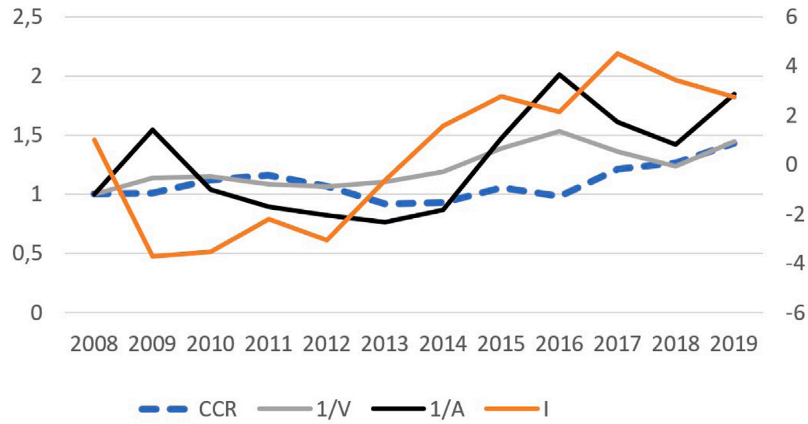

Fig. 4. Climate change risk (CCR), the inverse of the Norwegian petroleum related equity index (1/A), the inverse of the value of Norwegian exports of oil and gas as a share of total exports (1/V) and the difference between FDI as a percentage of GDP in the euro area and in Norway (I) (right axis). 2008=1.
Source: Statistics Norway, Macrobond, Oxford Economics, Swedbank and Sautner et al. (2023).

benchmark Brent oil price into supply, demand and residual shocks. Our analysis is inspired by Kilian (2009), who finds that the effects on the US real economy of shocks to the oil price depend on whether the shock stems from oil supply, demand for oil or demand for all industrial commodities. This may also be relevant for regressions of exchange rates on oil prices, and could cause breaks and instability if not accounted for.

Our analysis does not indicate that this is the case for the NOK-EUR exchange rate. On the contrary, none of these decomposed types of shocks appear to either significantly explain or help enhance the model's predictive power, either individually or taken together. This applies also whether the change in the Brent oil price is controlled for or not.

Second, we have downloaded a data set on climate change risk from Sautner et al. (2023). The observed increase in the climate change risk indicator from 2013 is accentuated from 2017, since when the NOK has not been in line with fundamentals. As shown in Fig. 4, the increase in the climate change risk indicator also corresponds with the developments of the variables intended to capture the risk premium; a drop in a Norwegian petroleum related equity index and in the value of Norwegian exports of oil and gas as a share of total exports (both inverted in the figure) and the difference between FDI as a percentage of GDP in the euro area and in Norway.

6. Conclusion

Exchange rates are important for economic activity, inflation, trade, the balance of payments and more, and thus affect individuals, businesses and governments and their decisions. To understand exchange rate dynamics and perform efficient macroeconomic policies in a globalized economy, empirical evidence of exchange rate determination is key.

Our paper contributes to the exchange rate literature by extending a traditional exchange rate model with a risk premium represented by variables inspired by theory and claims to insights made by market participants. We have used data spanning from 2001 to 2019 and estimate a conditional dynamic model for the krone-euro exchange rate.

The variables representing the risk premium increase the explanatory power of the model and help explain the weak NOK from 2017. They are also correlated with the oil price and, we have argued, should be seen in relation to the risk associated with the expected transition of the Norwegian economy related to fading petroleum revenues and the green shift. Our approach could also be relevant to other commodity currencies that have experienced a similar depreciation as the Norwegian krone in the same period.

A limitation of the analysis is that we only allow for a fully simultaneous structure when designing the long term properties of the model. A more sophisticated approach could be to also apply a similar strategy when designing the model's short term dynamic structure. Such an approach would also benefit from a more theory-based understanding of the expectation formation. However, we assess these issues to be beyond the scope of the present paper and have chosen to leave such an endeavour for future research.

