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A macroprudential approach to compound climate risks

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Summary

Climate change is often characterised as a standalone risk for the financial system. In practice, however, the emergence and materialisation of climate-related shocks interact with general macro-financial conditions, implying potentially novel and difficult-to-predict interactions. In such an environment, macroprudential buffers earmarked for specific risks have limitations, as they might not account for important correlations between climate-related shocks and other sources of financial vulnerability, nor for the extent to which climate-related shocks might compound existing challenges in the real economy and financial sector. In light of such complex challenges, this report investigates how a holistic approach can enhance the financial system's ability to absorb compound shocks. It finds that consolidated capital buffers accounting for the amplifying effects of combined shocks, which single-risk buffers might underestimate, offer general insurance against several sources of uncertainty (both reducible and irreducible).

- **Climate-related shocks will not occur in isolation but will unfold within existing macro-financial conditions and vulnerabilities.** Their interaction with other stressors — such as recessions, asset price collapses and geopolitical tensions — can give rise to complex constellations of shocks. This dynamic can generate compound economic and financial losses from the direct interaction of shocks and through their amplification via financial sector interconnections and feedback loops between the financial system and the economy. Losses from compound risks impact financial institutions and the system as a whole.
- **Macroprudential capital buffers can strengthen the financial system's resilience to compound risks.** They expand the banking sector's capacity to absorb unexpected losses beyond those covered by individual institutions' loss provisions and standing capital requirements, which is particularly relevant for compound losses amplified by financial interconnections and feedback loops with the economy. In this way, macroprudential capital buffers can constitute a system-level provision against losses from 'severe but plausible' combinations of heightened climate shocks and fragile macro-financial conditions and associated undiversifiable systemic vulnerabilities.
- **In this context, taking a holistic view of prospective losses — capturing various sources of interactions and amplification — may offer significant advantages.** The current practices across key jurisdictions rely on adding several capital buffers, each earmarked to address specific risk drivers (e.g. credit cycles, systemic institutions, structural risks). This may lead to a miscalibration of the macroprudential buffer, as this approach fails to account for interactions between risks and the compound losses they imply. Climate-related risks, which have yet to be included in many countries' macroprudential frameworks, may benefit from implementing a consolidated approach for capital buffers to account for their interactions with other sources of risk.
- **Incorporating compound risks into a consolidated approach involves navigating substantial uncertainties, for which a growing set of empirical methodologies can help.** Novel and complex risks, such as climate risks and their interactions with other risks, are subject to multiple distinct forms of uncertainty: epistemic, aleatory, fundamental (Knightian) and strategic. Yet, practical empirical methods, often developed by central banks and supervisors in the context of climate-related risks, can be leveraged to tackle them. Epistemic uncertainty stemming from knowledge gaps about risk interactions can be reduced through improved data, models and scenario analysis. Aleatory uncertainty, which arises from intrinsic randomness, can be addressed using probabilistic modelling and stochastic scenario approaches. Knightian uncertainty, which is linked to fundamental 'unknown unknowns', calls for precautionary approaches, 'what if'

scenarios and robust stress testing. Strategic uncertainty, related to coordination failures and inaction, can be mitigated through mechanisms for collective action, credible transition planning and flexible policy frameworks.

- **Macroprudential authorities can play a key role in strengthening the financial system's resilience to address compound climate and macro-financial risks by adopting a holistic, forward-looking and adaptive approach.** Policymakers face the unenviable task of safeguarding financial stability amid an increasingly intricate landscape of compound risks and uncertainty. Here, we recommend adopting a holistic approach to macroprudential buffer setting while being mindful of the limits of earmarked buffers in the context of compound risks. In this context, macroprudential policy responses range from a maximalist approach where buffers are built to cover multiple sources of systemic risk to a more minimalist strategy that prioritises a holistic risk assessment to ensure the robustness of existing earmarked buffers under compound risk conditions.

- **There are several practical ways in which macroprudential authorities can navigate the uncertainty associated with assessing compound risks and implementing macroprudential capital buffers.** In particular, we recommend leveraging methodologies developed by supervisors to address uncertainty, including in the context of climate-related risks, to better prepare for the unpredictable and often unprecedented nature of compound risk. We also recommend adopting an adaptive and forward-looking approach to macroprudential policy implementation to better reflect the evolving landscape of risks and the progress in knowledge about them.

1. Introduction

Climate-related shocks will not occur in isolation. Instead, they will unfold within an existing macro-financial environment, where their interaction may lead to compound losses. In this context, general prudential capital buffers that take a holistic view of prospective loss — capturing various sources of interactions and amplification — may offer significant advantages over the current practice of de facto adding up specific, earmarked capital buffers. Although uncertainty persists regarding the impact of novel shocks such as climate risks and their combined effects — making buffer calibration challenging — emerging climate assessment methods can help address these uncertainties. This report presents a case for a holistic approach to macroprudential buffer setting, which captures interactions between novel sources of systemic risk, such as climate-related risks, and more established sources of systemic risk, such as macro-financial conditions.

Ensuring that the financial system can withstand multiple interacting risks is central to macroprudential policy, and its mission of safeguarding financial stability. In this vein, a macroprudential view entails a need to contextualise any given source of shocks — such as climate related shocks — into a prevailing macro-financial environment. Indeed, the interplay of shocks can materially impact the amplitude and persistence of impacts, should it entail scope for reinforcing mechanisms such as interconnections within the financial sector, and the feedback loops between the financial sector and the economy. Ultimately, compound aggregate losses can substantially differ from the sum of the parts attributable to any given specific category of shocks.

The current macroprudential buffer framework, with earmarked requirements to address specific sources of risk, may face limitations in addressing such compound risks. A stacking of earmarked buffers would fail to account for interactions and amplification channels typically associated with compound risks. Yet, in practice, macroprudential capital buffer frameworks have evolved to consist of several requirements stacked atop microprudential ones, addressing individual sources of risk based on largely independent calibrations.

This report takes a deeper look at the potential for compound losses resulting from the interactions between shocks resulting from climate change and more traditional macroeconomic and financial shocks. It explores the conceptual implications of shock interaction for a *consolidated* approach to macroprudential buffers, rather than an *earmarked* approach in which a specific capital buffer is assigned to each source of risk. It also offers a practical view on how the existing macroprudential framework might be adapted to account for consolidated approaches, leveraging emerging methodologies to address significant uncertainty surrounding novel, complex and difficult-to-predict risk interactions. Faced with such uncertainties, a forward-looking, adaptive approach may be best suited to tackling compound risks. This, in turn, can contribute to a more resilient financial system capable of withstanding the evolving challenges posed by climate change, economic shocks, and their complex interplay.

The remainder of this report is structured as follows:

- **Section 2** introduces compound risks and explores their statistical properties relevant for calibrating macroprudential buffers.
- **Section 3** presents a stylised analytical framework illustrating how macroprudential buffers are calibrated to address systemic shocks, including compound risks.
- **Section 4** compares a framework with earmarked buffers with a consolidated framework in the presence of compound risks.

- **Section 5** presents the current macroprudential buffers framework, tendentially adopting an earmarked approach, and the recent discussions around it.
- **Section 6** highlights potential strategies to deal with the uncertainty associated with calibrating consolidated buffers.
- **Section 7** concludes.

2. Framing compound risks

Compound risks arise when individual shocks interact and generate economic losses larger than the sum of their individual impacts. Climate-related risks can interact with other macro-financial risks in this way. This section presents examples of compound climate-related and macro-financial risks and highlights the statistical properties of compound shocks that affect the calibration of macroprudential capital buffers.

Compound climate-related and macro-financial risks

Compound economic risks are situations where **multiple risk factors interact simultaneously or sequentially, resulting in amplified economic impacts greater than the sum of the individual risks.**[1] Compound risks are characterised by non-linear effects that arise due to complex interactions within the environment and among households, firms, government and the financial system. These effects can cascade across economic, environmental, societal, geopolitical and technological systems at multiple spatial and temporal scales. As such, the economic impacts of compound shocks cannot be deduced from the sum of the impacts of their constituent shocks (NGFS, 2023; Ranger et al., 2021).

In this report, we focus on compounding risks from two independent sources: deteriorations in macroeconomic and financial conditions — **macro-financial conditions risks** — through, for example, a recession, an increase in commodity prices or geopolitical tensions, and **climate-related risks** stemming from increasing extreme weather events (physical risks) or a disorderly transition to net zero (transition risks).[2] This report focuses on compound shocks that arise when climate-related and macro-financial condition shocks co-occur.[3] We consider cases in which compound effects can accentuate or attenuate aggregate direct economic losses.

Climate-related shocks can compound in different ways with major macroeconomic and financial shocks (macro-financial shocks hereafter). Table 2.1 provides possible examples of compound interactions between climate-related and macro-financial condition risks and Figure 2.1 illustrates these compounding channels. First, **climate-related and macro-financial shocks can occur independently** — that is, the materialisation of one shock does not depend on the materialisation of the other, or in statistical terms, they are uncorrelated — **but when they co-occur, their economic losses compound** and their total is greater than the sum of economic losses that each shock would generate in isolation. The amplification can go from one shock to another. For example, a prolonged drought's economic and social consequences can be larger in the context of trade tensions or supply-chain disruption linked to geopolitical conflicts. Shocks can also reinforce each other. For example, a hurricane or storm can aggravate a country's fiscal situation with high public debt problems.

Second, **climate-related and macro-financial shocks can depend on each other and are more likely to co-occur.** This happens when one shock triggers another or amplifies a small shock, making it a systemic shock. For example, a prolonged drought — a climate-related physical shock — can lead to crop failures and food shortages, resulting in rising food prices and falling rural incomes that

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[1] See IPCC (2022) for a definition focused on climate risks.
[2] In this report, we do not address compound risks stemming from climate hazards only. Compound risks from different climate drivers are the subject of a growing literature (see, for example, a foundational paper by Zscheischler et al., 2018).
[3] Generally, four types of compounding shocks can be distinguished (NGFS, 2023; Zscheischler et al., 2020): preconditioned shocks (where a climate or macro-financial precondition aggravates the impacts of macro-financial or climate shocks), multivariate compound shocks (where multiple macro-financial and climate shocks co-occur), temporally compound shocks (where a succession of climate and macro-financial shocks compound) and spatially compounded shocks (where macro-financial and climate shocks occur in multiple connected locations).

can trigger or exacerbate pre-existing social tensions — a major source of macroeconomic shocks. Similarly, introducing carbon taxes — a climate-related transition shock — can also generate social unrest. A ban on internal combustion engines — another climate-related transition shock — can potentially trigger trade tensions — another major source of macroeconomic shocks — if countries heavily reliant on automotive industry exports accuse climate policies of being protectionist. The causality can also go from macro-financial shocks to climate-related shocks. A fossil fuel price spike generated by geopolitical tensions can accelerate investment in renewable energy and the implementation of policies catalysing the transition. When climate-related and macro-financial shocks are not independent, large shocks from one source are likely to be associated with large shocks from the other sources. Statistically, they are correlated.

