Macroprudential Stress Testing for Climate Change Shocks: A Case Study of the Indonesian Banking System

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Abstract

Using a combination of three approaches—climate change disasters, damage functions, and the G-CUBED model—this study develops macroeconomic scenarios that consider climate change risks and address the limitations of traditional macroeconomic scenario design. The analysis focuses on the impact of climate change shocks on productivity and financial channels, including labour, total factor productivity (TFP), household risk, and asset prices. Additionally, it examines how these shocks influence economic output and inflation, two macroeconomic variables critical for transmitting the impact of shocks to the banking system. This paper extends the analysis to evaluate the banking industry's resilience to these shocks. The findings underscore the importance of considering all potential risk transmission channels in assessing the impact of climate change. When such shocks significantly affect the banking system, they can lead to notable deterioration in banks' Capital Adequacy Ratio (CAR). Moreover, the economy's internalisation of these losses can result in a substantial reduction in economic output.

Section 1. Introduction

Historical crises have shown that focusing solely on one aspect of potential shock sources and vulnerabilities is insufficient for economic and financial system stability. This condition also applies to stress-testing frameworks, which make the assessment result insufficient. Originally developed to assess the banking system's ability to withstand shocks, stress testing has evolved into a critical tool for identifying banks that might encounter difficulties under adverse macro-financial conditions.

Stress testing typically involves evaluating the resilience of banking and financial systems through adverse and severe scenarios. It builds upon concerns highlighted by Diamond and Dybvig (1983) and Friedman and Schwartz (1963) about how pressures on groups of banks can lead to financial instability. This framework helps capture the banking system's resilience when facing various shocks.

Shocks may stem from several sources, including idiosyncratic distress in banks with similar business models, exogenous shocks from macroeconomic conditions, or endogenous disturbances within the financial system (Tirole, 2011). Recent developments indicate that shocks can be amplified and propagated through transmission channels tied to financial and informational networks (Hałaj & Christoffer, 2013; Dang et al., 2015; Taruna et al., 2020a).

The COVID-19 pandemic highlighted that current stress-testing frameworks often fail to adequately integrate liquidity and solvency concerns. Even prior to this crisis, Borio et al. (2014) noted the limitations of existing frameworks in detecting financial vulnerabilities before crises emerge. This limitation was evident during both the Global Financial Crisis and the pandemic.

Key issues in current stress-testing frameworks involve at least three challenges. Firstly, the implausible macroeconomic scenario designs do not effectively mimic historical distress dynamics. Secondly, stress testing modules are unable to capture risk transmission resulting from credit restructuring policies, varying restrictions on community activities, and unexpected externalities. Finally, business-related shocks remain unaccounted for, as these frameworks rely heavily on historical data.

This paper explores the challenges and opportunities associated with stress testing in the context of climate change. Using the G-CUBED model (version 6G), it examines how severe climate change shock affects economic and financial systems. The analysis focuses on two primary risk channels:

1. Productivity Channel: Total factor productivity, labour, and household risk.
2. Financial Channel: Financial asset risk premiums manifest as unanticipated changes in asset prices.

This paper proposes several adjustments to current stress-testing frameworks to incorporate climate change shocks. These adjustments include developing macroeconomic scenarios that integrate climate change and its transmission effects using the G-CUBED model, as well as employing Indonesian banking data from tranquil periods (2022) and projected distress periods (2023 and 2024).

The analysis highlights the resilience of Indonesia’s financial system, as demonstrated during the Global Financial Crisis and the COVID-19 pandemic. Indonesia’s capital markets offer critical insights into transition risk dynamics and the transmission of exchange rate risks, as evidenced during the Asian Financial Crisis.

This paper concludes that a sudden and severe climate change shock can significantly disrupt the economy and the financial system, leading to substantial economic losses. Such a shock adversely affects the operations of financial agents, capital market transactions, and household consumption, ultimately resulting in a marked decline in economic growth. Furthermore, decreasing productivity diminishes the repayment capacity of economic agents.