Declaration of competing interest

The present paper is partly financed by the Norwegian Ministry of Finance. This financial support is without constraints or conditions.
Andreas Benedictow

My employer, Housing Lab at Oslo Metropolitan University is a research centre that receives partial funding from the Norwegian Ministry of Finance, the Norwegian Ministry of Municipalities and Modernization, OBOS (a house construction firm), Selvaag Bolig (a house construction firm), and Sparebanken 1 (a bank). This financial support is without constraints or conditions. I also hold a position as Chief economist at the consultancy Samfunnsøkonomisk analyse. Samfunnsøkonomisk analyse holds no commercial or other interest in the results.
Roger Hammersland

I have nothing to disclose

Data availability

Data will be made available on request.

Appendix A. Statistical testing

A.1. Stationarity tests

See Table 4.

A.2. From a VECM of order 6 to a VECM of order 2

The analysis started out with a five-dimensional VECM of order 6 and was initially reduced to a VECM of order 3. This reduction is shown to be valid, as the F-test for the removal of all lags greater than 3 from the model is given by F(75,143)=1.3377[0.0694], where the figure in parentheses is the test's significance probability. Nor were any of the partial reductions of the model reduction scheme – from a VECM of order 6 all the way down to a VECM of order 3 – rejected. With the

Table 4
Augmented dickey fuller tests.

Variable	Levels	First difference	Conclusion
s	−0.8026(1)	−4.924***	I(1)
p	0.4249(1)	−7.666***	I(1)
p*	−2.600(1)	−5.764***	I(1)
v	−2.684(1)	−10.35***	I(1)
op	−1.988(1)	−6.749***	I(1)
s + p*-p	−1.638(1)	−5.054***	I(1)
a	−1.778(1)	−5.225***	I(1)
i	−2.873(1)	−4.168***	I(1)
i*	−2.223(1)	−4.894***	I(1)
i − i*	−2.459(1)	−3.368**	I(1)
I	−1.409(1)	−6.775***	I(1)

Note: The five and one percent critical values of the ADF-test are taken from MacKinnon (2010), and are equal to respectively -2.90 and -3.52 when a constant has been included in the specification of the model and the number of observations is equal to 78. Figures in brackets indicate the number of lags, while ** and *** indicate significant to a level of 5 and 1 percent, respectively.

exception of a deviation from normality in the FDI equation, notably due to a structural break in the first quarter of 2017 that we will later allow for, none of the individual equation hypotheses for normality or absence of residual autocorrelation and heteroscedasticity are rejected in this model at conventional significance levels. The system diagnostics of the VECM(3) model, given below, where the figures in square brackets are the significance probabilities of the various tests, do not give rise to any concern either.

Vector AR 1-5 test:	$F(125,98)$	=	1.0771[0.3519]
Vector Normality test:	$\chi^2(10)$	=	15.4444[0.1167]
Vector Heterosc. test:	$F(260,95)$	=	0.9689[0.5840]

To remedy problems related to the relatively small sample and as a consequence, low number of degrees of freedom, we have chosen to carry out the final cointegration analysis on a VECM of order 2. Although the reduction from an order 3 VECM to an order 2 VECM is partly valid (F(25,164)=1.44[0.09]) it does not pass the test for the removal of all lags greater than two from the model. The reduction also comes at the expense of somewhat poorer diagnostics at the system level, especially with respect to autocorrelation.

A.3. Cointegrating relations

See Fig. 5.

A.4. Recursive tests

See Figs. 6–8.