Finally, note that **climate-related and macro-financial shocks can sometimes mitigate each other,** generating economic losses that offset one another instead of compounding. For example, a carbon tax can generate fiscal revenues and improve public finance in countries with debt issues. Similarly, technological developments in artificial intelligence significantly reduce transition costs by improving efficiency, decision-making, innovation and risk management, while at the same time introducing novel risks for financial stability.[4]

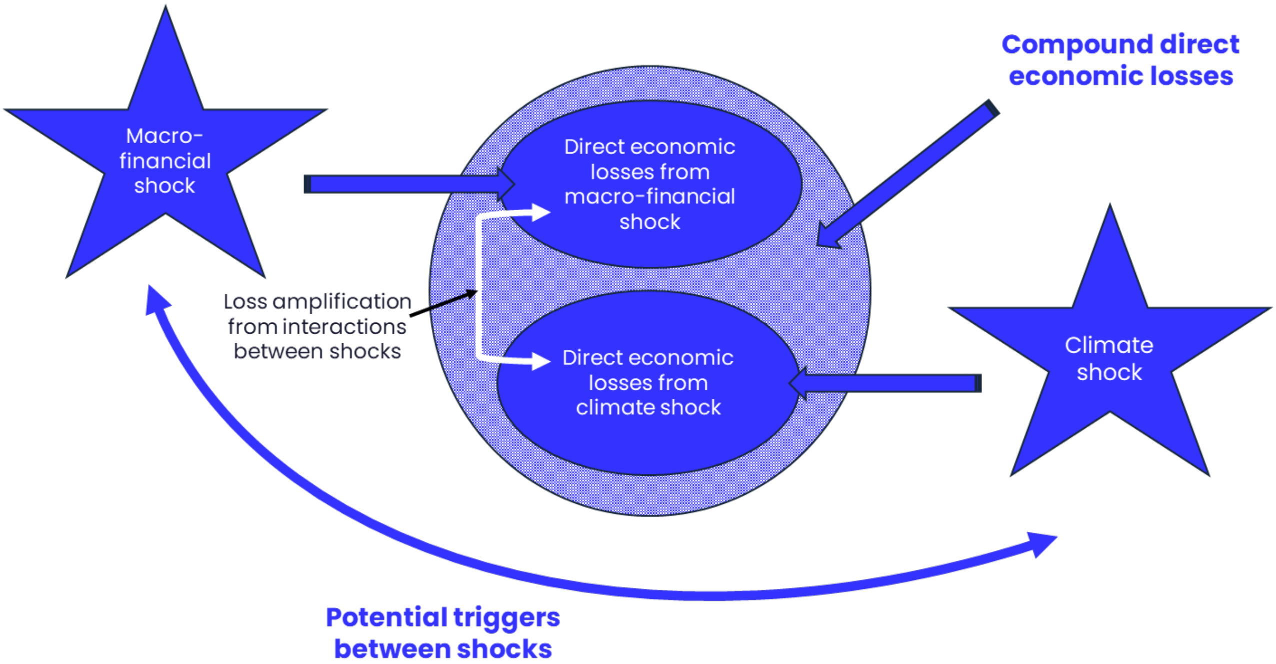
Table 2.1. Example of interactions between macro-financial conditions and climate-related risks

Interaction type	Description	Illustration
Independent versus correlated		
Independent	Shocks materialise distinctively from other shocks but amplify each other's economic impact when they co-occur.	A prolonged drought occurs independently of supply-chain disruptions caused by geopolitical tensions but has larger economic consequences within this context.
Correlated	Shocks from one source of risk can trigger or amplify shocks from another. Shocks can amplify each other's economic impact, but they do not necessarily do so.	Prolonged droughts lead to shortages that trigger social unrest or exacerbate pre-existing social tensions, without necessarily amplifying the economic losses from equivalent social events that occur independently of droughts.
Compounding versus offsetting		
Compounding	Economic consequences from one source of risk interact with those of another, amplifying each other's economic losses.	Economic consequences of drought are exacerbated when trade tensions or supply-chain disruptions limit the mitigating potential of food imports.
Offsetting	A negative shock stemming from one source of risks positively impacts the economic consequences of another source of risks.	A carbon tax can generate fiscal revenues that improve public finances in countries facing pressure due to high public debt.

Source: Authors

[4] See, for example, Danielsson (2025).

Figure 2.1. Compounding channels



Source: Authors

A statistical exploration of compound risks

Independent and correlated compounding risks have distinct analytical specifications, which imply specific impacts on the aggregate loss distribution function relevant for calibrating macroprudential capital buffers.

Specifying direct compound economic losses

When climate-related and macro-financial shocks compound, the direct initial economic losses — that is, before their potential amplification through internal financial sector channels and feedbacks from the interactions with the economy — are **larger than the sum of direct economic losses** stemming from individual shocks. Mathematically, this translates into the following expression:

$$X = M + C + g(M, C)$$

Where X is the total direct economic losses, M and C are the direct losses from the macro-financial condition shock and the climate-related shocks, respectively, and $g(M, C)$ are the indirect losses stemming from (non-linear) compounding effects.

Introducing correlated risks

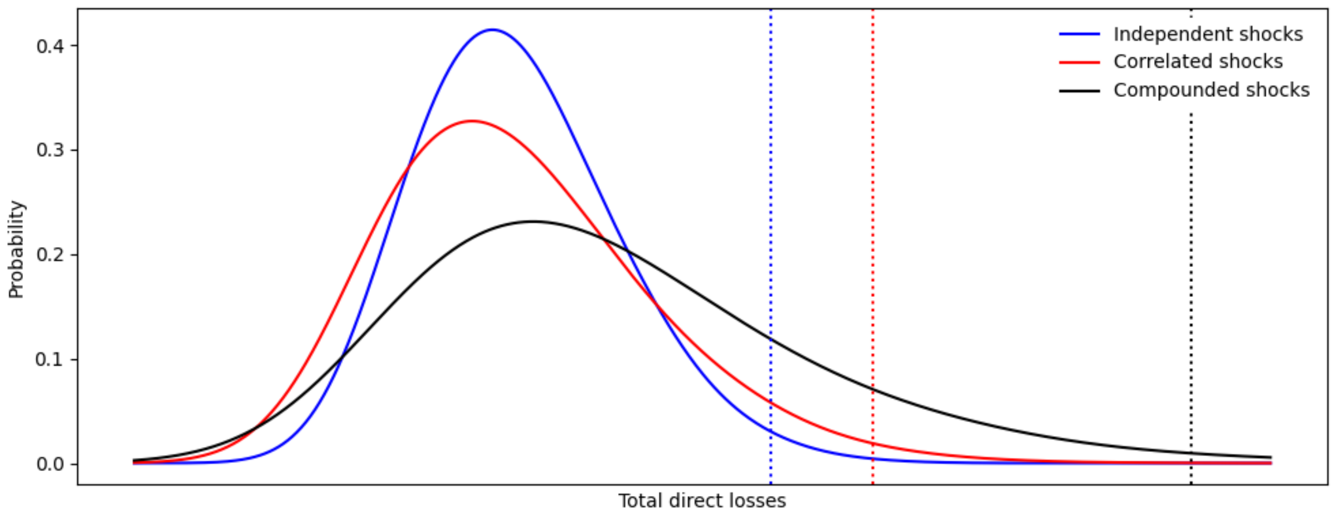
When shocks are correlated, their **compounding effects depend partly on the shocks' joint distribution.** This joint distribution reflects the likelihood of co-occurring climate-related and macro-financial shocks before they translate into economic consequences. This usually translates into a non-linear and asymmetric dependence structure, with tail dependence, meaning that extreme values in one shock are likely to be associated with extreme values in another. In statistical terms, this translates into a non-zero covariance.[5]

[5] It can also possibly imply non-zero co-skewness, co-kurtosis or higher co-moments of the joint distribution.

Impact of compound risks on the distribution of economic losses

Figure 2.2 compares the expected aggregate loss distribution in situations in which shocks (1) are independent and non-compounding (independent shocks) — that is, they do not influence each other at all — (2) dependent but non-compounding (correlated shocks) — that is, one shock's occurrence affects the likelihood of the other risk's occurrence but not its economic impact — and (3) dependent and compounding (compounded shocks) — that is, shocks are likely to co-occur and amplify the economic impact of each other.

Figure 2.2. Comparison of total losses between independent and compound shocks



Notes: Simulation of 10,000 pairs of shocks. Shocks are drawn from a standard skew-normal distribution with a skewness parameter equal to 5. The correlation is set to 0.7 for correlated and compounded shocks. The compound factor is 0.25 times the product of both shocks. The dotted lines show the value-at-risk (VaR) at a 99% confidence level for each case.
Source: Authors

The expected total losses are identical for independent and correlated non-compounding shocks. However, the correlation between shocks expands the range of potential losses. This translates into larger maximum economic losses at risk or a higher value-at-risk (VaR) statistically.[6] When compound effects are added, the expected total losses increase, reflecting the additional expected losses from compounding. The distribution range is further expanded, which is reflected in an increase in VaR.

Expected direct compound losses and their variance

The VaR is key in calibrating macroprudential capital buffers (see Section 3). The expected losses and their variance are important parameters for assessing this value. In the case of compound shocks, expected losses and their variance depend crucially on the dependence structure between macro-financial and climate-related shocks — their joint distribution function — and the functional form that the compound effect takes.

To illustrate how the joint distribution and the compound function impact the expected value and the variance of aggregate direct losses, we estimate them around average shocks using a first-order Taylor approximation. The expected direct losses are

$$\boldsymbol{E}(X) = \boldsymbol{E}(M) + \boldsymbol{E}(C) + \boldsymbol{E}(g)$$

Where $\boldsymbol{E}(X)$ is the expected compound losses, $\boldsymbol{E}(M)$ and $\boldsymbol{E}(C)$ are the expected direct losses from the macro-financial condition and climate-related risks, respectively, and $\boldsymbol{E}(g)$ are the expected

[6] The VaR is a widely used statistical measure that quantifies the potential maximum loss given a certain confidence level.

losses from compound effects evaluated at the average macro-financial condition and climate-related shocks $\boldsymbol{E}(M)$ and $\boldsymbol{E}(C)$.[7]

For the variance, we have

$$\boldsymbol{Var}(X) = (1 + g_M) \cdot \boldsymbol{Var}(M) + (1 + g_C) \cdot \boldsymbol{Var}(C) + 2\left(1 + g_{M,C}\right) \cdot \boldsymbol{Cov}(M, C)$$

where g_M, g_C and $g_{M,C}$ are parameters from the first derivatives of the compound effect function relative to macro-financial conditions and climate-related shocks, respectively.

