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**Staff Discussion Paper/Document d’analyse du personnel—2023-23**
Last updated: October 12, 2023

# A Blueprint for the Fourth Generation of Bank of Canada Projection and Policy Analysis Models

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**DOI:** https://doi.org/10.34989/sdp-2023-23 | **ISSN** 1914-0568 

## Acknowledgements
Thanks to Paul Beaudry, Fabio Canova, Sharon Kozicki, Douglas Laxton and Stephen Murchison for helpful conversations. Thanks to Gino Cateau and Oleksiy Kryvtsov for comments on an earlier draft. This plan has also benefited from feedback received from participants at the 25th annual Central Banker's Macro Modelling Workshop (November 10, 2022). Recent central bank model reviews at the European Central Bank (2021) and Norges Bank (2019) were particularly helpful. The views expressed here are my own.

## Abstract
This paper outlines a strategic plan for the development of the fourth generation of Bank of Canada projection and policy analysis models. The plan features a new Canadian workhorse macroeconomic model as well as a suite of alternative models to better support a risk management approach to monetary policy. This new generation of models seeks to improve our understanding of inflation dynamics, the supply side of the economy and the underlying risks faced by policy-makers coming from uncertainty about how the economy functions. New approaches for dealing with idiosyncratic trends in the data and for leveraging the power of large data sets will be employed.

*Topics: Economic models, Inflation and prices, Labour markets, Monetary policy and uncertainty*
*JEL codes: C50, C51, C52, C53, C54, C55*

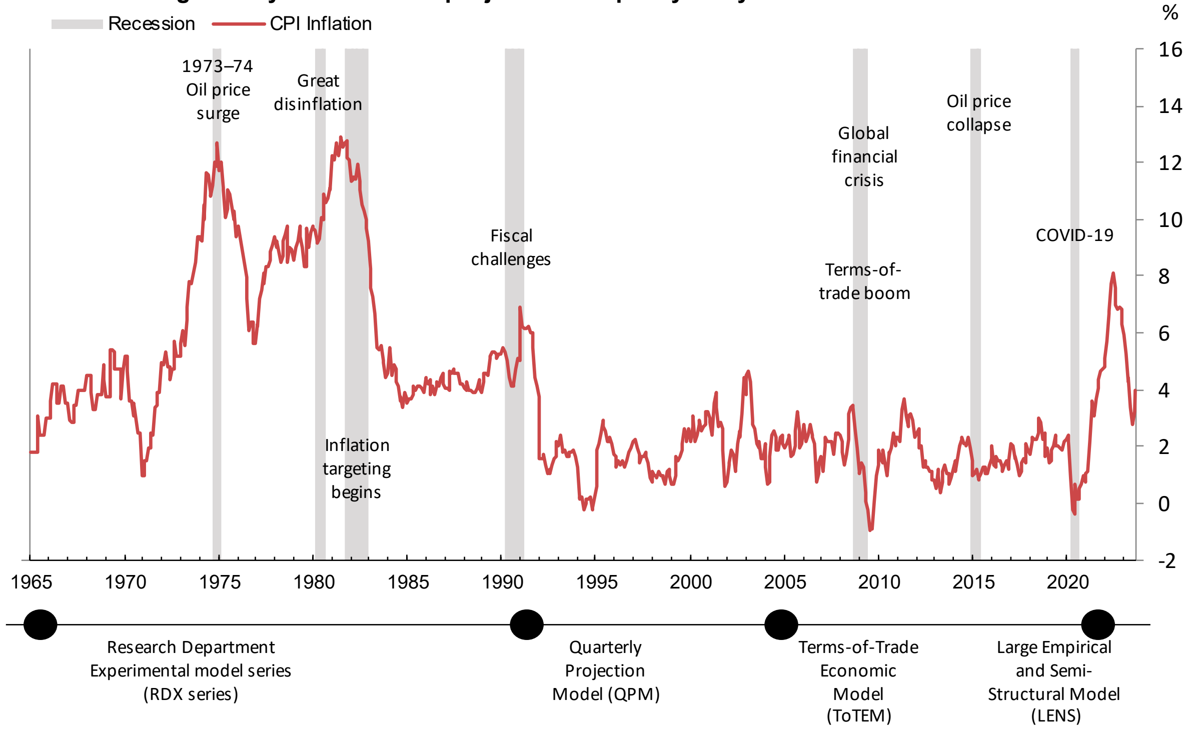
## Résumé
Nous présentons ici un plan stratégique pour la conception de la quatrième génération de modèles utilisés par la Banque du Canada pour effectuer des projections et des analyses. Le plan décrit un nouveau modèle macroéconomique canadien de référence et un ensemble d'autres modèles. Le but de cette démarche est d'améliorer l'intégration de la gestion des risques dans la conduite de la politique monétaire. Cette nouvelle génération de modèles est destinée à approfondir notre compréhension de la dynamique de l'inflation, de l'offre au sein de l'économie et des risques sous-jacents auxquels sont confrontés les décideurs publics, causés par l'incertitude qui entoure le fonctionnement de l'économie. Il est prévu que de nouvelles méthodes soient utilisées pour composer avec les tendances idiosyncrasiques présentes dans les données et exploiter la puissance associée à la taille des vastes ensembles de données.

*Sujets : Modèles économiques; Inflation et prix; Marchés du travail; Incertitude et politique monétaire*
*Codes JEL : C50, C51, C52, C53, C54, C55*

# 1. Introduction and motivation

Macroeconomic models play an essential role in the conduct of monetary policy. The Bank of Canada has a long history of developing and using these models for projections and policy analysis (Poloz 2017). New workhorse macroeconomic models are built infrequently, about every 20 years or so (**Chart 1**). These are large-scale efforts that require significant investments in human capital and technology.

**Chart 1: A long history of models for projection and policy analysis**




Note: See details in S.S. Poloz, "Models and the Art and Science of Making Monetary Policy" (remarks at the University of Alberta, Edmonton, January 31, 2017).
Sources: Statistics Canada and Bank of Canda calculations
Last observation: August 31, 2023

There have been three generations of Bank workhorse models. The earliest vintage, the RDX series, was rooted in traditional Keynesian theory and focused on the demand side of the economy (Helliwell et al. 1969). The Quarterly Projection Model (QPM) was adopted in the early 1990s (Black et al. 1994; Coletti et al. 1996). It was borne out of the revolution in macroeconomics and model building stemming from the stagflation of the 1970s, and it reflected a profound paradigm shift at central banks (Taylor 2016).

The current generation of Canadian projection and policy analysis models includes two models. The Terms-of-Trade Economic Model (ToTEM) (Murchison and Rennison 2006; Dorich et al. 2013; Corrigan et al. 2021) was built upon the advances of QPM and is an example of a dynamic stochastic general equilibrium (DSGE) model. With its multi-sector structure, ToTEM offers a much deeper understanding than its predecessor of how terms-of-trade shocks impact the Canadian economy. The Large Empirical and Semi-Structural Model (LENS) (Gervais and Gosselin 2014) was added in 2015. LENS is a semi-structural model—the same class of models that include QPM. Fewer cross-equation restrictions and greater flexibility regarding the nature of rigidities lead to increased adaptability and better in-sample fit.