A.5. Structural estimates from IV estimation

In the final dynamic version of our exchange rate model, we have conditioned on the real interest rate differential being a valid contemporaneous explanatory variable. However, as the domestic real interest rate can conceivably be assumed to be an endogenous variable it may not be legitimate to treat the real interest rate differential as a valid conditioning variable. Hence instrumental variables (IV) should be used.

$$\begin{aligned}\Delta(s+p^*-p)_t &= \underset{(0.09)}{0.21} + \underset{(0.12)}{0.22}\Delta(s+p^*-p)_{t-1} + \underset{(0.09)}{0.32}\Delta(s+p^*-p)_{t-2} - \underset{(0.015)}{0.07}\,\Delta op_t \\ &+ \underset{(0.02)}{0.08}\Delta op_{t-1} - \underset{(0.02)}{0.076}\Delta(i-i^*)_t + \underset{(0.01)}{0.05}\Delta(i-i^*)_{t-1} + \underset{(0.001)}{0.004}\Delta(I*SD171)_{t-1} \\ &- \underset{(0.05)}{0.14}\Delta(a*SD171)_{t-1} + \underset{(0.0004)}{0.0010}\Delta\mathrm{VIX}_t - \underset{(0.015)}{0.045}(ID024+ID031)_t \\ &- \underset{(0.04)}{0.11}((s_{t-1}+p^*_{t-1}-p_{t-1}) + 0.023a_{t-1} - 0.004I_{t-1} + 0.23v_{t-1} - 0.004VIX_{t-1}) \\ &- \underset{(0.0007)}{0.002}((i_{t-1}-\Delta p_{t-1}) - (i^*_{t-1}-\Delta p^*_{t-1})) + \underset{(0.015)}{0.04}\,ID133_t + \epsilon^s_t\end{aligned} \tag{5}$$

Instrumented variable: $\Delta(i-i^*)_t$
Additional instruments: $\Delta(i-i^*)_{t-2}$, $\Delta(i-i^*)_{t-3}$, $\Delta(i-i^*)_{t-4}$

Specification test:	$\chi^2(2)$	=	1.9406[0.3790]
Testing beta =0	$\chi^2(13)$	=	114.83[0.0000]***
AR 1-5 test:	$F(5,57)$	=	0.77171[0.5741]
ARCH 1-4 test:	$F(4,68)$	=	0.30883[0.8711]
Normality test:	$\chi^2(2)$	=	2.4130[0.2992]
Heterosc. test:	$F(23,51)$	=	0.66619[0.8552]

The equation above shows the results of estimating a model where we have instrumented the contemporaneous interest rate differential variable. The first thing to notice is that the specification χ^2-test for the validity of the instruments– where we in addition to the set of exogenous variables have included three extra lags of the variable being instrumented as additional instruments – does not reject. Furthermore the χ^2-test for whether all the coefficients except the constant term are zero (the testing beta =0-test) strongly rejects the null at the same time as the estimated effects do not deviate significantly from the original results. Taken together with the diagnostic test for spherical noise, i.e. the test of normality, absence of autocorrelation and heteroskedasticity, this indicates that our basic model specification is sound in the sense of not being mis-specified.

Appendix B. Variable sources and definitions

Variables:

- NOK = krone per euro exchange rate. Source: Macrobond
- $NOKne$ = krone nominal effective exchange rate. Source: Macrobond
- $EURne$ = euro nominal effective exchange rate. Source: Macrobond
- i = nominal interest rate Norway. Source: Statistics Norway
- i^* = nominal interest rate euro area. Source: Statistics Norway
- P = consumer price index Norway. Source: Statistics Norway
- P^* = consumer price index euro area. Source: Statistics Norway
- VIX = S&P500 volatility index. This is a measure of the volatility on the S&P500 equity index, which is made up of 500 of the largest companies traded on US stock markets. Source: Chicago Board Options Exchange
- WUI = World uncertainty index. Source: Federal Reserve Economic Database (FRED)
- $WTUI$ = World trade uncertainty index. Source: FRED
- AUI = Uncertainty index for advanced economies. Source: FRED
- $Brent\ blend$ = oil price per barrel in USD. Source: IMF
- OP = oil price in USD. Source: IMF
- A = Norwegian petroleum-related equity index. Source: Macrobond
- I = the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway: Sources Macrobond, Oxford Economics and Swedbank.
- V = ratio of the value of Norwegian oil and gas exports to the value of total Norwegian exports. Source: Statistics Norway
- CCR = Climate change risk indicator. Source: (Sautner et al., 2023)[18]

Definitions

- s = logarithm of the nominal exchange rate (NOK)
- p = logarithm of the consumer price index in Norway

[18] Data can be downloaded at https://osf.io/fd6jq/.