To sum up, when macro-financial and climate-related shocks are correlated and compound, both the expected value and the variance of aggregate direct losses increase compared to a baseline case with independent, non-compounding shocks. The expected value rises because compound effects introduce additional losses through reinforcing channels. The variance grows even more significantly because compound effects amplify the contribution of each shock to overall uncertainty, while the dependency — that is, correlation — between shocks introduces a covariance term that reinforces the combined effects on individual variances.

[7] Note that we used a first-order Taylor approximation of $g(M, C)$ to get this expression. A second-order Taylor approximation would add terms reflecting the variance and covariance of M and C to it.

3. Macroprudential buffers: a stylised analytical framework

How do systemic risks affect macroprudential capital buffers? This section explores the question using a simple analytical framework that combines an elementary representation of the banking sector with embedded systemic risk. It also presents a stylised calibration of macroprudential capital buffers based on aggregate unexpected losses in the banking system resulting from systemic shocks.

Systemic risk is the risk of widespread disruption to the provision of financial services caused by an impairment of all or parts of the financial system, which can have serious negative consequences for the real economy (FSB et al., 2009). Such widespread disruptions can result from **significant losses in the banking sector arising from adverse macroeconomic events** — such as a severe recession, sharp interest rate hike, or a collapse in asset prices — that affect many institutions simultaneously. Systemic risk is exacerbated when initial aggregate losses from a common shock are amplified through interconnected institutions and feedback loops within the financial system and the economy.[8]

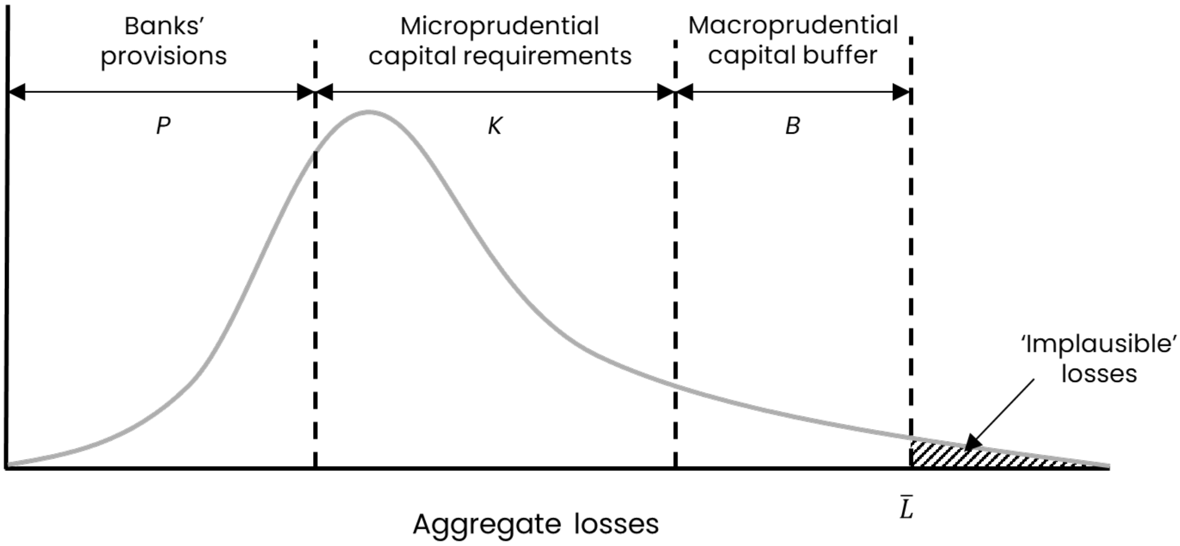
In this context, macroprudential capital buffers aim to enable banks to absorb losses while maintaining the provision of key services to the real economy. They are placed on top of minimum capital requirements to enhance banks' resilience against shocks and **provide banks with space to absorb losses** as they are incurred.[9]

Macroprudential capital buffers as absorbers of aggregate losses

Macroprudential capital buffers complement other financial resources banks already have to absorb losses, like the provisions they set aside for expected losses and the capital required by microprudential regulation. In this vein, **macro- and micro-prudential measures are complementary** (Coelho and Restoy, 2024). Whereas microprudential supervisors take action primarily to ensure bank-specific resilience to shock materialisation, macroprudential capital buffers can offer an additional powerful complement to ensure systemic risks from 'severe but plausible' tail risk scenarios are also catered for.[10] The general case for prudential capital buffers stems from the prospect of unexpected losses (in contrast to expected losses, which can be provisioned for). The specific case of macroprudential buffers stems from losses that exceed financial institutions' direct exposures to specific risk categories through indirect amplification channels. Figure 3.1 illustrates the banking sector's aggregate expected loss distribution function and highlights the different aggregate resources available to absorb them.

[8] See, for instance, margin and loss spirals as described in Brunnermeier and Pedersen (2009).
[9] See, for example, Behn et al. (2020), who focus on buffer usability — arguing that a greater share of capital buffers that can be released in a crisis would enhance macroprudential authorities' ability to act countercyclically.
[10] Traditional stress tests tend to explore *severe but plausible* scenarios such as economic downturns or recessions associated with transitory macroeconomic and financial shocks. As noted in BCBS (2024a), climate scenario analysis might also have a broader exploratory scope.

Figure 3.1. Aggregate loss distribution and loss-absorption layers in the banking sector



Source: Authors

In this illustration, a combination of provisions for *expected loss* alongside capital requirements to absorb *unexpected loss* collectively enhances the banking sector's loss-absorption capacity. **Macroprudential capital buffers** (B) in this respect, act as a lever to absorb any additional **plausible losses** $(\bar{L})$ borne by the banking sector that might arise from shocks not catered for by **banks' expected loss provisions** (P) or base **capital requirements** (K) from microprudential measures:

$$B = \bar{L} - P - K$$

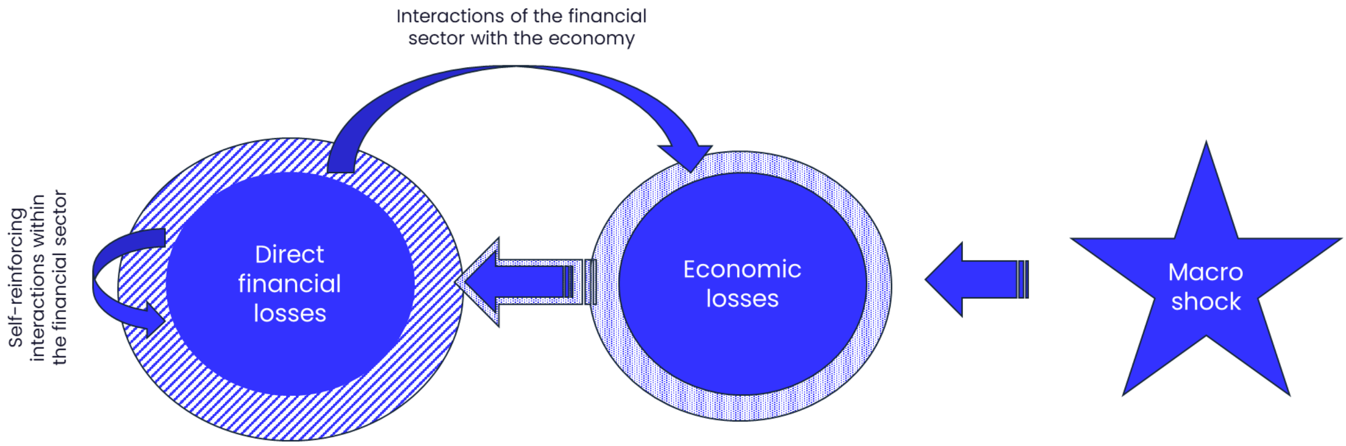
To fulfil this loss-absorption objective, a macroprudential capital buffer should be set such that aggregate losses will most likely remain within the banking sector's **absorption capacities**.[11] Conversely, the buffer should be calibrated so that aggregate losses exceed the banking sector's absorption capacity only with a specified, very low probability over a chosen horizon — for example, with an expected probability below 1%. This corresponds to calibrating the buffer on the expected VaR of aggregate losses for a chosen confidence level. This value is determined by the **distribution of aggregate losses** expected by macroprudential authorities. The wider the range of the expected distribution of aggregate losses, and the fatter its tails, the higher the absorption capacity threshold.

Losses from shocks and their amplification as systemic risk

In our stylised framework, a shock generates direct economic losses through, for example, lower profits for firms and lower household income. These economic losses translate into direct financial losses for the banking system through, for example, higher default rates, losses given defaults and market losses. Direct financial losses can possibly be amplified internally by the financial sector and through feedback with the real economy. The final losses for the banking sector are the combination of the initial direct losses and their amplification. Figure 3.2 illustrates our framework.

[11] Our approach extends the logic for setting capital buffers at the microprudential level — as presented in Holscher et al. (2022) — to the macroprudential level.

Figure 3.2. Transmission of shocks and their amplification



Source: Authors

We consider two primary sources of externalities that can amplify initial losses from a shock.

- A first class of externalities that could amplify losses stem from self-reinforcing interactions **within the financial sector.** An illustrative amplification mechanism could be forced 'fire sales' of assets, whereby quantitative adjustments are accompanied by reinforcing price spirals when institutions (often leveraged ones) are forced to raise liquidity when confronted with a market selloff.[12] Internal systemic risks arising from direct losses at the individual level being amplified across the financial system could arise from banks' interconnectedness and related channels — for example, direct counterparty risks, asset fire-sale spirals, and collateral value decline — phenomena extensively studied in policy and academic research[13] and underpinning some macroprudential measures implemented by central banks and supervisors.[14]
- A second class of externalities that could amplify losses pertain to feedback from the **interactions of the financial sector with the economy.** An illustrative amplification mechanism relates to the scope for procyclical credit supply shocks emanating from the collective lending behaviour of the banking sector, which ensues at low levels of capitalisation, which can exacerbate economic and financial downturns (see, for instance, Acharya et al., 2017; or Budnik et al., 2023).

Mathematically, the total losses L from a shock for the banking sector, after amplifications, can be expressed as follows

$$L = X\left(1 + \eta(X)\right)$$

where X are the direct economic losses from the shock and $\eta(X)$ is the factor by which initial losses are amplified through internal financial sector channels and feedback from interactions with the economy, resulting in indirect losses. This specification allows for non-linear, state-dependent amplification of the initial losses, with a magnitude depending on their value.

Calibrating macroprudential capital buffers for systemic risks

To calibrate macroprudential buffers for systemic risks, financial supervisors must assess what share of aggregate losses is already covered by banking sector provisions (P) and by microprudential capital requirements (K).[15] In our simplified framework, we assume that the banking sector

[12] Sydow et al. (2024) present second-round impacts of forced selling in a system-wide stress testing.
[13] Alla et al. (2018), for example, propose a methodology based on market data to empirically assess the impact of the banking sector's interconnectedness on systemic risk losses.
[14] The additional capital required by the Basel Committee for Banking Supervision (BCBS) for global systemically important banks (G-SIBs) is an example of such measures.
[15] See the equation in the previous section.

provisions equal the expected direct losses from shocks. In addition to these provisions, supervisors set **microprudential capital requirements to limit the maximum direct losses** each bank must absorb with a pre-defined, high-confidence level (e.g. with a 99% probability).