The Bank's projection and policy analysis models have vastly improved through the years and have many strengths. But important limitations suggest that it is time for a major revision. For example, the models feature a rich demand side but an underdeveloped supply side—a shortcoming that became particularly important during the COVID-19 pandemic. Moreover, Bank projection models have difficulty explaining inflation in the 2020s as well in the aftermath of the 2008–09 global financial crisis.[1] And even during more tranquil periods when the models fit the data more closely, they are no better at forecasting inflation out-of-sample than simple autoregressive models.

This paper outlines a strategic plan for the development of the fourth generation of Bank of Canada projection and policy analysis models (known internally as the NexGen project).[2] The plan features two intertwined initiatives:

- a new Canadian workhorse projection model
- a suite of models to better support a risk management approach to monetary policy

Once completed and fully tested, the new models will replace LENS and ToTEM in the projection process.

The new workhorse model will build on the strengths of the Bank's current models. It will feature at its core a structural business cycle model, similar in spirit to ToTEM III (henceforth ToTEM).[3] This core model will capture general equilibrium effects and ensure the internal consistency of the underlying macroeconomic narrative.

The focus of this core model will be on improving our understanding of inflation dynamics. Importantly, it will include a more modern characterization of how firms set prices, a more realistic depiction of how inflation expectations are formed and more elaborate modelling of the supply-side of the economy.

Like the Bank's semi-structural models LENS and IMPACT (International Model for Projecting Activity, Blagrave et al. 2020), aspects of the business cycle and the long-term trends will be simultaneously considered in NexGen model estimation. This helps ensure against important biases in parameter estimates that can affect the projection and policy advice. It will also help with forecasting.

In a break from the past, the new model will be estimated using "data-rich" techniques. Harnessing information from large datasets has been proven to improve the properties and forecasting ability of structural models. Using these techniques, Bank staff can also add new details to the projection without having to rederive the structural model, which is typically a time-intensive exercise. This will add agility to the projection environment, an important advantage over conventional DSGE models like ToTEM.

[1] Kryvtsov, MacGee and Uzeda (2023) discuss the challenges of anticipating the COVID-19 inflation surge that central banks faced.

[2] Many of the themes around developing the next generation of central bank models are discussed in Dorich et al. (2017).

[3] A model is structural when it includes period-by-period optimizing behaviour by private agents given explicit assumptions about tastes, technology, information and market structure. Structural models include sufficient assumptions that permit estimation of model-consistent structural shocks. In contrast, time-series models exploit statistical regularities in the data and do not attempt to identify behavioural parameters. For example, they do not attempt to separate intrinsic and expectational dynamics. Shocks are reduced-form in nature and not interpretable without auxiliary assumptions. Vector autoregression models are an example. Semi-structural models cover a vast range between structural and time-series models. They tend to have more flexible specifications, containing a mix of optimizing and ad hoc behavioural equations. Semi-structural models are often estimated equation by equation and thus their shocks are not interpretable from a system-wide perspective.

These techniques also position staff to explore the potential benefits from recent advances in machine learning for model estimation and for forecasting, particularly over shorter horizons.

The second element of the strategic plan is to create the infrastructure needed to improve the staff's ability to support a risk management approach to monetary policy. Risk management acknowledges that monetary policy is conducted in an environment of significant uncertainty (Macklem 2020; Poloz 2020; Kozicki and Vardy 2017). Of particular importance is the uncertainty about how the economy functions, including the possibility of strong nonlinearities that can pull the economy into "dark corners" (Blanchard 2014).[4]

In a risk management approach, central bankers systematically assess the implications of their policy choices across multiple economic models that depict alternative views of how the economy functions. They then choose a policy path that balances these considerations and include it as part of the base-case economic outlook. This shifts the policy-making focus from optimizing the policy path for the most likely future to explicitly addressing uncertainty and ensuring policy agility (Archer, Galstyan and Laxton 2022).

To facilitate this approach Bank staff will build variants of the workhorse model. Each variant will consider a change in one of the model's key features. At first, the variants will focus on alternative models of price-setting behaviour and different ways to model inflation expectations. Other variants will explore alternative depictions of the economy's supply side such as the labour market and production networks.

Specialty models will also be built to consider alternative plausible economic structures that are too complex to include in the core model or its variants. Examples include:

- models that focus on the interactions between monetary policy, financial vulnerabilities and the real economy
- models that explore uncertainties surrounding the macroeconomic implications of the transition to a zero-carbon economy

The rest of this paper is organized as follows. Section 2 outlines the model criteria and lessons learned from previous models. Section 3 discusses the new workhorse macroeconomic model for Canada. Some options for modelling inflation and the supply side of the economy are considered. Section 4 covers new tools to better support risk management. Boxes on selected topics provide more detail for interested readers.

## 2. Guiding principles and lessons learned

The Bank's long history of using models for projections and policy analysis has shown that a workhorse macroeconomic model needs to:

- provide a rich narrative about how the economy functions over a wide range of shocks
- include a central role for monetary policy and a rich monetary policy transmission mechanism
- provide a credible interpretation of history
- fit the data well and forecast out-of-sample at least as well as simple statistical benchmarks
- respond to the demands of the projection environment by:

[4] "Dark corners" are situations where the economy could badly malfunction. Examples include strong nonlinearities and multiple equilibria.

- being as simple as possible, without being too simple
- leveraging a wide variety of information and data
- delivering the required level of disaggregation
- being highly adaptable to shifting needs[5]

Based on these criteria, a recent assessment of the Bank's existing projection and policy analysis models shows the following:[6]

- LENS responds sensibly to demand shocks. ToTEM can tell a richer narrative about supply shocks, including cost-push shocks. At the same time, TOTEM's performance in some demand shocks, such as those emanating from foreign demand, is not as compelling as that of LENS.
- Inflation determination and the monetary transmission mechanism in LENS are simple and clear. ToTEM has a richer inflation narrative and monetary transmission mechanism. For example, inflation in ToTEM is linked directly to the production function of firms. It emphasizes firms' costs and desired markups in the consumption sector as the key determinants of consumer price index (CPI) inflation, rather than the economy-wide output gap. ToTEM also tells a compelling narrative about the impact of high household debt on the monetary policy transmission mechanism. On the downside, the infinitely lived rational expectations framework in ToTEM means that promises to change interest rates well into the future are highly substitutable with policy actions today.
- LENS does a good job at tracking the data in-sample during the global financial crisis and the 2014–15 oil price collapse (Bounajm et al., forthcoming). One notable exception is the behaviour of inflation during and immediately after the global financial crisis. However, since LENS is estimated on an equation-by-equation basis, the model shocks are difficult to interpret. ToTEM tells a richer story and its shocks are interpreted more easily. In some instances, however, the shocks in ToTEM reveal tensions between the model and the data. For example, the exchange rate in ToTEM is excessively sensitive to commodity price shocks. Furthermore, ToTEM fails to capture the degree of positive co-movement between Canadian and US consumption.
- In general, Bank projection models forecast on par with simple univariate statistical models, but there are notable exceptions (Beaudoin et al., forthcoming). For example, LENS's forecasts of core inflation over the 2008 to 2017 period are not as accurate as those of an autoregressive (AR) (2) model. Similarly, ToTEM and IMPACT do not forecast growth in real gross domestic product (GDP) (in Canada and the United States, respectively) as accurately as AR(2) models do.
- LENS's disaggregation helps with some aspects of storytelling in the projection environment. Its modularity makes it easier to adjust on the fly. Its ad hoc elements and incomplete sectoral structure can, however, lead to some internal inconsistencies. For example, LENS is based on a one-good model paradigm. To deal with commodity price shocks, the model adds an extra layer of reduced-form relationships. However, there are no equations in the model that ensure that commodity supply equals demand. This leads to internal inconsistencies. ToTEM's added structure ensures that it is internally consistent but, if the assumed structure is wrong in one

[5] See Gosselin and Kozicki (forthcoming) for a discussion about some of the challenges faced in constructing economic projections in real time.