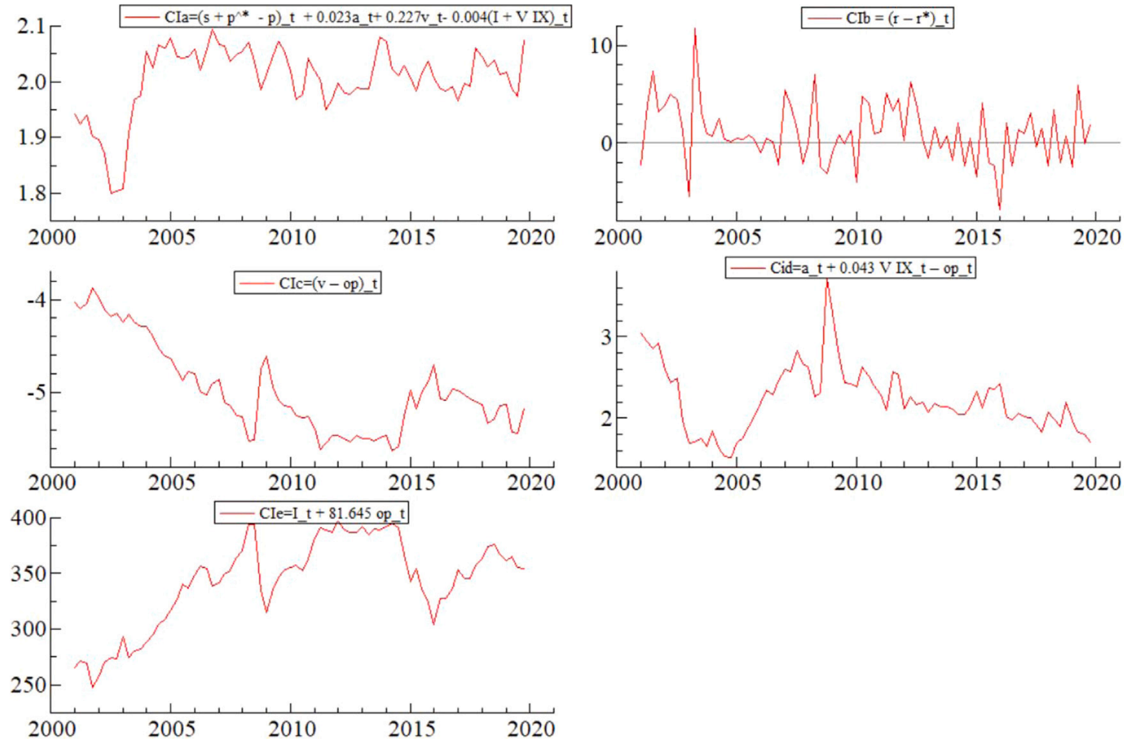

Fig. 5. Equilibrium correction terms.
Note: Fig. 5 shows the graphical representation of the five cointegrating relationships identified in Table 3. Although several of these show signs of non-stationarity at the very beginning of the estimation period, they all seem to converge towards a mean-reverting series, eventually. Note that the last cointegration vector (CIe) does not appear to be less stationary than the third (CIc) and thus should be treated accordingly.

- p^* = logarithm of the consumer price index in the euro zone
- $q = s - (p - p^*)$ = logarithm of the real exchange rate
- $r_t = i_t - (p_t - p_{t-1})$ = real domestic interest rate in period t
- $r_t^* = i_t^* - (p_t^* - p_{t-1}^*)$ = real foreign interest rate in period t
- $\tilde{r} = r - r^*$ = real interest rate differential
- v = logarithm of the ratio of the value of oil and gas to the value of total Norwegian exports
- a = logarithm of the petroleum-related equity index
- op = logarithm of the oil price in USD

Note: lower case letters indicate logs with the exception of the interest rate i. An asterisk indicates the euro area.