Under these assumptions, the aggregate provisions by banks and the aggregate level of individual capital requirements cover the direct impact of shocks — that is, the potential losses that banks directly incur from a large but plausible shock. However, they fail to cover the indirect losses from shocks — that is, the losses stemming from the amplification of the initial shock by the banking sector itself or by feedback effects for collective sector lending impacts on the real economy. This is equivalent to a situation in which banks and microprudential supervisors do not account for systemic risks. In this case, **a macroprudential capital buffer, adequately calibrated, must be added to address systemic risks arising from externalities** that can amplify initial losses from a shock.

Although the exact size of the buffer depends on the entire shape of the loss distribution function, it can be approximated with a Cornish-Fisher expansion of this function and a first-order approximation of the amplification function. This approximation highlights that the size of the macroprudential capital buffer is a **function of the intensity of the channels through which the losses from an initial shock are amplified** by the banking sector and its feedback effects on the economy. In mathematical terms, the size of the buffer is given by

$$B = \eta \, \boldsymbol{E}(X) + t \cdot (\eta + \eta') \, \boldsymbol{Var}(X)^{\mathbf{1/2}}$$

where $\boldsymbol{E}(X)$ and $\boldsymbol{Var}(X)$ are the expected value and variance of direct aggregate losses from the shock, η and η' are the amplification factor and its first derivative both estimated at $\boldsymbol{E}(X)$, and t is a fixed adjustment based on the 99% quantile of a standard normal distribution and the skewness and the kurtosis of the loss distribution function. The first term on the right-hand side of the equation is the additional expected losses for the banking system stemming from the amplification of initial losses. Banks' provisions do not include these additional expected losses since they only cover banks' direct losses. The second term reflects the increase in the range of large but plausible losses — that is, the breadth of the loss distribution function — generated by amplification channels. Microprudential capital requirements do not encompass this additional range, as they are calibrated solely on the distribution of direct initial losses.

4. Earmarked versus consolidated buffers

How do compound risks affect the calibration of macroprudential capital buffers? In this section, we compare an earmarked approach, in which a specific buffer addresses each risk separately, and a consolidated approach, in which a single buffer addresses both risks. We show that the earmarked approach can lead to a miscalibration of the macroprudential buffer due to the fallacy of composition that compound risks imply.[16]

Addressing shocks with earmarked buffers

We first consider the case in which two different sources of loss-generating risks for the banking sector — macro-financial conditions shocks and climate-related risks — are addressed separately with two distinct macroprudential capital buffers. For that, we assume that **provisions, microprudential capital requirements and macroprudential capital buffers are set independently for each source of risk.** This corresponds, for example, to a situation in which banks analyse each source of risk distinctly and then provision separately against each — noting that, in practice, financial institutions very often assess risk families separately and then aggregate them (Hamar, 2010). Similarly, microprudential capital requirements are determined independently for each source of risk. This is the case, for example, when capital requirements are based on banks' risk assessments, such as in the internal rating-based (IRB) approach, and sources of risks are assessed separately. Finally, we assume that supervisors also assess risks independently and calibrate macroprudential capital buffers separately for each source of perturbation.[17]

This risk-by-risk or earmarked approach leads to additive macroprudential capital buffers in the system. The total of buffers covers the systemic risk associated with each source of risk. However, in this configuration, the **interactions between two risks and their consequences on systemic risk are not accounted for.**

$$B = B(M) + B(C) = \eta\left(\boldsymbol{E}(M) + \boldsymbol{E}(C)\right) + t \cdot (\eta + \eta')\left(\boldsymbol{Var}(M)^{\mathbf{1/2}} + \boldsymbol{Var}(C)^{\mathbf{1/2}}\right)$$

where $B(M)$ and $B(C)$ are the macroprudential capital buffers addressing the source of macro-financial conditions risk (M) and climate-related risks (C) respectively.[18]

With the earmarked approach, the buffer is calibrated to absorb the large but plausible losses stemming from the amplification of each shock through financial channels and feedback with the real economy.

From an earmarked to a consolidated approach

We now consider the case in which **macroprudential authorities analyse risks together** and calibrate macroprudential capital buffers accordingly. We still assume that banks' provisions and

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[16] The fallacy of composition is a logical error that arises when it is incorrectly assumed that if something is true for an individual part, it must also be true for the entire system of those parts.
[17] This could be the case, for example, in Europe, where national supervisors separately apply a countercyclical capital buffer (CCyB) to counter procyclicality in the financial system and a systemic risk buffer (SyRB) to address other systemic risks.
[18] Note that, for the simplicity of the illustration, we assume that the loss distribution functions of M and C are identical, which implies identical parameters t, η and η'.

microprudential capital requirements are set risk-by-risk. This setting implies that authorities now consider the interlinkages between shocks through compounding effects.

The main implication of this approach is that the **expected distribution of aggregate losses must account for the links between shock distributions and their compound effects.** Accounting for links between shock distributions translates into higher expected aggregate losses when such shocks compound with a positive reinforcing mechanism, and imply a wider range for expected aggregate losses — that is, a larger variance. Since the expected losses and their variance are at the heart of macroprudential buffers' calibration, the buffers' size must reflect these additional terms to account for the dependencies of risks.

The earmarked and consolidated approach leads to different calibrations for the aggregate buffer. The calibration difference is the following:

$$\Delta B = \eta\, \boldsymbol{E}(g) + t \cdot (\eta + \eta') \left(g_M \cdot \boldsymbol{Var}(M)^{\mathbf{1/2}} + g_C \cdot \boldsymbol{Var}(C)^{\mathbf{1/2}} + 2\left(1 + g_{M,C}\right) \cdot \boldsymbol{Cov}(M, C)^{\ \mathbf{1/2}} \right)$$

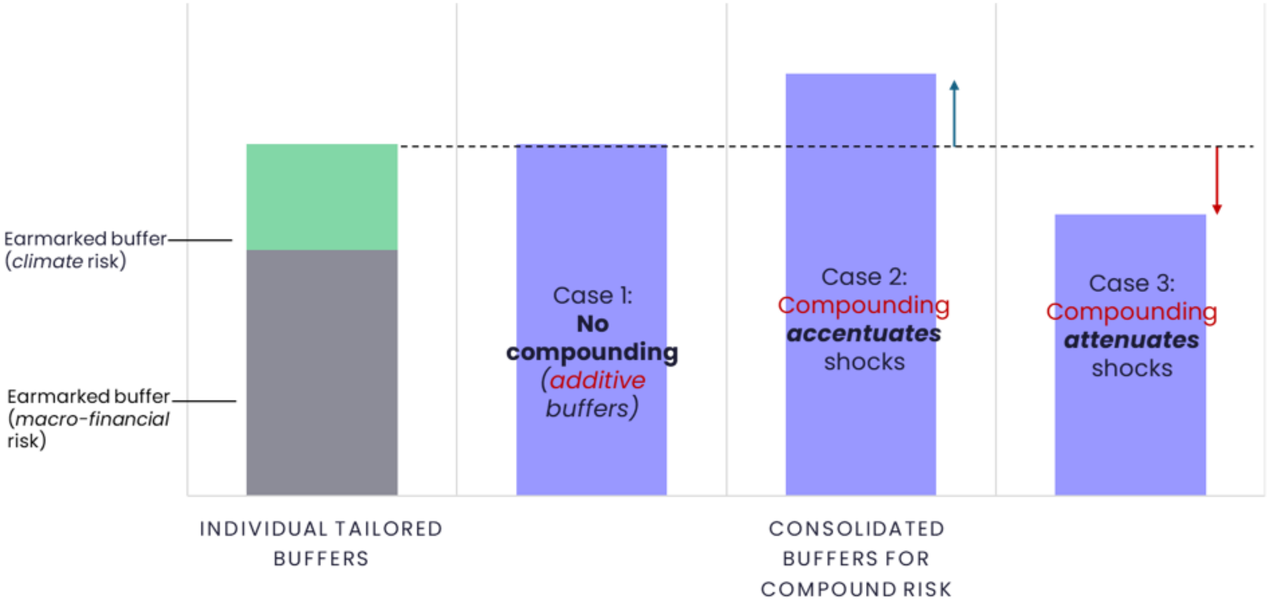
When shocks compound and amplify losses, the optimal buffer is larger. For example, when one shock increases the other — for example, when a climate-related shock induces a deterioration of macro-financial conditions — then additional layers of capital are required in the buffer compared to the case in which risks do not compound — that is, in the case in which supervisors take an earmarked approach and do not account for compounding effects. These additional layers reflect three components:

1. The impact of compounding on **expected aggregate losses** through the deterioration of macro-financial economic conditions that it generates
2. The impact of compounding on **the range of aggregate losses' distribution** — that is, its variance — through the additional variability that compounding interactions generate between risks
3. The **amplification of the compounding impacts** on expected aggregate direct losses and their range by internal financial sector channels and feedback from the interactions with the economy.

Note that **when risks offset rather than compound, the buffer becomes smaller** with a consolidated approach compared to an earmarked approach. The reason for this is that, with an earmarked approach, the addition of the buffers does not account for the mitigating effect of one shock on another, which decreases total expected losses and their variance. Mathematically, this translates into negative parameters associated with the first derivatives of the function $g(M, C)$ and a negative covariance. Figure 4.1 illustrates these different cases.

In summary, when risks compound, a risk-by-risk approach underestimates the expected aggregate losses and their distribution range because it overlooks the links and feedback loops between shocks. Consequently, buffers calibrated using this approach are unlikely to absorb shocks to the extent expected by supervisors. This can be corrected by adopting a consolidated view of risks, accounting for their links.

Figure 4.1. Earmarked vs consolidated buffers



Source: Authors

5. Current macroprudential practices

The macroprudential capital buffer framework typically combines internationally agreed standards with country-specific requirements tailored to national financial systems. These buffers are designed to address diverse sources of systemic risk, including credit cycle fluctuations, the impact of systemically important institutions, and structural vulnerabilities. However, the current configuration often leads to a fragmented and overlapping capital stack, where buffers are calibrated for discrete risks but lack an integrated, system-wide perspective. Ongoing policy discussions on reforming the framework offer a timely opportunity to move towards a more coherent approach — one that explicitly accounts for compound risks and their potential amplification effects.

A fragmented macroprudential capital buffer stack

Macroprudential capital buffer frameworks differ across jurisdictions. However, most consist of **several macroprudential capital buffers stacked** atop microprudential requirements. The sum of micro- and macroprudential capital requirements ensures banks' resilience to shocks from different sources. Some macroprudential capital buffers are defined in the Basel frameworks at the international level, while others are specific to national macroprudential regulation. The combination of these international and domestic buffers results in aggregate macroprudential capital requirements that vary across jurisdictions.