[6] These results are based on the versions of IMPACT, LENS and ToTEM in the third quarter of 2021.

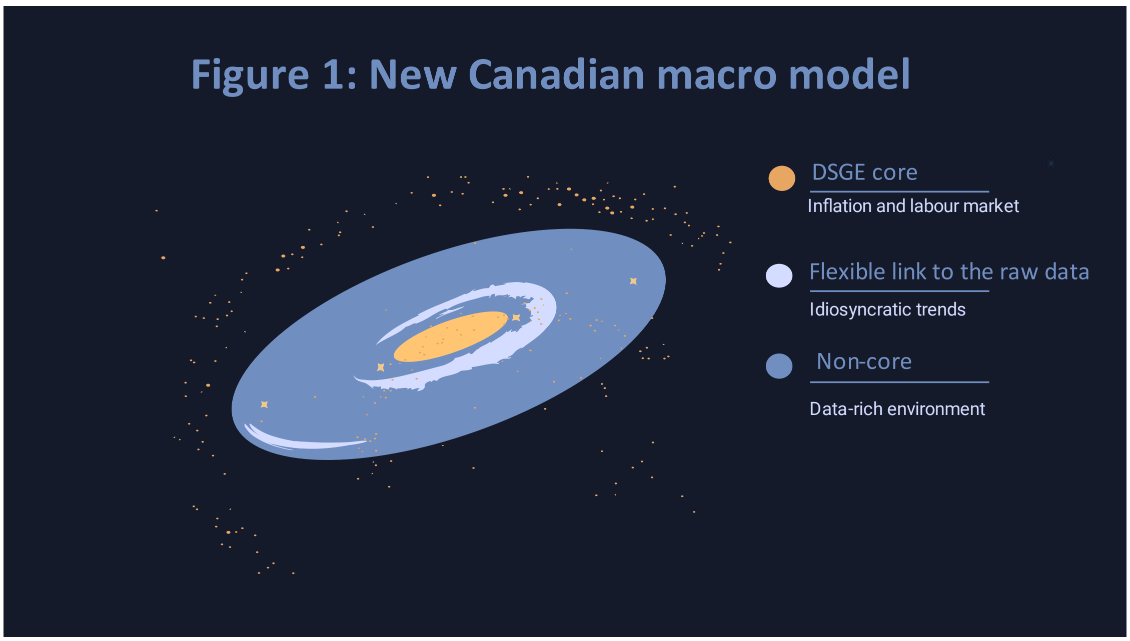
sector, then the entire interpretation of shocks and transmission channels can be affected. ToTEM lacks the same level of disaggregation and flexibility that LENS has.

## 3. A first look at the new workhorse model

The next generation workhorse macroeconomic model for Canada will build on the best attributes of the Bank's existing models. The model design follows the **"**Practical DSGE" philosophy (Canova 2019).

### The core model

The new model starts with a DSGE model at its core (**Figure 1**). The core embeds the fundamental macroeconomics that underpin the projection narrative. It features period-by-period optimizing behaviour by private agents based on assumptions about tastes, technology, information and market structure. For each sector in the model, supply and demand are clearly articulated. The model is estimated as a system, which makes it easier to interpret the shocks. The core model ensures internal consistency and a prominent role for general equilibrium features. In these respects, the new model builds on the key strengths of ToTEM.




The core model will be smaller than ToTEM or LENS. A smaller core model will be easier to understand and work with. It will also make it easier to bring the model to the data using the latest techniques. The core will model the high-level expenditure categories, their associated prices, the commodities sector, labour market and wages, consumer prices, monetary and fiscal policy and open economy elements such as foreign demand, import prices and the exchange rate.[7]

### Modelling inflation

Bank models, like those of other central banks and forecasters, have had notable difficulty accounting for the surge in inflation in the 2020s and its persistence. The focus of the NexGen project will be to

[7] To provide greater disaggregation, the new framework will use satellite models and modules as well as auxiliary forecasting equations coming out of the data-rich approach to model estimation (see the **Data rich and the non-core** section).

improve our understanding of inflation dynamics. This involves not only developing a better workhorse macroeconomic model but also being better equipped to quantify the risks around the inflation outlook. For NexGen, quantifying the risks will include systematically considering the implications of alternative models of inflation determination and the supply-side of the economy.

### *Inflation determination in the current models*

Core consumer price inflation in ToTEM is governed by a structural New Keynesian Phillips curve. ToTEM uses real marginal cost in the consumption sector as the measure of economic slack. It combines wages adjusted for productivity, the cost of capital, commodity prices and imported goods prices. Prices are sticky and follow the standard Calvo set up. Some firms behave in a forward-looking manner, while others follow a simple rule of thumb in the spirit of Galí and Gertler (1999). Inflation expectations are rational. Rule-of-thumb firms set prices to the inflation target or to lagged inflation. The model is nonlinear but is log-linearized for estimation and simulation purposes. All the data that enter ToTEM are de-trended outside of the model.

The core consumer price inflation Phillips curve in LENS is reduced-form but incorporates some elements of the micro-founded Phillips curve in ToTEM. Inflation is driven primarily by the economy-wide output gap, which is defined as the difference between output and potential output. Potential output is defined as the level of aggregate supply that could be produced in the economy without adding inflationary pressure. It is estimated outside of LENS. The Phillips curve also includes the price of non-commodity imports. Price-setting behaviour depends on forward-looking and rule-of-thumb firm behaviour. Inflation expectations are modelled as a function of survey-based measures, lagged inflation, model-consistent expectations and the inflation target. The Phillips curve in LENS is linear.

### *Firms' price-setting behaviour*

A number of alternative models of price determination are explored in this subsection for a possible role in the new core model or as one of its variants. For example, Harding, Lindé and Trabandt (2022a and 2022b) feature a convex structural New Keynesian Phillips curve. It is flat when inflation pressures are subdued and steep when inflation is elevated. The convexity arises due to a kinked demand curve for goods produced by firms. Profit maximization implies that, in response to changes in marginal cost, firms change their prices by more when inflation is high and by less when it is low.[8] The authors show that the convex Phillips curve can simultaneously account for both the mild drop in inflation following the global financial crisis and the sharp rise in inflation in the 2020s in the United States.

Another option is the approach taken in Gasteiger and Grimaud (2023), who also generate a convex price Phillips curve. They do so by introducing an endogenous and time-varying Calvo share into a trend inflation New Keynesian model. Rather than resetting prices at random intervals, firms update their prices optimally when expected benefits outweigh expected costs. In this framework, firms change prices more often during expansions and less often during recessions.[9]

[8] Firms are reluctant to change prices much when their marginal cost is low and their markup is high. This occurs because lower prices do not crowd in much extra demand. In contrast, when their marginal cost is high and markups are low, firms have a large incentive to increase their prices. This is true even as higher prices result in a large drop in demand. The concavity of marginal revenue resulting from the rising elasticity of demand as a function of price is key to the asymmetric pricing behaviour (Harding, Lindé and Trabandt 2022a and 2022b).