Appendix C. Derivation of the theoretical background

Based on the hypotheses of purchasing power parity (PPP) and uncovered interest parity (UIP) we can express the nominal exchange rate as a function of relative prices and relative interest rates plus a risk premium.

PPP in its most restrictive form is based on the law of one price, which states that (in the long run, or in equilibrium) the cost of a commodity or a commodity group is the same regardless of the currency (or country) in which you pay; see for example (Sarno and Taylor, 2002). Then the bilateral exchange rate between two countries can be expressed as the relative price ratio between the two countries,

$$S_t = P_t / P_t^*, \tag{6}$$

where S is the nominal, bilateral exchange rate, and P_t and P_t^* are the price levels in the two countries in period t. Let us for the sake of simplicity call them 'home' and 'abroad', where the latter is marked with an asterisk (*). PPP must be considered to be an equilibrium, and hence (6) an equilibrium condition.

If we multiply both sides of (6) by P_t^*/P_t and take the logarithm, we obtain $q_t = s_t + p_t^* - p_t = 0$ in equilibrium, where Q is the real exchange rate and lower case letters indicate logarithmic form. This equation may equivalently be written as

$$q_t = s_t - p_t + p_t^*. \tag{7}$$

As we see from (7), the real exchange rate can be interpreted as a deviation from PPP.

UIP states that the interest rate differential between two countries is equal to the expected change in the bilateral exchange rate between the countries, and can be expressed as

$$E_t \Delta s_{t,T} = i_{t,T} - i_{t,T}^*, \tag{8}$$

where E_t is the expectation operator, $E_t \Delta s_{t,T} \equiv E_t s_T - s_t$ is the expected (at time t) percentage change in the exchange rate in the period from time t to T and $i_{t,T}$ and $i_{t,T}^*$ are the nominal interest rates at home and abroad on deposits or securities with a maturity equal to $T - t$.

If we express UIP in real terms and allow for a risk premium, z_t, (8) can be rewritten as

$$q_t = E_t q_T - (E_t R_{t,T} - E_t R_{t,T}^*) + z_t, \tag{9}$$

where $E_t q_T$ is the expected real exchange rate in period T, $E_t R_{t,T} = i_{t,T} - [E_t p_T - p_t]$ is the ex ante expected real interest rate and $E_t p_T - p_t$ is expected domestic inflation in the period t to T. $E_t R_{t,T}^*$ is the corresponding expected real interest rate abroad.

If we combine PPP and UIP, represented by Eqs. (6) and (9), respectively, by substituting for q_t, we get

$$s_t = p_t - p_t^* + E_t q_T - (E_t R_{t,T} - E_t R_{t,T}^*) + z_t. \tag{10}$$

According to Eq. (10), the nominal exchange rate is determined by the current relative prices between the two countries, the expected long-term real exchange rate and the expected future real interest rate