The current common international macroprudential framework set by the Basel Committee on Banking Supervision (BCBS) — that is, the Basel framework — includes three separate macroprudential capital buffers (BCBS, 2019a; BCBS, 2019b).

- **Capital Conservation Buffer (CCoB).** The CCoB level is fixed and applies uniformly to all banks in jurisdictions implementing the Basel framework.
- **Countercyclical Capital Buffer (CCyB).** The CCyB is implemented at the jurisdiction level and can vary over time to reflect national authorities' systemic risk assessment based, among other indicators, on the evolution of the aggregate private sector credit-to-GDP ratio.
- **Global Systematically Important Banks Capital Surcharge (G-SIB surcharge).** The G-SIB surcharge is mandatory for all institutions classified as global systemically important banks by the BCBS.[19]

In addition, national authorities apply various macroprudential buffers in addition to those in the Basel framework. Some examples are:

- **Domestic Systematically Important Banks Capital Surcharge (D-SIB surcharge).** The D-SIB surcharge is similar to the G-SIB surcharge but it applies to banks of systemic domestic importance.[20]
- **EEA's Systemic Risk Buffer (SyRB).** In the European Economic Area (EEA), national authorities members of the European Systemic Risk Board (ESRB) can deploy an SyRB when their

[19] See BCBS (2021a).
[20] Although the Basel framework does not formally include the D-SIB surcharge, the BCBS has set principles for the identification of domestic systemically important banks and the implementation of the national G-SIB surcharge (BCBS, 2019b; BCBS, 2019c).

domestic banking system is exposed to specific sources of systemic risks.[21] Currently, 15 jurisdictions have an SyRB in place.[22]

- **Canada's Domestic Stability Buffer (DSB).** In Canada, domestic systemically important banks must set aside funds to cover losses during financial uncertainties, in addition to the D-SIB surcharge. The Office of the Superintendent of Financial Institutions (OSFI) regularly adapts the DSB to account for the current systemic risk level.

Note that the US Federal Reserve applies an individual buffer — the **Fed's Stress Capital Buffer (SCB)** — to ensure that each bank has sufficient capital to absorb losses during stressful macroeconomic conditions. Although this buffer is not formally considered a macroprudential measure — it is considered a Pillar 2 measure — it is akin to a macroprudential buffer given its macroeconomic approach based on stress tests.

A myriad of purposes and calibrations

The macroprudential capital buffers implemented at both the international and national levels are designed to mitigate several sources of systemic risk. However, each usually focuses on a narrow set of risk sources rather than a holistic approach.

Addressing an array of systemic risk sources

The macroprudential capital buffers contained in the Basel framework and in national frameworks address different individual sources of risks:

- The **CCyB** is closely linked to **systemic credit cycle risks.** It aims to protect the banking system against potential future losses when excess credit growth is associated with an increase in system-wide risk (BCBS, 2010). It follows from the observation by macroprudential authorities that periods of excess aggregate credit growth have often been associated with the build-up of systemic risk.
- Systemic buffers for the most important financial institutions, notably **surcharges** for **G-SIBs** and their domestic counterparts **(D-SIBs),** aim at mitigating **systemic risk internal to the financial sector.** It follows from the observation that the impairment of many large financial institutions creates enormous stress in the financial system and the real economy due to their size, their interconnectedness with other financial institutions, and the lack of substitutability for their counterparts. The G-SIB surcharge also aims to mitigate the moral hazard costs associated with potential implicit public guarantees that could be linked to institutions deemed too big to fail.
- In Europe, **SyRBs** address **structural, non-cyclical systemic risks** not covered by other capital requirements. National authorities have implemented SyRBs for several individual sources of systemic risk, from common exposures to specific economic sectors — for example, the petroleum sector in Norway — to exposure to specific geographical risks — for example, Eastern European countries for Austrian banks — or to similar business models, like in Sweden. Bartsch et al. (2024) present an application of such a buffer for climate-related risk.
- In Canada, the **DSB** aims to address **an extensive range of key vulnerabilities and system-wide risks.** The types of vulnerabilities that it covers include domestic households, corporate and sovereign indebtedness, financial and real estate asset imbalances, and external global developments such as pandemics, conflict or political unrest (OSFI, 2024).
- In the US, the **SCB** addresses **two specific macroeconomic shocks:** a severe global recession and heightened stress in debt markets, a global market shock. The scenarios differ slightly from year to year in terms of the amplitude of the shocks they test, such as unemployment

[21] Authorisation from the European Commission may be required depending on its proposed level and the potential impact on other EU Member States.
[22] In Italy, climate considerations are explicitly mentioned as a factor which could motivate additional macroprudential policy space unrelated to the financial cycle, and an associated systemic risk buffer (see Catapano et al., 2024).

increases, real estate price declines, interest rate assumptions, and global economic conditions.

Note that the CCoB does not focus on systemic risk but is based on simple capital conservation rules designed to avoid breaches of minimum capital requirements (BCBS, 2019a). It recognises that banks are likely to occasionally face unexpected losses, which can bring their capital below the minimum capital requirements. The role of the CCoB is to provide a buffer to prevent this situation from happening.

Finally, note that shocks emanating from **climate-related factors do not have a specific prescribed role** in buffer setting. At the same time, the consensus is that climate-related shocks will impact traditional forms of risk for banks, such as credit risk, market risk, and liquidity risk (see BCBS, 2021b). In this regard, the distinction between climate-related shocks and macro-financial shocks is unclear. For example, the latest version of the EU Capital Requirement Directive (CRD VI) mentions climate-related risks in the lists of systemic risks that SyRBs can address.[23] No jurisdiction has used this possibility so far.

Relying on heterogeneous calibration methodologies

The calibrations of the different macroprudential capital buffers rely on very different methods and data. For example, the CCoB is calibrated on **historical data** on episodes of significant losses in the banking sector (Hirtle, 2011). **Credit growth** in the economy is the leading indicator that macroprudential authorities must use to calibrate the CCyB. Still, they can complement their calibration with other indicators that they deem relevant (BCBS, 2010). The G-SIB and D-SIB surcharges are based on a score reflecting banks' structural dimensions, such as their size, interconnectedness, substitutability, complexity, and cross-jurisdictional or nationwide activities. The SCB is calibrated based on the estimated losses of banks using **stress test scenarios.** The calibration of the DSB relies on a combination of **near-term systemic risk and systemic vulnerability indicators,** including banks' financial performance indicators, financial conditions indicators, and macroeconomic indicators. For the SyRB, national authorities use different indicators, depending on the systemic sources of risk they aim to address. Note that all guidelines underpinning macroeconomic capital buffers leave space to apply **supervisors' judgement** in the calibration.

Current debate around macroprudential capital buffers

Sparked by the experience of elective buffer release during COVID-19, a debate has been ongoing about buffer usability. As part of this, a **general reflection has been gaining momentum on the complexity of the buffer framework,** alongside a potential higher weight of macroprudential buffers in the capital stack, which would be releasable when collective bank lending requires a countercyclical push. Several propositions are on the table to improve the current framework. These ongoing policy discussions offer a timely opportunity to move towards a more coherent approach — one that explicitly accounts for compound risks and their potential amplification effects.

As noted by Hernández de Cos (2023), banks seem to be unwilling to dip into their unreleased buffers when losses materialise, which means that buffers may not fulfil their role as shock absorbers. Factors why banks hesitate to dip into capital buffers (CCyB, CCoB) include market stigma, automatic distribution restrictions, and unclear supervisory signals. At the same time, releasable buffers (the CCyB, mainly) seem to be used by banks when released by macroprudential authorities. Against this backdrop, the BCBS (2022) issued a report encouraging **clearer communication and operational guidance** to enhance buffer usability.

New approaches are being explored to make releasable buffers, such as the CCyB, more **dynamic, pre-emptive,** and **rules-based,** such as time-varying models using credit gaps, systemic stress indicators, and forward-looking metrics, positive neutral CCyBs with a baseline above zero in normal times to allow smoother activation and use, and sectoral CCyBs targeting real estate, corporate debt, or other systemic concentrations (see e.g. Muñoz and Smets, 2025; and BCBS, 2024b).

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[23] Directive (EU) 2024/1619 of the European Parliament and of the Council of 31 May 2024 amending Directive 2013/36/EU as regards supervisory powers, sanctions, third-country branches, and environmental, social and governance risks Article 133 (1).

More radical proposals have also been floated for combining micro- and macroprudential buffers. Woods (2022) argues that the capital stack could be made more efficient by **removing multiple buffers** serving different purposes and masters — and collapsing all existing buffers into a low minimum with a single releasable buffer (possibly for both risk-weighted and leverage-based measures).

Beyond this, a growing consensus is that strengthening the financial system's shock absorption capacity during stable economic periods also creates valuable **macroprudential policy space** for policymakers. By building a general capital buffer in advance, they can respond more effectively when structural shocks — individual or combined — impact the financial system. Releasing this buffer promptly during a crisis helps maintain the flow of credit to the economy, bolstering its resilience and reducing the reliance on central bank and government interventions. This approach demonstrated its effectiveness during the COVID-19 crisis when the release of capital buffers was one factor enabling the banking sector to continue fulfilling its critical role in lending and economic support.

6. Factoring uncertainty into buffer implementation

Perfect foresight is limited when it comes to compound macroeconomic shocks. Climate-related shocks already carry significant uncertainty, and their interaction with macro-financial shocks further complicates policy response calibration. This section considers how different types of uncertainty associated with compound risks can be addressed and highlights emerging practices. A growing set of empirical approaches, developed by central banks and supervisors in managing climate-related risks, can help tackle these challenges. Advanced scenario analysis that combines sources of shocks and model averaging can reduce some uncertainties, while stochastic scenarios and precautionary approaches can address irreducible ones. Mechanisms fostering collective action – such as streamlined transition planning – may also ease complexity and counter inaction bias. Streamlining detailed transition planning could be one step in this direction. Finally, capital buffer calibration should remain forward-looking and dynamic, reflecting both evolving risks and progress in knowledge. All told, these uncertainties call for a macroprudential approach that is precautionary yet gradualist in managing risk build-up.

Tackling uncertainty in a world of compound risks

In theory, calibrating macroprudential buffers to address compound risks requires estimating the distribution of potential losses for the banking sector. In practice, this task is challenging for macroprudential policymakers because the estimation of compound risk distribution is subject to considerable uncertainty stemming from different sources. We can distinguish at least four distinct types of uncertainty associated with compound risks (see Table 6.1): epistemic, aleatory, fundamental (Knightian), or strategic.