[9] St-Cyr (2018) provides a summary of the empirical literature that considers a nonlinear relationship between excess capacity and inflation.

Since 2021 many central banks have stressed the joint role played by both persistent increases in input costs and excess demand in boosting inflation. Yet, excess demand plays no direct role in the workhorse New Keynesian models. Under the typical assumption of constant elasticity of substitution preferences, variations in aggregate consumption shift the firm's profit function up and down, but they do not influence its curvature. As a result, the optimal markup is not a function of demand. Murchison (forthcoming) proposes an alternative structure based on non-homothetic household preferences over varieties of consumption goods. Specifically, the elasticity of substitution between goods is state-dependent, declining during periods of strong consumption and rising during periods of weak consumption. This captures the possibility that consumers are less price-sensitive during economic booms and more price-sensitive during downturns. These substitution effects in turn give the firm an incentive to adjust its markup in response to consumption demand. Overall, this generates procyclical desired markups while making observed markups less countercyclical (or procyclical) in the presence of nominal price rigidity.

### *Inflation expectations*

In most modern macroeconomic models, economic agents are assumed to have rational expectations. They have an infinite planning horizon and perfect knowledge of the model economy, including a common understanding of the shocks at play. Agents understand the role of the central bank and fully believe its commitment to the inflation target. In this specification, inflation expectations converge to the target when the central bank's actions respect its policy rule.

The Bank's projection models go one step further. To match the 20 years of inflation data preceding the COVID-19 pandemic, Bank models require a large role for the inflation target and a relatively flat Phillips curve. In LENS, the inflation target appears with a significant weight in the determination of inflation expectations. In ToTEM, rule-of-thumb price setters set their rate of price increases equal to the inflation target. In either case, inflation is "hard-wired" to the target. As a result, the impact of shocks to inflation tend to fade quickly without significant policy actions—a free lunch exists.

Behavioural macroeconomists have questioned the realism of the rational expectations framework and have introduced systemic ways to deviate from full rationality. Some form of bounded rationality will be an important ingredient in the new workhorse macro model. It will have important implications not only on the behaviour of inflation but also on many other key macro variables as well as the resulting monetary policy prescriptions.[10] For example, bounded rationality addresses the forward guidance puzzle ( Del Negro, Giannoni and Patterson 2023) inherent in many DSGE models.[11]

A few different approaches have been suggested in the literature. Gabaix (2020) modifies a standard New Keynesian model under the assumption that agents do not fully understand their world. His approach leads to a straightforward modification of the New Keynesian model that adds an over-discounting parameter to all the standard expectations terms. This includes real marginal cost in the Phillips curve. Wagner, Schlanger and Zhang (2023) provide a quantitative assessment of the

[10] In a series of papers Kozicki and Tinsley (2001a, 2001b, and 2005) model imperfect monetary policy credibility and learning in an empirical macro model. Murchison and Rennison (2006) address imperfect monetary policy credibility in ToTEM through a simple learning model, as in Erceg and Levin (2003).

[11] Semi-structural models have dealt with this problem through over-discounting.

macroeconomic impacts of alternative monetary policy regimes using this approach. Chen et al. (2023) feature this approach in an estimated open economy DSGE model.

Woodford (2018) combines some elements of both forward-looking and backward-looking behaviour. In this model, decision-makers form rational expectations up to a point, reflecting their cognitive capacity. Empirical work suggests the horizon turns out to be relatively short, at under two years. Decision-makers then use a coarse value function based on their past experiences to evaluate situations beyond that point. This work suggests that households update their beliefs slowly. This allows the model to explain persistent trends seen in many key macroeconomic variables, including inflation. It also helps explain the significant output costs of disinflation without resorting to price-indexation contracts tied to lagged inflation.[12] Gust, Herbst and López-Solido (2022) deem it a promising framework for explaining aggregate data and analyzing monetary policy.

Another option is to assume limited information and learning, as in Hommes and Lustenhower (2019) and Ozden (2021). Some agents form inflation expectations rationally. Others are less sophisticated and learn about inflation based only on lagged inflation. The addition of these types of agents is based on evidence from laboratory experiments that study how people forecast inflation (e.g., Mankiw et al. 2003; Assenza et al. 2014; Pfajfar and Žakelj 2018; Kryvtsov and Petersen 2021). The share of each type of agent moves endogenously with its relative forecasting accuracy. As a result, the persistence of both inflation expectations and inflation becomes endogenous and inflation expectations can become de-anchored without a sufficiently aggressive policy response. This is an example of how adding greater heterogeneity of agents into models can help provide new insights (**Box 1**).

This mechanism has been included in an alternative version of ToTEM. The model has been used to quantify the costs of insuring against the de-anchoring of inflation expectations as well as to explore a scenario in which inflation expectations become de-anchored (Bank of Canada 2022).

Other inflation modelling options such as k-level thinking and rational inattention have also garnered increased interest in academic and policy-making circles.[13] Beaudry, Carter and Lahiri (2022) introduce a model of price and wage determination that features the possibility of wage-price spirals. One of their main findings is that the optimal policy response to supply shocks varies dramatically depending on whether expectations are rational, adaptive or based on k-level thinking. Under rational expectations, it is always optimal to fully look through supply shocks. Under adaptive expectations, policy-makers never fully look through supply shocks, but their optimal degree of look-through is constant.

In contrast, optimal policy under k-level thinking is discontinuous: as long as past inflation is below some threshold, it is optimal for central banks to mostly look through supply shocks. However, once past inflation exceeds the threshold, it becomes optimal for central banks to abandon this look-through policy in favour of aggressive tightening. Intuitively, this is because k-level thinking makes inflation expectations partly a backward-looking function of past inflation and partly a forward-looking function of the central bank's announced policy stance. Pressures associated with the backward-looking component are manageable when past inflation is close to target. This leaves policy-makers with lots of room to look through supply shocks without worrying about a de-anchoring in expectations. However,

[12] See Woodford and Xie (2022) for an application to the question of policy options at the effective lower bound.
[13] Under k-level thinking, firms and households form expectations based on an assumption about the degree of rationality of others.

## Box 1: Endogenous heterogeneity

ToTEM III includes several types of households. But the share of each type of agent is exogenous and fixed. Endogenous heterogeneity is when the share of different types of agents changes with economic circumstances. It is a powerful device to introduce in macro models, but it can add a significant amount of complexity.

Heterogeneous agent models feature households (or firms) that differ in dimensions such as income or wealth. The heterogeneity impacts aggregate economic fluctuations. In turn, aggregate fluctuations shape the heterogeneity. This class of models has become increasingly relevant for the study of monetary policy. Alves et al. (2022) provide a comprehensive review of recent advances. Bank staff have been very active in this field. See, for example, Acharya and Dogra (2020), Acharya, Challe and Dogra (2021) and Djeutem et al. (2022). Bank staff have also made considerable progress using microdata to look at household heterogeneity in Canada. For example, see Bilyk, Chow and Xu (2021) and MacGee, Pugh and See (2022).