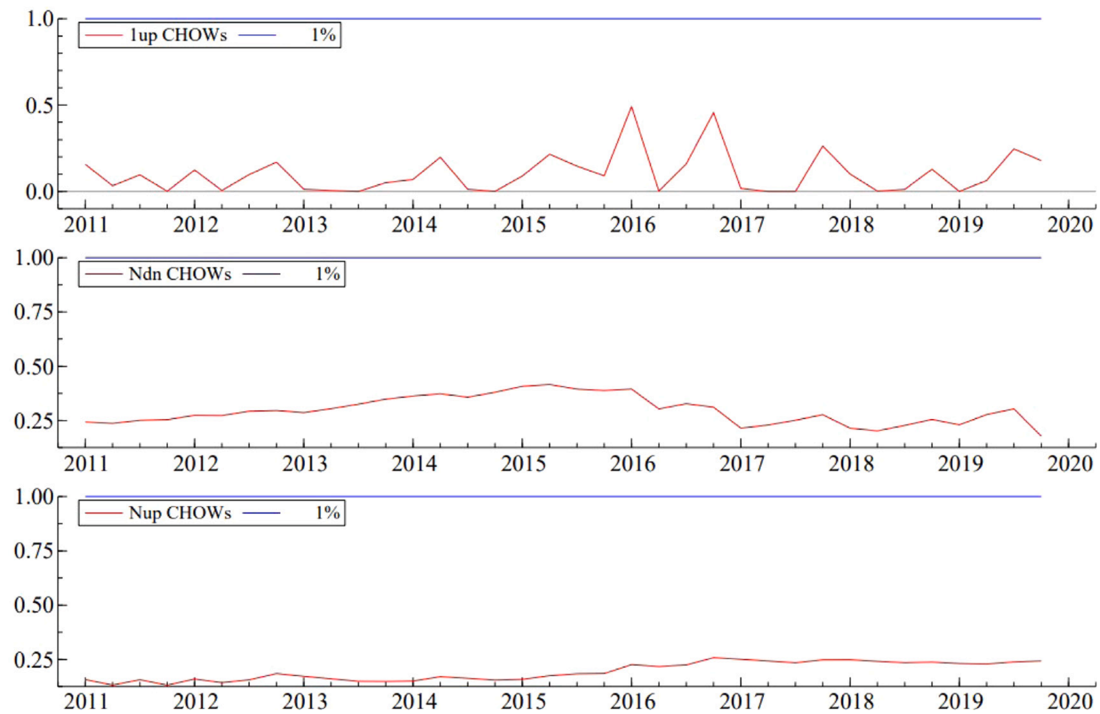

Fig. 6. Stability tests.
Note: Fig. 6 shows 1-step and break-point Chow tests. These are the main tests of parameter constancy and have the form:

$$(((RSS_{T+H} - RSS_T)/H)/RSS_T/T-k) \sim F(H, T-k),$$

where RSS is the residual sum of squares, k the number of right-hand side variables, H the forecast horizon and T a date index. The one-step test implies that the time horizon H is fixed at one period as the test is computed sequentially for t=T and up to t=T+H. As far as the Ndn Chow tests are concerned, each point is the value of the Chow F-test for that date in relation to the final period, here 2019Q4, scaled by its 1 percent critical values, implying that the forecast horizon N decreases from left to right (hence the name Ndn tests). The opposite is the case for the Nup Chow tests, where each point is the value of the Chow F-test for that date in relation to the final period in the initialization sample, here 2009Q4, implying that the forecast horizon increases from left to right. None of the tests shown above reject the null hypothesis that the parameters are stable over time (to a level of 1 percent), thereby corroborating the visual impression given by Fig. 7.

differential plus a risk premium. This equation forms the basis for our empirical analysis, in which we also try to capture the effect of a risk premium via the use of a number of indicators, as explained in Section 4.

Appendix D. Identification

The principle underlying a scheme of exact identification is that the restrictions must be of such a nature that only the identity matrix will constitute a valid transformation matrix of the structural system, in the sense that it is the only matrix that will imply that the transformation is both data- and theoretically admissible. This means that none of the equations in an exactly identified system can be formed by taking linear combinations that give weight to the other equations in the system.

In footnote 8 we refer to an explicit example of how a precisely identified long-term structure might look like, and such an example is given below.

In this scheme, where the coefficients of the endogenous variables have all been normalized to 1 in the equations to which they implicitly pertain, an asterisk implies an unrestricted coefficient, ‘0’ a null restriction and ‘c’ a linear restriction; here the two coefficients pertaining to the foreign direct investment variable and the VIX index are assumed to be equal in the first equation. As should be apparent from the identification scheme of Table 5, the restrictions encompass the restrictions referred to in footnote 8.

Table 5
Exact identification.