In this respect, compound risks do not fundamentally differ from climate-related risks, which are subject to the same types of uncertainty. In recent years, macroprudential policymakers have developed emerging reflections and techniques to address these types of uncertainty in the context of climate-related risks, taken in isolation. These methods can potentially be extended to address compound risks, including climate-related risks. We present some of these approaches below.

Addressing epistemic uncertainty

Epistemic uncertainty associated with compound risks is reducible. Specifically, it can be reduced by **improving the understanding and modelling of how two shocks interact** and amplify or partly offset each other. In the context of climate-related risks, macroprudential policymakers have been relying extensively on scenario analyses and stress tests to develop models and better understand how physical and transition risks play out in the economy and the financial system. A similar approach could be taken to start addressing compound risks.

Table 6.1. Distinguishing between relevant types of uncertainty

Type	Description	Illustration	Option to tackle
Epistemic (or *knowledge uncertainty*)	• Lack of knowledge or incomplete information • Can potentially be reduced through further research, improved models, or enhanced data	• Incomplete, imprecise or imperfect knowledge about the interaction of macro-financial and climate-related shocks	• Collect more data and analyses (data uncertainty) • Average across different approaches to reduce scope for misspecification (model uncertainty)
Aleatory (or *stochastic uncertainty*)	• Intrinsic randomness, reflecting natural fluctuations that cannot be reduced by more knowledge, but can only be managed through probabilistic modelling • Irreducible as inherent to process	• Inherent randomness or variability in economic variables like interest rates, commodity prices or the financial consequences of weather events	• Seek to understand (even if not reducing) scope for contingent risk • Modelling prospective outcomes, e.g. through standard probability theory
Fundamental (Knightian) (or 'unknown unknowns')	• Probabilities are unknown, or even unknowable ('radical' uncertainty) • Unpredictable, though possibly partly irreducible	• Deep structural unknowns, such as unprecedented technological disruptions, regime shifts or geopolitical ruptures, that defy modelling and are not even probabilistically predictable in the absence of a known model or stable structure	• 'What if' blue sky thinking, benchmarking to previous events (scaled up as needed) • Agility to unfolding risk
Strategic (or game theoretic)	• Probability or outcome depends on interactions with other actors whose actions are not a priori known • Partly reducible to the extent actions of others are known (or can be modelled)	• Interdependent decisions, such as limited to individual carbon reduction at scale in the absence of collective action, given externalities	• Encourage mechanisms which generate helpful collective action • Ease the burden of facing complexity, through less binding policy action • Tackle high discount rates through transition planning

Source: Authors

Combining sources of shocks in scenario analysis

Carefully constructed scenario analysis can help shed light on how two sources of risk interact and compound before reaching the financial system (first-round effects), and how they are amplified within the financial system and through feedback with the real economy (second-round effects).

Ranger et al. (2021), for example, provide a framework for assessing the economic losses associated with compounding climate-related, economic and pandemic shocks. They summarise their results with a new metric, the **compound risk multiplier,** to measure the scale of the amplification effect and estimate that the GDP impacts of the compound shock can be 50% larger than the sum of the individual shocks. Although their framework does not directly assess losses for the financial sectors — the relevant metrics for macroprudential capital buffers calibrations — it can serve as a base for evaluating the economic impact of compound shocks before translating them into the banking sector's losses.

Compound shocks are also explored in ECB/ESRB (2023) with a scenario analysis for shocks involving climate-related and financial disruptions. The results indicate that the materialisation of climate-related risk under an adverse macroeconomic scenario may lead to compounding effects as feedback loops intensify bank losses. The evaluation of the 'Fit for 55' European climate transition, performed by the European Central Bank and others (EBA et al., 2024), is another example of an **approach combining sources of risks.** It combines transition risks with macro-financial stress and assesses aggregate losses for the financial sector, highlighting:

1. **Shock compounding interaction.** Concretely, losses for the financial sector are assessed in three scenarios: a baseline scenario in which the transition happens in a normal economic environment, an adverse scenario in which transition risks are amplified by a run on carbon-intensive firms' assets, and finally a second adverse scenario in which transition risks are amplified by a run on carbon-intensive firms' assets and happen in conjunction with standard macro-financial stress.
2. **Financial sector amplification.** In all these scenarios, the initial shocks are amplified by financial markets through fire sales, creating price-volume margins and loss spirals as detailed in Brunnermeier and Pedersen (2009). This analysis could, in principle, support the calibration of compound capital requirements.

Building robust scenario analysis

Relying on one model to underpin a scenario of compound risk raises questions about the errors associated with its misspecification. To address this, policymakers can utilise a suite of models to ensure a comprehensive search over plausible but severe alternatives. This approach has been de facto deployed by central banks to uncover prospective climate-related losses. The ECB, for example, in the last year, has performed several estimations of banks' losses from climate risks, each using different models, scenarios and methodologies (bottom-up vs top-down), and each addressing specific questions, such as the time horizon (long-run cost–benefit vs short-run transition dynamics) or scope (banking vs system-level interactions).[24] A practical option in this respect is to minimise data or model uncertainty by **averaging across different approaches** to reduce the scope for misspecification.

Addressing aleatory uncertainty

Lasting unpredictability is referred to as aleatory (or stochastic). Such uncertainty, as the dice icon in Table 6.1 would suggest, pertains to intrinsic randomness. This strand of uncertainty is, in this respect, inherent to the process and is therefore irreducible. A practical option in this respect is to seek to understand, even if not reduce, the potential for contingent risk to materialise in the vein of extreme systemic risk events.

[24] See Alogoskoufis et al. (2021), ECB (2022), Emambakhsh et al. (2023), ECB and ESRB (2022), and EBA et al. (2024).

Uncovering correlations

While the changing correlation between climate-related and macro-financial shocks may not have been specifically examined, the standing banking regulation contains provisions to cater for **correlations between two or more financial variables** that can change unfavourably:

- As noted in Meissner (2019), several methods exist to estimate such correlations, from simple statistical correlation models such as cointegration, to deterministic financial correlation models such as copulas, or stochastic correlation models such as dynamic conditional correlations.
- Associated methods have also informed Basel regulation, such as CVaR (credit value-at-risk), which derives correlated credit risk for standard debt portfolios such as bonds and loans, or CVA (credit value adjustment), which derives correlated credit risk for derivatives.
- Risks with shifting correlations can, to some extent, be managed through diversification, and, in that case, finely calibrated microprudential actions can remove systematic risk. At the same time, shifting correlations also imply some degree of undiversifiable risks, which can be sources of systemic risk and financial instability.

Tackling intractable model uncertainty with stochastic scenarios

In a setting of high uncertainty, traditional scenario analysis and stress testing may face limits as interactions of climate-related financial risk with standard macro-financial shocks are hard to predict. One practical alternative to finely specified 'narrative-based' stress testing is moving to a stochastic scenario approach to assess the banking sector's vulnerability in **multiple plausible climate-related and macro-financial scenarios.** Confronting aleatory (or stochastic) uncertainty can be best achieved by examining combinations and permutations of numerous, inherently unpredictable shocks. Constructing decision trees is one possible approach to addressing uncertainty, and 'what if' shock approaches can help assess what shock interaction could yield significant increases in left-tail risk.

The IMF (2022) illustrates an **approach in which decision trees are deployed** to build out corporate loss distributions from various paths of transition risk. It uses binomial tree structures to conceptualise multiple states of the world consisting of pathways branching out into the future instead of a single deterministic path of global action (see Figure 6 in IMF, 2022). The latter is then simplified using a simple stochastic Monte Carlo simulation at each point in time. These simulations, in turn, can be processed in a financial model. A jump diffusion methodology is deployed to assess the scope for sudden and large increases in corporate spreads from the continuous and large jumps modelled with the tree structures, including shocks such as conflicts and fragmentation (see Figure 8 in IMF, 2022). The resulting corporate default probabilities are then mapped into shifting tails in the loss distribution for bank capital (see Figure 11 in IMF, 2022).

Similarly, one could also envisage the case in which, following different policy decisions as time passes, the **economy switches between different scenarios** and sometimes reverts to previous policy conditions. For example, Hambel and van der Ploeg (2025) propose a model in which transition risk results from probabilistic changes between three climate policy states: no, modest and ambitious carbon pricing. This model accounts for the possibility for policymakers to, for example, move progressively from no carbon price to a modest and then an ambitious carbon pricing policy, but then revert to no carbon price a few years later.

Keeping stochastic scenarios tractable

One possibility for converting stochastic scenario analysis into metrics directly usable for the calibration of buffers is to **combine several single scenario analyses into one probabilistic loss distribution function** by assigning probabilities to each climate scenario and the associated losses. This approach enables accounting for possible path outcomes and summarises them into one loss distribution function that can serve as a basis for buffer calibration. For example, Rebonato et al. (2025) propose a novel framework for attributing probabilities to long-term climate scenarios.

A further approach is to **deploy recent advances in machine learning and artificial intelligence to assist in analysing a high volume of prospective severe scenarios,** as well as ensuring that stochastic scenarios do not overfit the data in-sample, thereby avoiding the risk of 'fighting the last war'. Several methods exist for this purpose. As noted in Osbat et al. (2025), there are several methods to tackle this through 'regularisation' — both linear (ridge regressions, least absolute shrinkage methods, or elastic nets), or non-linear (random forests and decision trees). For example, a popular approach like random forests can be strengthened through bootstrapping, associating robustness with different shocks, subsampling at each split of a decision branch, or shrinking the universe of alternatives by pruning branches. This helps mitigate the risks of fitting training data too closely.

Advances in quantile regression methods are another approach to strengthen the suite of scenarios for compound risk. For example, Adrian et al. (2025) offer a Bayesian methodology based on quantile regressions to bridge scenario analysis and risk forecasting. This approach allows for validating or augmenting standard narrative stress testing with statistical inference. This method also provides a synthetic 'backstop' scenario which can act as a 'red flag' for macroprudential supervisors when the set of scenarios they consider fails to account for risks, especially tail risks, supported by statistical inference.

Another way to address the computational challenges of stochastic scenario analysis is to **downsize the number of possible outcomes.** Aikman et al. (2024), for example, identify macro-financial risk factors of particular relevance for the banking system and individual banks and search only for the scenarios that could push them towards their worst outcomes. Expressing scenario narratives as causal models could also narrow down possible scenarios. For example, Colesanti Senni and Goel (2025) provide a Bayesian algorithm that probabilistically evaluates whether a quantitative scenario is consistent with a certain narrative about nature–economy linkages. This data-driven approach allows the user to choose plausible scenarios from several possibilities.

Addressing fundamental (Knightian) uncertainty

Unlike epistemic or aleatory uncertainty, fundamental uncertainty arises when key variables, causal mechanisms or future scenarios are unknown or unknowable. **Compound climate-related and macro-financial risks are subject to fundamental uncertainty** because they involve deep structural changes, complex feedback loops and unprecedented interactions, such as the potential tipping points in climate systems or political responses to economic shocks, that cannot be fully anticipated or probabilistically modelled.