Two-agent New Keynesian (TANK) models provide useful insights into monetary and fiscal policy. But going beyond a TANK model involves considerable challenges. Problems related to the data, solution technicalities and computational needs require addressing. Recent advances suggest that much progress is likely over the next five years. In the near term, however, the focus will remain on using small heterogeneous agent models to help answer specific questions.

Nonetheless, staff will likely include some endogenous heterogeneity in the next generation of policy macro models. For example, the Bank's Financial Stability Department has developed a model in which some households face an occasionally binding leverage constraint related to their mortgage loan-to-value ratio (Harding and Duprey, forthcoming). In a positive shock to house prices, the leverage constraint may no longer bind for some households. As a result, these agents will behave more like optimizing borrowers. The change in behaviour is important for the macroeconomy and for the conduct of monetary policy. The sensitivity of the economy to monetary policy decreases as the share of optimizing households rises.

Emenogu, Hommes and Khan (2021) use a model based on Bolt et al. (2019) with endogenous heterogeneity in house price expectations to study the Canadian housing market. Some agents expect house prices to converge toward fundamentals. Others are trend followers, believing prices will further deviate from fundamentals. The shares of these two types of households depend on the past performance of the competing forecasting strategies. This approach determines whether house prices are in a mean-reversion regime or in a temporary explosive regime. Ozden (2021) uses the same approach to model inflation expectations and policy credibility.

Another class of models that incorporates insights based on heterogeneity is agent-based models. Agent-based models have been used at the Bank for financial stability analysis for some time. See, for example, HRAM and HRAM 2.0. The latter is from MacGee, Pugh and See (2022). Bank staff also built a behavioural agent-based macro model for Canada (Hommes et al. 2022). This model is one of the specialty models featured in section 4.

past inflation outcomes sufficiently above target lead to a situation where a pivot in the policy stance is needed to avoid de-anchoring.

## Modelling the supply side

### *The labour market*

The labour market is a key element of the economy's supply side. In ToTEM it plays a central role in determining real marginal cost and inflation. ToTEM focuses on the intensive margin—total hours worked. Wages, interpreted as labour compensation per hour worked, equate the marginal product of labour with the marginal rate of substitution between consumption and leisure. The modelling of wages also reflects nominal wage rigidities, staggered wage-price setting and market power in the labour market. Market power in the labour market, which stems from specialized labour supply, implies a positive wage markup on average.

A priority for the new core model is to introduce the notion of an extensive margin—the level of employment, the labour force and the unemployment rate. Another priority is having more accurate forecasts of wage growth. Modelling of wages has been identified as an area that requires improvement relative to that in LENS and ToTEM.

One way to model unemployment is as in Galí, Smets and Wouters (2011). The number of hours worked by the representative household in the standard model gets reinterpreted as variations in the number of people working. Cast this way the model determines the equilibrium level of employment, the labour force and the unemployment rate.[14] Unemployment in the model results from the presence of market power in the labour market, which is reflected in positive wage markups. Fluctuations in the unemployment rate come from variations in the average wage markup due to the presence of nominal wage rigidities. The modelling of wages is consistent with that in ToTEM except that it is interpreted as compensation per worker rather than per hour.

Another alternative that could allow for a deeper examination of the labour market is a search and matching model (Mortensen and Pissarides 1994). A recent example worth investigating more closely is Guerra-Salas, Kirchner and Tranamil-Vidal (2021) who introduce search and matching frictions into the Central Bank of Chile's DSGE model for projections and policy analysis.

Unemployment results from the frictions preventing job-worker matches in a decentralized labour market. Employment is driven by employee turnover and the cost of hiring, with hiring more difficult when the labour market is tight. Firms post jobs at a rate that equates the marginal cost of a posting to profits lost from leaving the job vacant. In this framework, labour market tightness is measured by the vacancy-to-unemployment ratio.[15]

Wages are interpreted as quarterly salaries and are assumed to be sticky, as in ToTEM. Wages are set through Nash bargaining, which maximizes the common surplus of firms and workers generated by newly created jobs. This surplus is divided according to the bargaining power of both sides. Workers have more bargaining power if they are harder to replace or if it is easier for them to find other jobs. Average hours worked adjust until the marginal rate of substitution between consumption and leisure equals the marginal product of labour of an additional hour worked.

The experience with labour search and matching frictions in central bank projection models has been mixed. Staff at the Central Bank of Chile have found that introducing search and matching into their model helps it better fit labour market developments and other macroeconomic data. It also forecasts better out-of-sample. In contrast, in Sveriges Riksbank's new model MAJA (Corbo and Strid 2020),[16] staff

[14] The labour block in LENS reflects some elements of this approach.

[15] Several recent empirical papers have emphasized the usefulness of the vacancy-to-unemployment ratio as an indicator of labour market tightness. For example, see Bernanke and Blanchard (2023).

[16] MAJA is an acronym for the Swedish "Modell för Allmän Jämviktsanalys," which means "Model for General Equilibrium Analysis."

moved away from the added complexity of a labour market search and matching model in favour of the simpler approach in Galí, Smets and Wouters (2011).[17]

Recently, Benigno and Eggertsson (2023) have developed a New Keynesian model with search and matching frictions in the labour market complemented by a form of downward nominal wage rigidity. The authors show that a very tight labour market and strong nonlinearities in this model can help explain the surge in US inflation in the 2020s.

### *Production networks*

Relative to its predecessors, ToTEM represents a major advance in terms of modelling the supply side of the economy. It includes a multi-stage production process. In the first stage, intermediate goods are produced by identical, perfectly competitive firms using capital, labour, commodities and imports as production inputs. In the second stage, monopolistically competitive firms produce both final goods and manufactured inputs using intermediate goods and a composite of manufactured inputs. Including multiple stages of production in the model adds strategic complementarities to the pricing decisions of producers and increases the sluggishness of aggregate real marginal cost. This helps the model better match the typical pattern in aggregate output and inflation.

But the production network in ToTEM is highly stylized and does not have the granularity required to analyze the impact of sectoral shocks. In recent years, a new branch of the literature has added realistic production networks to macro models to better understand how shocks to individual sectors could permeate throughout the economy. For example, Smets, Tielens and Van Hove (2019) build a multi-sector DSGE model that features an input-output production network and heterogeneous price stickiness of sectors. The model also accommodates both producer and consumer prices. The authors estimate the model for the United States and show that sectoral events and "pipeline pressures" are key sources of volatility in sectoral and headline inflation and a material source of inflation persistence.

Interest in this line of research surged through the pandemic. Motivated by the impact of supply chain disruptions, Afrouzi and Bhattarai (2022) build a model where production across several sectors has input-output linkages. The authors simulate the impact of a negative total factor productivity shock on the computers and electronics industry. The network structure propagates the impact of the shock by increasing the costs and prices of downstream sectors. In these sectors, prices rise and demand declines as production falls. This leads to a much bigger and more persistent overall inflation response than the increase predicted by the expenditure share of the computers and electronics industry.