Variable\Equation number	1	2	3	4	5
q	1	*	0	0	*
$\tilde{r}$	0	1	0	*	0
a	*	*	1	0	0
I	c	0	0	1	*
v	*	0	0	0	1
WUI	0	0	*	0	0
VIX	c	0	*	*	0
op	0	*	*	*	*

Note: In this table, the first column contains the names of all variables while the column header row indicates the equations to which the restrictions apply. The first equation represents the long-run structural equation pertaining to the real exchange rate (q), the second to the real interest rate differential ($\tilde{r}$), the third to the petroleum-related equity index (a), the fourth to the difference between foreign direct investment as a percentage of GDP in the euro area and in Norway (I) and the fifth to the ratio of the value of Norwegian oil and gas exports to the value of total Norwegian exports (v). With the exception of interest rates, lower case letters indicate logarithmic transformations. A 0 in row 1 and column 3 in the part of the matrix containing the restrictions therefore means that the parameter for the real exchange rate is set at zero in equation 3. The same applies to the other cells, the only difference being that an asterisk means that the parameter in question is not restricted, while ’c’ represents a homogeneity restriction.

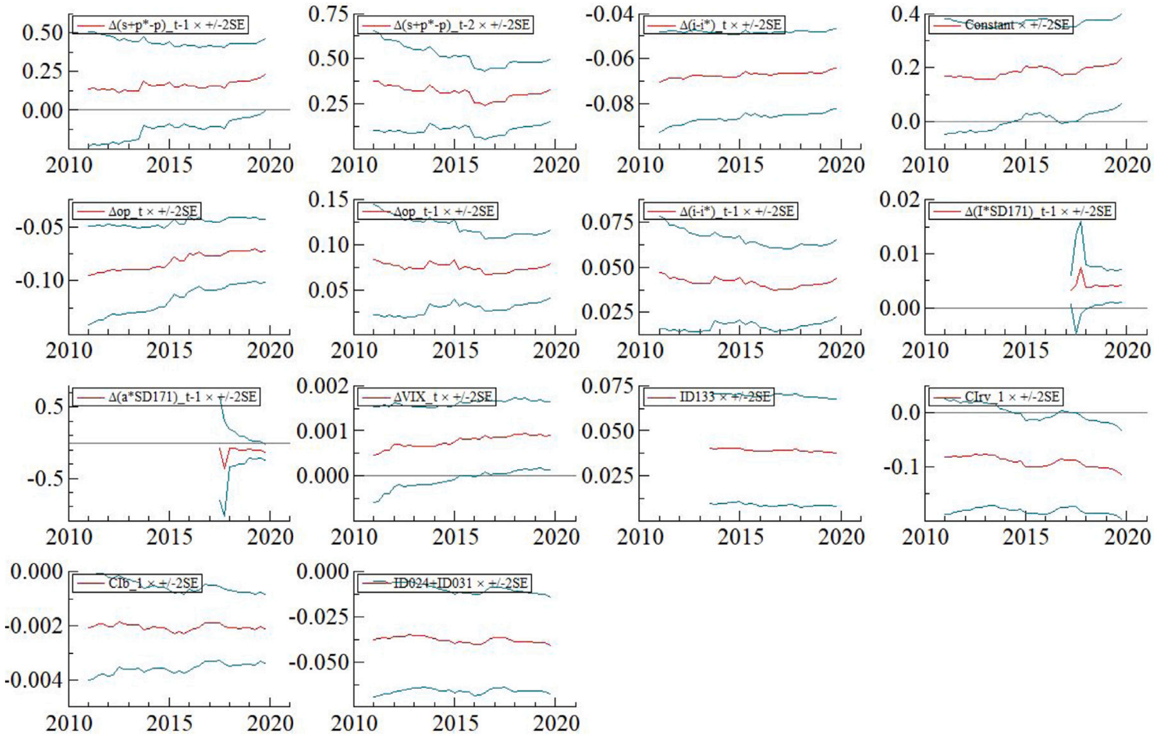

Fig. 7. Recursively estimated coefficients.
Note: Fig. 7 shows recursively estimated coefficients with the number of observations used for initialization set to 40. With the exception of the parameters pertaining to the variables that kick in 2017Q1, none of these coefficients lie outside the confidence interval based on the first 40 observations. The parameters pertaining to the two variables that kick in from 2017Q1 onwards both seem to stabilize fast towards their estimated values when the full sample is used. CIa and CIb stand for the parameters of the two cointegrating vectors, which pertain to the real exchange rate and the real interest rate differential, respectively.