When risks are subject to such complexity and deep uncertainty, Sharma (2025) suggests that **simpler heuristic approaches may dominate complicated optimisation strategies** when designing macroprudential policy. He recommends, in particular, using a simple leverage ratio instead of an overly complex and potentially misspecified risk-weighted asset approach to calibrate capital requirements. This approach could be adopted for macroprudential buffers, which currently rely on risk-weighted assets as the basis for calibration. Following Admati and Hellwig (2024) and many others, he also suggests increasing buffers for financial institutions to reflect heightened risks associated with such complex and deep uncertainty.

Addressing strategic uncertainty

A last class of uncertainty about climate-related and macro-financial risks is 'strategic'. Indeed, policy decisions are key in shaping the evolution of climate-related and macro-financial risks, but they involve the interplay of individual incentives, sometimes at odds with collective decision-making. Strategic uncertainty is closely linked to the distinction between cooperative and competitive equilibria in game theory, describing the outcomes of **strategic interactions among players.** The transition from a competitive equilibrium to a cooperative equilibrium requires several elements — from basic ones such as trust, to commitment mechanisms such as enforceable agreements and financial incentives, to catalysing forces such as strong leadership.

Inaction bias may be one potent outcome of strategic uncertainty. It occurs when individuals, organisations or governments are more likely to avoid making decisions or taking actions, even when those decisions or actions could potentially lead to better outcomes. Such biases can stem from various factors — notably externalities, complexity and discounting.

There's safety in numbers: collective action

A first class of inaction bias stems from externalities, which may be present if adjustments are costly, implying strength in collective adjustment. Narita and Wagner (2017) note that the equilibrium adoption of a breakthrough abatement technology may be indeterminate. Adopting breakthrough technology will be complete only if countries expect all other countries to adopt it. Network externalities are known to create strategic complementarities that may lead to tipping points, particularly for costly adjustments. Collective action can benefit from **cooperative mechanisms,** like credible long-term targets, binding or non-binding, to encourage collaboration, conformity or momentum.

Paralysis by analysis: complexity

A second strand of inaction bias may stem from complexity, which may imply limits to evidence-based policy relying on observed empirical regularities. When decisions are complex or involve uncertainty, the temptation to postpone them can be strong.

Hale and Sharma (2024) tackle the issue by updating both risk distributions and prior beliefs for physical risk. In so doing, they note at least three key differences between climate-related shocks and other shocks traditionally modelled in asset pricing literature: first, climate-related shocks do not come from a fixed distribution, but rather from a distribution with mean and variance that increase over time; second, there is fundamental uncertainty about the climate parameter that drives this distribution shift; third, there is uncertainty about climate scenarios due to policy and technology uncertainty concerning climate change mitigation actions. In such an environment, **strategic uncertainty may be exacerbated because divergent beliefs** (shifting priors) imply fundamental disagreements about complex and difficult-to-predict features of climate change. In this vein, prior belief updating from manifestations of climate-related shocks might come in four varieties, that is (i) rational updating, (ii) adaptive updating, (iii) step updating and (iv) denial/no updating.

When faced with complexity, postponement is often a way to avoid overwhelming tasks or to delay action until circumstances feel more manageable. Climate change, however, will only worsen, implying that mechanisms are warranted to **ensure a 'precautionary' approach.** Such an approach requires convincing forward-looking modelling of prospective climate-related loss, departing from backtesting common to the assignment of shock probabilities. As noted in Chenet et al. (2021), a highly complex financial system involving unpredictable reactions and interactions between market players (including governments) can create non-linear dynamics with high potential for positive feedback loops, covariance of risk probabilities and hard-to-quantify (at least ex ante) 'fat tails'. With this in mind, the authors call for a 'precautionary financial policy' approach, drawing on the 'precautionary principle' and macroprudential policy.

Exploring **less binding policy actions** can help increase the appeal of precautionary approaches and the implied easing of the buffer level when necessary. Specifically, this could be thought of as a relaxation of thresholds for conditional probabilities underpinning policy action. The presence of releasable buffers may reduce the perceived irrevocability of action and help shift policymaker preferences across type 1 (missed opportunities) and type 2 (unneeded action) errors.

Live for today, worry about tomorrow: discount rates

A last source of inaction bias may stem from **discount rates, which might be skewed towards the present** when the immediate costs of an action are visible, while the long-term benefits are uncertain or intangible. This might apply notably to political cycles, financial remuneration and other present-biased motives. Aikman et al. (2013) outline three prominent cases of such strategic global games in finance. A first is 'systemic risk shifting', or the effects of a limit in the supply of 'good' risky projects — projects that are risky but yield high returns with a relatively high probability. A second class of global games involves reputational concerns, whereby the privately optimal action depends on what others are doing. The third example of global gains outlined relates to moral hazard, whereby failing collectively may entail benefits.

Sound **transition planning** can help tackle high discount rates. Such planning clearly has a role to play as a commitment device in such settings. Smoleńska and Poensgen (2025) outline concrete ways in which transition planning can be translated into effective supervision and management of climate-related financial risk.

7. Conclusions and recommendations

This report has underscored the critical importance of addressing compound risks, particularly those resulting from the interaction of climate-related and traditional macro-financial risks. Such interactions can amplify systemic vulnerabilities in the financial sector, resulting in aggregate losses that exceed the sum of their parts. By exploring theoretical frameworks and practical approaches, the report has made the case for a consolidated macroprudential buffer framework to ensure the financial system's resilience under increasingly complex and uncertain conditions.

A combination of macroprudential capital buffers tailored and earmarked to specific risks strengthens the banking sector's resilience to systemic risks. These buffers are thus key instruments for macroprudential authorities. However, earmarked buffers might fail to account for the interactions of shocks, like those of compound climate-related and macro-financial risks. Thus, earmarked approaches possibly suffer from a *fallacy of composition*, whereby ultimate loss is not additive, and buffer stacks fail to address compound losses. This motivates a more careful consideration of the impacts of combined shocks and assessment of the merits of alternative approaches to address them.

Shifting from an earmarked to a consolidated approach to macroprudential buffers is a promising way to address compound risks. The traditional approach of stacking individual buffers may fail to capture the non-linear and compound effects of risk interactions, leading to an underestimation of systemic risks and inadequate unexpected loss-absorption capacities through macroprudential buffers. A consolidated framework, on the other hand, is less subject to the fallacy of composition inherent in separate calibrations. It thus provides a more robust mechanism for assessing compound aggregate losses and implementing buffers that account for them.

This holistic approach does have its limits, as novel risks, such as climate-related risks, are inherently harder to estimate given the significant uncertainty surrounding them. This uncertainty can be of different natures — epistemic, aleatory, Knightian and strategic — and the different types of uncertainty require different approaches. While recognising these challenges, the report has also provided practical ways to work around this uncertainty in calibrating macroprudential buffers, many of which are based on methodologies developed by regulators and supervisors to assess climate-related risks. The experience gained by supervisors in this area is a sound basis for developing methods to address the challenges associated with compound risks.

Recommendations

Macroprudential authorities can make an integral contribution to a more resilient financial system capable of withstanding the evolving challenges posed by climate change, economic shocks and their complex interplay. For that, we recommend that macroprudential policymakers:

- **Adopt a holistic approach to macroprudential buffer setting,** which captures interactions between novel sources of systemic risk, such as climate-related risks, and more established sources of systemic risk, such as macro-financial conditions.
- **Be mindful of the limits of earmarked buffers in the context of compound risks.** The policy response to mitigate these limits could lie on a continuum between a maximalist approach (consolidated buffers addressing multiple sources of prospective compounding systemic risk) and a more minimalist approach (holistic systemic risk assessments accounting for prospective compound risks that serve as a complementary cross-check for existing earmarked buffers).

While also recognising the uncertainty associated with assessing compound risks and implementing macroprudential capital buffers, we recommend the following practical ways to calibrate macroprudential buffers:

- **Leveraging the methodologies developed by supervisors to address uncertainty,** including in the context of climate-related risks. This way, policymakers can better prepare for the unpredictable and often unprecedented nature of compound risks with advanced scenario analysis, stochastic scenario modelling and probabilistic approaches. They can also overcome potential inaction biases by prioritising collective action, while strengthening resilience through transition planning mechanisms and forward-looking strategies.
- **Adopting an adaptive and forward-looking approach to macroprudential policy implementation.** A dynamic, forward-looking calibration of buffers can better reflect the evolving landscapes of risks and the development of knowledge about them. A progressive deployment of measures, factoring in learning that accompanies implementation, could help macroprudential authorities fine-tune buffer calibration.

References

Acharya V, Pedersen L, Philippon T and Richardson M (2017) Measuring systemic risk. *The Review of Financial Studies* 30(1): 2–47. https://academic.oup.com/rfs/article-abstract/30/1/2/2682977?redirectedFrom=fulltext

Admati AR and Hellwig MF (2024) *The parade of the bankers' new clothes continues: 44 flawed claims debunked*. European Corporate Governance Institute Working Paper, 951. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2292229

Adrian T, Giannone D, Luciani D and West M (2025) *Scenario synthesis and macroeconomic risk*. IMF WP/25/105. https://www.imf.org/en/Publications/WP/Issues/2025/05/29/Scenario-Synthesis-and-Macroeconomic-Risk-566954

Aikman D, Angotti R and Budnik K (2024) *Stress testing with multiple scenarios: a tale on tails and reverse stress scenarios*. ECB Working Paper No. 2941, May. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4830237

Aikman D, Haldane A and Nelson B (2013) Curbing the credit cycle. *The Economic Journal Volume* 125(585). https://onlinelibrary.wiley.com/doi/full/10.1111/ecoj.12113

Alogoskoufis S, Dunz N, Emambakhsh T, Hennig T, Kaijser M, Kouratzoglou C, et al. (2021). *ECB economy-wide climate stress test*. ECB Occasional Paper Series 281, September. https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op281~05a7735b1c.en.pdf

Alla Z, Espinoza RA, Li QH and Segoviano MA (2018) *Macroprudential stress tests: a reduced-form approach to quantifying systemic risk losses*. IMF Working Paper 18/49. https://www.elibrary.imf.org/view/journals/001/2018/049/article-A001-en.xml

Bartsch F, Busies I, Emambakhsh T, Grill M, Simoens M, Spaggiari M, et al. (2024) *Designing a macroprudential capital buffer for climate-related risks.* ECB Working Paper No. 2943. https://www.ecb.europa.eu/pub/pdf/scpwps/ecb.wp2943~1bf261835d.en.pdf

Basel Committee on Banking Supervision [BCBS] (2010) *Guidance for national authorities operating the countercyclical capital buffer*. Bank for International Settlements. https://www.bis.org/publ/bcbs187.pdf

Basel Committee on Banking Supervision [BCBS] (2019a) *RBC 30 Buffers above the regulatory minimum*. https://www.bis.org/basel_framework/chapter/RBC/30.htm?inforce=20191215&published=20191215