Bank staff have also been exploring this line of research. To study the impact of commodity price shocks, Cao and Dong (2020) build a model with nominal rigidities and input-output linkages across eight intermediate sectors of the Canadian economy: commodity; construction; utility; manufacturing (three sectors); wholesale, retail, transportation and warehousing; and other services. In the model, each sector's production requires a capital-labour bundle and an intermediate input bundle. The intermediate input bundle is in turn aggregated from domestic and imported goods. Each sectors' output is used toward consumption, investment, exports and supplying intermediate inputs to the rest of the economy. The production network is calibrated based on input-output tables. The authors demonstrate that complex adjustments to commodity price shocks take place not only through resource reallocation,

[17] Swarbrick and Zhang (forthcoming) introduce a labour market model with search frictions in a smaller version of ToTEM—B-ToTEM (Lepetyuk, Maliar and Maliar 2017).

currency movements and monetary policy response, but also importantly through the production network.

Including a production network in the new core model will allow for a more careful consideration of sectoral supply shocks on the macroeconomy. This could be useful for understanding the implications of a reconfiguration of supply chains, geopolitical shocks and the transition to a zero-carbon economy.

### *Other considerations*

Other important supply-side considerations that merit further investigation include hysteresis effects in unemployment or productivity growth. The impact of climate change and the transition to net-zero emissions are also important. These are discussed in the context of stand-alone specialty models in section 4.

## A flexible bridge to the raw data

Estimating DSGE models is challenging. For example, the models are not designed to explain all the trends evident in the data. The current approach for dealing with this in ToTEM is to pre-filter the data in order to remove the trends. But pre-filtering can lead to important biases in the parameter estimates of the structural model as well as pose additional challenges in forecasting.

To address this issue, the new model will be estimated using an approach suggested in Canova (2014). Building on work by Cayen, Gosselin and Kozicki (2009), Canova jointly estimates a structural model and a flexible non-structural link between the model and the raw data. This approach permits various time-series patterns for non-model-based components, including idiosyncratic trends. Thus, the approach picks up movements in the raw data that the structural model cannot explain. Controlling for the unexplained aspects of the data this way helps ensure the accuracy of model parameter estimates. It also allows model-based and non-model-based components to jointly appear at all frequencies of the spectrum.

By jointly estimating the parameters that govern the trends and cyclical dynamics, the new model can be estimated on data in levels, rather than gaps. This model feature builds on of one of the key strengths of the Bank's current semi-structural models LENS and IMPACT.

Another issue when trying to properly account for trends in the data is accounting for the influence that trend fluctuations have on business cycle dynamics. This can be accomplished by modelling the trends as stochastic. Canova's (2014) approach can be applied to models featuring transitory or both transitory and permanent shocks.

The Canova approach also naturally allows for tests of the structural model's fit. Ideally, most of the fluctuations in the macroeconomic data over the business cycle should be explained by the structural model and not by the flexible non-structural link. At each step, the core model will be estimated together with the flexible bridge to the raw data. As the development process continues, the model increases in complexity and size until the fit of the core model begins to deteriorate. At that point, the core structural model is complete. Other sectors will be modelled outside of the core.

## Data-rich and the non-core

While building on the strengths of its predecessors, the new workhorse macroeconomic model departs from the Bank's current models in important ways. For example, the new model will be estimated using data-rich techniques.

Sargent and Sims (1977), Stock and Watson (1989; 2003; 2009; 2011) and Bernanke, Boivin and Eliasz (2005) show that large datasets can hold valuable information for identifying unobserved common factors that are useful for forecasting the economy. Leveraging this work, Boivin and Giannoni (2006) propose an empirical framework for the estimation of DSGE models that exploits the relevant information from a data-rich environment. Del Negro and Schorfheide (2012) augment their estimation of a DSGE model with some extra external information from surveys. Gelfer (2019 and 2021) builds on these earlier works and shows how medium-sized structural models can be estimated using lots of informative data that do not explicitly appear in the model.

Sectoral indicators, foreign and financial variables, inflation expectations, as well as measures of sentiment and uncertainty have proven to be fruitful in other applications. Multiple data sources that measure the same model concepts (i.e., multiple wage and inflation measures) have also proven to be informative.

The relevant data are brought to bear on model estimation by adding reduced-form equations linking the data to the model observables and the structural model. The system is then estimated simultaneously. The data-rich approach has been shown to improve the precision of the estimates of the structural parameters and latent variables, such as potential output or real marginal cost, and lead to more intuitive model properties.

For forecasting, the reduced-form equations can be included as part of the model's non-core. Gelfer (2019 and 2021) has shown that data-rich techniques enhance forecasting performance and support a more agile projection environment in which forecast details can be added or dropped relatively easily (**Box 2**).

Potential disadvantages are also associated with the approach. For example, the economic narrative can be more difficult to form when non-core elements are included in the forecasting exercise.

### Satellites and modules

Other areas of the economy outside the core model can also be explored more deeply in satellite models or modules. For example, assume that the workhorse model includes a rudimentary representation of fiscal policy. A satellite fiscal model can be developed to provide greater detail about fiscal variables. But satellite models typically don't feed back into the core model. A more sophisticated fiscal module could, however, feed back to the core model. Modules can be developed using a semi-structural approach or vector autoregressions.

## Box 2: Advantages of data-rich techniques

**More precise estimates of model coefficients and latent variables**

- Estimating structural models with data-rich techniques reduces standard errors of the coefficient estimates of the structural models.
- Rich data can play an important role in the estimation of latent variables, given the considerable difficulty associated with pinning down potential output and r*, for example. Beaudoin et al. (forthcoming) document the importance of revisions to potential output in out-of-sample forecast errors.

**Improved model properties and forecasting ability**

- Gelfer (2019) shows that, for many variables, the Federal Reserve Bank of New York's DSGE model estimated using data-rich techniques can out-forecast the model estimated using standard techniques as well as the Survey of Professional Forecasters. Gelfer publishes the most recent forecasts on this website.
- Gelfer (2021) shows that the forecasting performance of a conventional open economy DSGE model estimated using a data-rich approach outperforms both the model estimated using standard techniques and Bank of Canada staff forecasts for gross domestic product, consumption, investment and trade.
  - Including a large amount of global macrofinancial data helps identify global shocks and strengthens international spillovers in the model—a noted challenge for ToTEM.

**A more agile projection environment**

- Additional forecast detail can now be easily added and dropped, as needed, without having to rederive the model's core structure. For example, there may be interest from time to time in exploring disaggregated forecasts of exports or consumption or alternative forecasts of a wide array of labour market indicators.

**Better positioned to explore the potential benefits from recent advances in machine learning**

- Advances in machine learning have proven to be quite fruitful for harnessing the power of large datasets for forecasting in other disciplines.
- The next step in using data-rich techniques is to explore the possibility of using big data and machine learning to help parameterize structural macroeconomic models and improve forecasting ability.

# 4. Risk management

Central bankers are keenly aware of the challenges they face from uncertainty, including in the use of forecasts.[18] Consequently, it is common practice to regularly consider the impact of risks around the base-case outlook.

Risk analyses usually involve assessing the monetary policy implications of a wide range of exogenous shocks. In practice, these risks have been typically analyzed in the context of linear models in which inflation expectations are "hardwired" to the inflation target. It's a friendly environment for central banks where the implications of policy errors are mitigated by the way in which inflation expectations are formed.