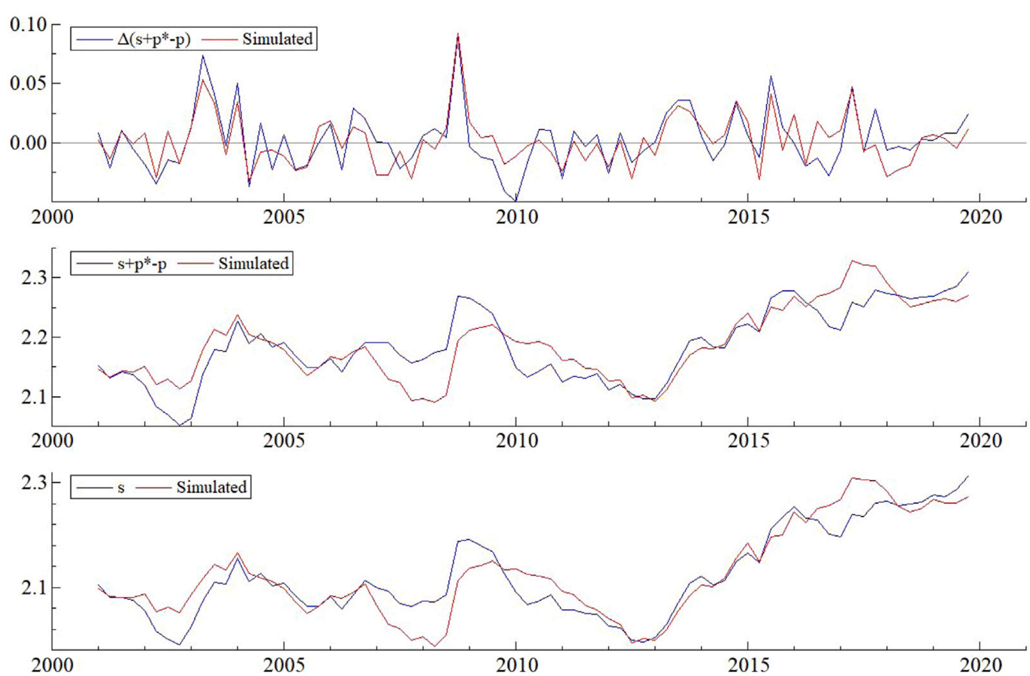

Fig. 8. Dynamic simulations.
Note: Unlike static one-step forecasts where actual data are used for all right-hand side variables, including the lagged values of the endogenous variable(s), dynamic forecasts, as presented in Fig. 8, refer to forecasts made utilizing current and former forecasts of these values, including the lagged endogenous ones. s and $(s + p^{-} p)$ are the nominal and real exchange rate, respectively, and Δ indicates change from the previous period. As was the case when making the dynamic forecasts in Section 4, these simulations have been produced by adding the following identities to the conditional exchange rate Eq. (4):

$$CIa_t = \Delta(s + p^* - p)_t + CIa_{t-1} - 0.004(\Delta VIX_t + \Delta I_t) + 0.023\Delta a_t + 0.227\Delta v_t$$
$$CIb_t = CIb_{t-1} + \Delta\{r - r^*\}_t$$
$$(s + p^* - p)_t = \Delta(s + p^* - p)_t + (s + p^* - p)_{t-1}$$
$$s_t = (s + p^* - p)_t + p_t - p*_t,$$

where $CIa = (s + p^* - p)_t + 0.023a_t + 0.227v_t - 0.004\{I + VIX\}_t$ and $CIb = \{r - r^*\}_t$.

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