Basel Committee on Banking Supervision [BCBS] (2019b) *RBC 40 Systemically important bank buffers.* https://www.bis.org/basel_framework/chapter/RBC/40.htm?inforce=20191215&published=20191215

Basel Committee on Banking Supervision [BCBS] (2019c) *SCO 50 Domestic systemically important banks.* https://www.bis.org/basel_framework/chapter/SCO/50.htm?inforce=20191215&published=20191215

Basel Committee on Banking Supervision [BCBS] (2021a) *SCO 40 Global systemically important banks.* https://www.bis.org/basel_framework/chapter/SCO/40.htm?inforce=20211109&published=20211109

Basel Committee on Banking Supervision [BCBS] (2021b). *Climate-related risk drivers and their transmission channels*. Basel Committee on Banking Supervision Discussion Paper, April. https://www.bis.org/bcbs/publ/d517.htm

Basel Committee on Banking Supervision [BCBS] (2022) *Buffer usability and cyclicality in the Basel framework.* Report of the Basel Committee on Banking Supervision, October. https://www.bis.org/bcbs/publ/d542.htm

Basel Committee on Banking Supervision [BCBS] (2024a) *The role of climate scenario analysis in strengthening the management and supervision of climate-related financial risks*. Basel Committee on Banking Supervision Discussion Paper, April. https://www.bis.org/bcbs/publ/d572.pdf

Basel Committee on Banking Supervision [BCBS] (2024b) *Range of practices in implementing a positive neutral countercyclical capital buffer*. Bank for International Settlements, November. https://www.bis.org/bcbs/publ/d585.pdf

Behn M, Rancoita E and Rodriguez d'Acri C (2020) Macroprudential capital buffers — objectives and usability. *ECB Macroprudential Bulletin*, October. https://www.ecb.europa.eu/press/financial-stability-publications/macroprudential-bulletin/html/ecb.mpbu202010_1~01c4f1a5f4.en.html#toc2

Budnik K, Groß J, Vagliano G, Dimitrov I, Lampe M, Panos J, et al. (2023) *Beast: A Model for the Assessment of System-Wide Risks and Macroprudential Policies.* ECB Working Paper No. 2023/2855. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4599639

Brunnermeier M and Pedersen L (2009) Market liquidity and funding liquidity. *Review of Financial Studies* 22: 2201–2238. https://markus.scholar.princeton.edu/publications/market-liquidity-and-funding-liquidity

Catapano G., del Vecchio L., Galardo GG and Petrarca I. (2024) *Increasing macroprudential space in Italy by activating a systemic risk buffer*. Banca d'Italia Occasional Papers 848, April. https://www.bancaditalia.it/pubblicazioni/qef/2024-0848/index.html

Chenet H, Ryan-Collins J and van Lerven F (2021) Finance, climate-change and radical uncertainty: towards a precautionary approach to financial policy. *Ecological Economics* 183(May). https://www.sciencedirect.com/science/article/pii/S092180092100015X

Coelho R and Restoy F (2024) *Capital buffers and the micro-macro nexus.* Bank for International Settlements, FSI Brief 24, July. https://www.bis.org/fsi/fsibriefs24.htm

Colesanti Senni C and Goel S (2025) Nature scenario plausibility: a dynamic Bayesian network approach. *Ecological Economics*, 236. https://www.sciencedirect.com/science/article/pii/S0921800925001302

Danielsson J. (2025) *Artificial intelligence and stability*. VoxEU.org. https://cepr.org/voxeu/columns/artificial-intelligence-and-stability

European Banking Authority [EBA], European Insurance and Occupational Pensions Authority [EIOPA], European Securities and Markets Authority [ESMA], and European Central Bank [ECB] (2024) *Fit for 55 climate scenario analysis*. Joint paper of the European Supervisory Authorities and the European Central Bank, November. https://www.eba.europa.eu/sites/default/files/2024-11/08fef16f-7505-4e32-9444-126cca0f69d5/Report%20on%20fit%20for%2055%20climate%20scenario%20analysis.pdf

European Central Bank [ECB] (2022) *2022 climate risk stress test*, July. https://www.bankingsupervision.europa.eu/ecb/pub/pdf/ssm.climate_stress_test_report.20220708~2e3cc0999f.en.pdf

European Central Bank [ECB] and European Systemic Risk Board [ESRB] (2022) *The macroprudential challenge of climate change*, July. https://www.esrb.europa.eu/pub/pdf/reports/esrb.ecb.climate_report202207~622b791878.en.pdf

European Central Bank [ECB] and European Systemic Risk Board [ESRB] (2023) *Towards macroprudential frameworks for managing climate risk*. Report of the ECB/ESRB Project Team on Climate Risk, December. https://www.esrb.europa.eu/pub/pdf/reports/esrb.report202312~d7881028b8.en.pdf?bc89d982ac0f87466507bbe82686f64a

Emambakhsh T, Fuchs M, Kördel S, Kouratzoglou C, Lelli C, Pizzeghello R, et al. (2023) *The road to Paris: stress testing the transition towards a net-zero economy*. ECB Occasional Paper Series 328.

https://www.ecb.europa.eu/pub/pdf/scpops/ecb.op328~2c44ee718e.en.pdf?7793485730460e4e0b4e170237eb7429

Financial Stability Board [FSB], International Monetary Fund [IMF] and Bank for International Settlements [BIS] (2009) *Guidance to assess the systemic importance of financial institutions, markets and instruments: initial considerations*. Report to G20 Finance Ministers and Governors. https://www.bis.org/publ/othp07.pdf

Hale G and Sharma B (2024) Climate beliefs and asset prices. *VoxEU column,* October. https://cepr.org/voxeu/columns/climate-beliefs-and-asset-prices

Hambel C and van der Ploeg F (2025) Policy transition risk, carbon premiums, and asset prices. *Journal of Monetary Economics* 152. https://www.sciencedirect.com/science/article/pii/S0304393225000510

Hamar A (2010) *Stress-testing a credit portfolio with correlations and strategically managing portfolio limits*. Moody's Analytics. https://www.moodys.com/sites/products/ProductAttachments/Stress%20Testing%20a%20Credit%20Portfolio%20with%20Correlations.pdf

Hernández de Cos P. (2023) *The role of macroprudential policy in the stabilisation of macrofinancial fluctuations.* Speech at Conference on Financial Stability/Banco de Portugal, October. https://www.bis.org/review/r231002d.pdf

Hirtle B (2011) *How were the Basel 3 minimum capital requirements calibrated?* Liberty Street Economics, New York Fed. https://libertystreeteconomics.newyorkfed.org/2011/03/calibrating-regulatory-minimum-capital-requirements/

Holscher M, Ignell D, Lewis M and Stiroh K (2022) *Climate change and the role of regulatory capital: a stylized framework for policy assessment*. Finance and Economics Discussion Series, Federal Reserve Board. https://www.federalreserve.gov/econres/feds/files/2022068pap.pdf

Intergovernmental Panel on Climate Change [IPPC] (2022). *Glossary.* https://apps.ipcc.ch/glossary/

International Monetary Fund [IMF] (2022) *Mexico financial sector assessment program: technical note on climate risk analysis*. IMF Country Report No. 22/360. https://www.imf.org/en/Publications/CR/Issues/2022/12/08/Mexico-Financial-Sector-Assessment-Program-Technical-Note-on-Climate-Risk-Analysis-526754

Meissner G (2019) *Correlation risk modelling and management.* Risk Books; 2nd Edition. https://www.riskbooks.com/correlation-risk-management-and-modelling-2nd-edition

Muñoz M and Smets F (2025) *Macroprudential policy for banks: build the countercyclical capital buffer when there is headroom for doing so.* CEPR, July. https://cepr.org/voxeu/columns/macroprudential-policy-banks-build-countercyclical-capital-buffer-when-there-headroom

Narita D and Wagner UJ (2017) Strategic uncertainty, indeterminacy, and the formation of international environmental agreements. *Oxford Economic Papers* 69(2): 432–452. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2747315

Network for Greening the Financial System [NGFS] (2023). *Compound risks: implications for physical climate scenario analysis*. https://www.ngfs.net/system/files/import/ngfs/media/2023/11/07/ngfs_compound_risks_implications_for_physical_climate_scenario_analysis.pdf

Osbat C, Vidal-Quadras Costa I and Kuik F (2025) *Earth, wind, fire and grocery bills: exploring the nonlinear relationship between food prices and the weather in the euro area.* ECB Working Paper.

OSFI (2024) *Domestic stability buffer*. https://www.osfi-bsif.gc.ca/en/supervision/financial-institutions/banks/domestic-stability-buffer

Ranger N, Mahul O and Monasterolo I (2021) Managing financial risks of climate change and pandemics: what we know (and don't know). *One Earth* 4(10): 1375–1385. https://www.sciencedirect.com/science/article/pii/S259033222100539X

Rebonato R, Melin L and Zhang F (2025) *How to assign probabilities to climate scenarios*. EDHEC Climate Institute. https://climateinstitute.edhec.edu/publications/how-assign-probabilities-climate-scenarios?_cldee=wL5Uute8WM-vY8yDQeDZds_XeW4mqL4oUbkLwrBGj5Yls2IMu1hto-w84RFk-oRM&recipientid=lead-8c929a16d8a8ea11a812000d3a4aab49-13d401be82da4889bc1308479bb96535&esid=7397c119-593a-f011-b4cc-6045bd8ce8aa

Sharma S (2025) Financial resilience in an age of environmental change: central banks and financial regulators feel the heat. *Banking and Financial Services Policy Report* 44(6). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5366651

Smoleńska A and Poensgen I (2025) *Integrating transition planning into prudential supervision.* London: Centre for Economic Transition Expertise, London School of Economics and Political Science. https://cetex.org/wp-content/uploads/2025/05/Integrating-bank-transition-planning-into-prudential-supervision_CETEx.pdf

Sydow M, Schilte A, Covi G, Deipenbrock M, Del Vecchio L, Fiedor P, et al. (2024) Shock amplification in an interconnected financial system of banks and investment funds. *Journal of Financial Stability* 71. https://www.sciencedirect.com/science/article/abs/pii/S1572308924000196

Woods S (2022) *Bufferati.* Speech by Sam Woods Given at City Week, April. https://www.bankofengland.co.uk/speech/2022/april/sam-woods-speaking-at-city-week-2022-developments-in-prudential-regulation-in-the-uk

Zscheischler J, Westra S, van den Hurk BJJM, Seneviratne SI, Ward PJ, Pitman A, et al. (2018) Future climate risk from compound events. *Nature Climate Change* 8: 469–477. https://www.nature.com/articles/s41558-018-0156-3

Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, et al. (2020*) A typology of compound weather and climate events. Nature Reviews Earth and Environment* 1: 333-347. https://www.nature.com/articles/s43017-020-0060-z?utm_source=chatgpt.com