The innovation here is to address, more explicitly, uncertainty about how the economy functions. This includes the impact of possible nonlinearities that can pull the economy into "dark corners." Examples

[18] Evans et al. (2015) review the minutes of the meetings of the Federal Open Market Committee for evidence that the committee appealed to uncertainty to justify positioning the funds rate at a different level than implied by the staff forecasts alone. Of the 128 minutes reviewed, 31 included an appeal to uncertainty, while 14 cited insurance against adverse outcomes as an important consideration in the stance of policy. See also Bullard (2021), Galstyan (2022), Hawkesby (2021), Macklem (2020), Poloz (2020), Evans (2019) and Powell (2018).

include models that feature endogenous monetary policy credibility, a state-contingent Phillips curve, financial vulnerabilities, climate change or extreme events like wars, natural disasters and pandemics.

In a risk management approach, central bankers give weight to different model economies.[19] They then choose a policy path that balances these considerations and include it as part of the base-case economic outlook. This shifts the policy-making focus from optimizing the policy path for the most likely future to ensuring policy agility.

For example, consider the rise in inflation in early 2021. The initial view was that it would be temporary and that high credibility would allow central banks to look through it without raising interest rates. A risk management approach also puts weight on the possibility that, if left unchecked, long-term inflation expectations would become de-anchored from the inflation target, necessitating an aggressive policy response. A policy path is then chosen that balances the risks presented by the alternative views. As new data come in, policy-makers could adjust their assessments of the relative probabilities and set policy accordingly.

The world economy appears in store for a period of heightened uncertainty from supply shocks due to geopolitical risks, potential deglobalization and climate change.[20] Having a set of tools in place to help policy-makers deal with these and more familiar sources of uncertainty would be helpful.

## Variants and specialty models

As part of the risk management approach, several alternative models of the economy will be used to examine key uncertainties—this will include variants of the workhorse model and distinct specialty models (see **Figure 2**). New projection infrastructure will facilitate their use.

Each variant of the workhorse model will consider a change in one of the model's key features. The first priority will be on alternative models of price-setting behaviour and different ways to model inflation expectations. For example, if the core model includes inflation expectations hardwired to the inflation target, then one of the variants should consider endogenous policy credibility. The second priority will be to explore alternative depictions of the economy's supply side. This will include alternative models of the labour market.

Specialty models will also be built to consider other plausible economic structures that are too complex to include in the core model or its variants. This will include models that allow for interactions between monetary policy, financial vulnerabilities and the real economy. Other models will focus on the macroeconomic implications of climate change or on the conduct of monetary policy in and around the effective lower bound of the policy interest rate.

Staff can run a projection using the specialty model with its added complexity dialed down. The added features of the specialty model can then be fully activated, and the projection re-run. The marginal implication on policy interest rates can then be used as an approximation of the impact of the specialty models on the base-case policy advice.

The following discussion outlines some potential specialty models.

[19] It is also possible to incorporate a moderate amount of aversion to ambiguity if policy-makers are particularly adverse to making large errors (Cateau 2006; Cateau 2007; Küster and Wieland 2005).

[20] See Jordan (2022) and Schnabel (2022).

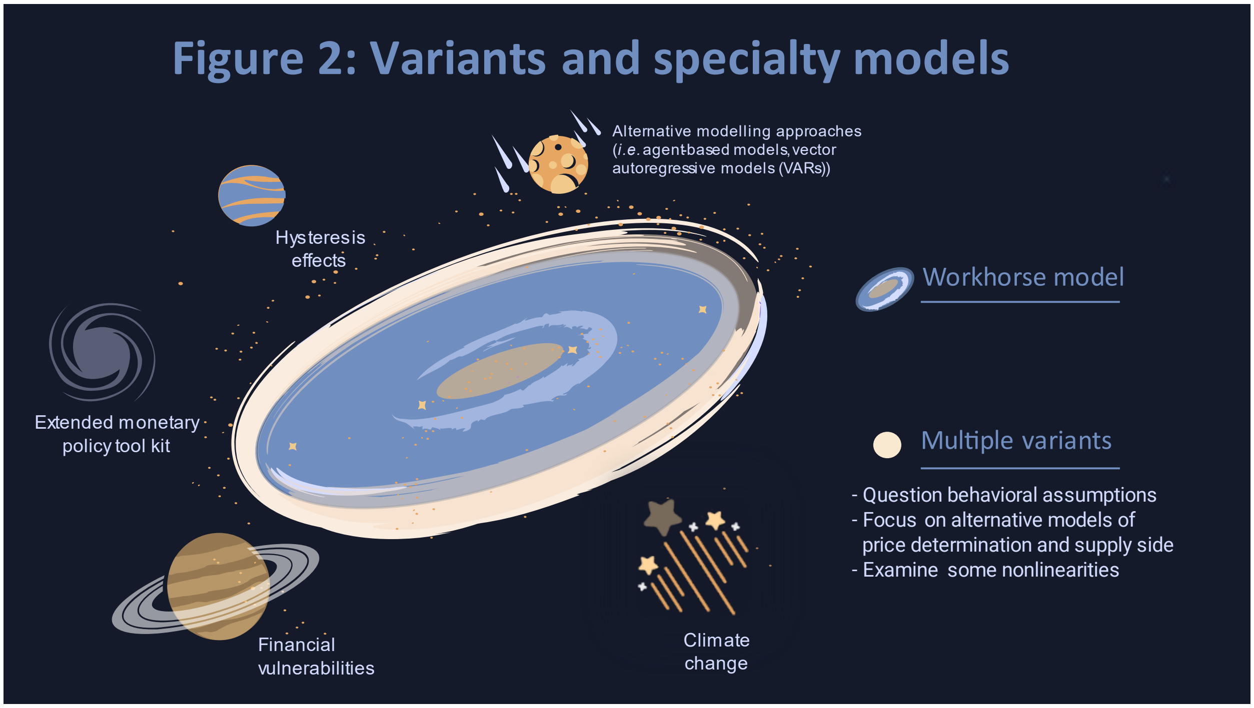



Figure 2: Variants and specialty models

## Financial vulnerabilities

The next generation of models should better capture the links between monetary policy, financial vulnerabilities and the real economy. The ultimate objective is to operationalize an economic model that articulates the mechanisms at play behind empirical growth-at-risk models (Beaudry 2020). These models capture an intertemporal trade-off between the mean and the tail of the distribution of GDP growth. See Duprey and Ueberfeldt (2020) for an application to Canada.[21] An economic model along these lines would allow us to more deeply explore endogenous crises and the interactions between macroprudential and monetary policies.

A substantial literature suggests monetary policy affects the economy and financial system through endogenous risk taking (Borio and Zhu 2012) and a financial vulnerabilities channel (Adrian, Covitz and Liang 2014). The risk-taking channel of monetary policy (Rajan 2005) refers to monetary policy's impact on the perception and pricing of risk by economic agents. All else being equal, lower interest rates, given financial frictions, lead to greater risk taking. This, in turn, can set off a financial cycle that supports economic activity in the near term but eventually leads to an economic downturn. Moreover, the greater the risk taking in the financial system and economy, the higher the sensitivity to adverse shocks—the vulnerabilities channel.

Multiple micro foundations support this narrative. The value-at-risk constraint in financial intermediaries and the resulting leverage cycle are featured in the New Keynesian Vulnerability model developed by Adrian and Duarte (2016). Similar dynamics can also be generated through certain departures from

[21] At this point, practitioners, including the Bank, rely on a reduced-form growth-at-risk framework. It is a nonlinear quantile model that uses the state of financial vulnerabilities to predict the distribution of GDP growth several years ahead. Staff often use this model to assess how tail risks evolve over time or how monetary or macroprudential policy choices impact tail risks.

rational expectations. Some researchers have argued that mixed adaptive and rational house price expectations can generate boom-bust cycles in housing markets. See Gelain, Lansing and Mendicino (2013), Granziera and Kozicki (2012) and Emenogu, Hommes and Khan (2021).

The Bank's Financial Stability Department is working on a new modelling framework, called NEXUS, that features heterogeneity and nonlinearities to focus on macrofinancial vulnerabilities associated with housing and indebtedness in a general equilibrium model.[22] It will be particularly useful for capturing interactions between financial vulnerabilities and monetary policy.

Staff have also developed specialized models to study macroprudential policy in Canada's housing market and its interaction with monetary policy. See Alpanda, Cateau and Meh (2018), Allen and Greenwald (2021) and an extension in Emenogu and Peterson (2022).

### Climate change, the transition to net zero and its interactions with monetary policy[23]

Climate change and the transition to net-zero carbon emissions will have important macroeconomic implications in Canada, where energy production represents about 10% of GDP. Moreover, Canada's cold climate, dispersed population and large industrial base makes its energy intensity the second highest among members of the Organisation for Economic Co-operation and Development.

Transition channels to the macroeconomy are complex. To properly capture them requires a suite of models and enhancements to current tools. Staff have brought in the G-cubed model (McKibbin and Wilcoxen 1995), which could help capture additional sector detail associated with the transition. It could also be used to model a broader set of policy actions in addition to carbon pricing and investment tax credits.

While G-cubed will help address some modelling challenges, key gaps remain. The plan is to exploit the sectoral coverage of G-cubed and the business cycle frictions of ToTEM. In addition, we propose introducing some enhancements to ToTEM, including the addition of green-energy production. Other improvements are also needed, including modelling labour market frictions and investment decisions and introducing uncertainty related to the speed of the transition. These will overlap to some degree with the Bank's broader modelling priorities discussed in this paper. Specifically, the addition of search and matching frictions in the labour market will add additional realism to the climate scenario but could also be used in the next generation of projection models. Similarly, by going beyond the simple adjustment cost model of business investment used in ToTEM to allow for time to build lags, irreversible investment and uncertainty effects would allow future models to better capture the procyclicality of investment and its correlation with consumption.

[22] For example, see Alves et al. (2022) and Kuncl and Ueberfeldt (2021). See also Duprey and Harding (forthcoming). Moreover, Bank staff have developed a suite of semi-structural (Tuzcuoglu 2023), reduced-form and agent-based models (MacGee, Pugh and See 2022) to support the analysis.

[23] This section was written by Stephen Murchison.

### Extended monetary policy tools

The effective lower bound on the policy interest rate is another form of nonlinearity in the economy. It will be included as part of the workhorse model, but the modelling of the extended monetary policy tools in the workhorse model will be kept as simple as possible.

For this reason, a specialty model that focuses on the limitations, potential interactions and unintended side effects of a wide range of extended monetary policy tools is needed. Other major central banks already follow a similar approach. This specialty model could draw on some important papers in the literature.

Sims and Wu (2021) study quantitative easing (QE), forward guidance and negative interest rate policy in a unified framework. QE works by relaxing funding constraints on financial intermediaries. This, in turn, leads to an improvement in credit supply. The authors introduce negative interest rates in the model through a reserve requirement, which allows the policy rate and the deposit rate to deviate.[24] The size of the central bank balance sheet matters importantly for policy effectiveness. Sims and Wu (2021) also include, in a reduced-form way, imperfect credibility for studying the impact of forward guidance. This allows the authors to include a signalling channel motivation for QE.[25]

Wu and Xie (2023) extend the model to incorporate agent heterogeneity. Hashmi and Nsafoah (2021) extend the model to an open economy setting and calibrate a two-country version to Canada and the United States. Additional insights on the international dimension of QE can be gleaned from Alpanda and Kabaca (2020).

### Hysteresis effects

Another important supply-side issue is possible hysteresis effects. The idea is that the long-run evolution of the economy depends on the shocks it faces and policy-makers' responses. Modelling hysteresis is highly complex because it involves multiple equilibria.

One stream of this research focuses on total factor productivity and output (see Elfsbacka, Schmöller and Spitzer 2021). Hysteresis effects occur endogenously because recessions reduce firm profits and expected gains from investment in research and development and adoption of technology. This mechanism leads to deeper and longer-lasting recessions.

Other related work looks at hysteresis effects coming from the labour market. The idea is that long spells of unemployment cause workers to lose skills and become increasingly costly to retrain. For a recent example in the context of a structural model, see Acharya et al. (2022). Staff have also developed a version of LENS that incorporates very persistent rather than hysteresis effects in the labour market after long spells of unemployment, following the approach suggested in Delong and Summers (2012).[26]

Adding hysteresis effects should help slow the rapid rebound in GDP after shocks, a feature that was evident in the event study using LENS and ToTEM (Beaudoin et al., forthcoming). Hysteresis effects also mean that monetary (and fiscal) policy becomes non-neutral over the medium term. Policy can mitigate scarring effects on the economy by responding aggressively to shocks. Having a model that includes

[24] The model will need to be adapted to better fit the Canadian financial system.

[25] A similar strategy is followed in Coenen, Montes-Galdón and Schmidt (2021).

[26] The impacts in LENS are not technically hysteresis but instead lead to a long departure from steady state.

hysteresis effects could be quite valuable, particularly when faced with large and persistent shocks to economic activity.

### Other types of models

Specialty models could also include fundamentally different approaches to modelling the economy. For example, Hommes et al. (2022) build a behavioural agent-based model for Canada. It combines detailed Canadian input-output tables with learning and decision heuristics for characterizing the behaviour of heterogeneous firms and households. A detailed production network features important nonlinearities that can magnify the impact of shocks. Learning and behavioural heuristics also propagate the shock through the economy. Firm-level response can be analyzed in terms of sector averages and distributions. This new model provides useful insights into how sector-specific cost shocks impact overall inflation and GDP in Canada in a dynamic setting.

Another example is a time-series model. Several central banks run vector autoregressions (VARs) as a check on their main model results. The NexGen project includes the development of a VAR that will be used to help assess and validate the empirical properties of the new model. The VAR can also be used to generate forecasts.

## A platform for alternative scenario analysis

Better support of a risk management approach to monetary policy requires Bank staff to be able to efficiently and accurately:

- estimate and simultaneously run multiple models (the NexGen model, its variants and specialty models)
- analyze and communicate output from multiple models
- optimize the base-case policy path in the presence of model uncertainty

These steps need to be done on a relatively short timeline and in a way that can be easily maintained going forward. This requires an upgrade to the current modelling and projection platform, which focuses on producing a base case using a single model.

The new infrastructure will have a modular and scalable architecture. It will take advantage of the Bank's parallel computing capacity to improve efficiencies. And it will feature greater automation, improved visualization and more easily sharable reporting. Several features will be added to help support a risk management approach to monetary policy.

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