Through detailed bank-by-bank stress testing, the study assesses the resilience of Indonesia's banking system in the face of climate change shocks. The findings indicate that while the banking system is generally resilient enough to withstand such shocks, at least one bank has defaulted as a direct consequence of these events. Although the aggregate banking system remains stable, the risks of amplification and contagion could pose significant challenges if not adequately addressed. Therefore, targeted policy responses must be developed to mitigate the adverse effects of climate change-induced shocks on the financial sector.

This research is structured as follows: Section 2 provides an overview of historical crises, contemporary stress-testing frameworks, and the macro-financial dynamics of climate change. Section 3 outlines the data and methodologies, which include the G-CUBED model and the banking stress-testing framework. Section 4 presents the estimation results and discusses potential central bank policy responses. The paper concludes in Section 5, which also includes recommendations for future research.

Section 2. From Crises to Climate Shocks: Understanding Macrofinancial Risks in Indonesia

2.1. Historical Crises

Historical crises such as the Great Depression (1930s), the Asian Financial Crisis (1998), the Global Financial Crisis (2008), and the COVID-19 pandemic illustrate the difficulty of incorporating unexpected externalities into macroeconomic scenarios. These crises significantly impacted GDP, with medium-term effects (three years or more) worsening economic outcomes. For example, during the Asian Financial Crisis, Japan's real GDP growth dropped by 2.15% year-over-year (YoY) between 1996 and 1997, while Indonesia's plummeted to -13.1% YoY in 1998.

Despite advancements in financial resilience, unforeseen risks continue to pose significant challenges in prediction. For example, during the COVID-19 pandemic, Indonesia experienced a contraction in real GDP growth of -2.1% year-on-year, underscoring the capacity of unforeseen shocks to disrupt even the most resilient systems. Such instances illuminate the profound effects of crises on economic output and related indicators, including wages, deflation, and credit disbursement. An illustrative case for Indonesia is the impact of exchange rate shocks during the Asian Financial Crisis, culminating in escalating debt levels and defaults, further exacerbating adverse economic conditions. Additionally, the Global Financial Crisis of 2008 marked a profound transformation in global liquidity dynamics.

While financial authorities have endeavoured to analyse the root causes of vulnerability, historical financial crises have consistently demonstrated that unknown factors often instigate them. Given the inherent nature of financial agents, which tends to overlook the potential for significant disruptions that can trigger financial crises, a comprehensive evaluation of economic and financial system stability is imperative. The failure to accurately assess and mitigate potential vulnerabilities and shocks can have profound implications for economic performance. The historical repercussions of financial crises on real GDP underscore the critical importance of developing strategies to mitigate the risk of future financial upheavals.

2.2. Macrofinancial Dynamics & Solvency Stress Testing

Designing realistic macroeconomic scenarios is critical for effective stress testing. Borio et al. (2014) argue that current frameworks fail to capture real-world dynamics due to limitations in scenario design. These frameworks often underestimate the amplification and propagation of shocks and the ever-changing risks in banking systems. Improvements in data and methods, such as using multiple credit loss models or IFRS 9 credit loss modules, could enhance stress-testing accuracy. These arguments are also documented by Wiersema et al. (2020), BIS (2020), Judge (2020), Bonucchi and Catalano (2020), and De Meo (2022). Although some of these studies try to answer Borio et al. (2014) concerns, they have not considered the possibility of shock amplification and propagation, as well as solvency and liquidity risk interaction. Previous studies failed to see two main issues in the ST framework: (i) amplification and propagation mechanism of a shock, and (ii) ever-changing risks in the banking system.

Like macroeconomic scenario design, calculating a solvency stress test (ST) requires elaborate data that may be difficult to obtain. A simple approach due to data constraints may cause an under- or overestimation of the risk. In any distress period, the solvency ST framework lacks expected credit risk in its calculation. Expected credit loss after the restructured credit is not realised until the financial authority announces the normalisation policy. Furthermore, the expected losses might not be fully realised since the financial agent will regain its repayment capacity and pay the restructured debt over time. For instance, one bank might suffer 80% of realised credit loss from restructured credit, while another might only face 60%[1]. Thus, the current scenario design and the solvency ST framework are lacking in this area. One possible way to estimate the expected credit loss is by using multiple credit loss models (Hirtle et al., 2009). Although multiple modules might help capture expected credit loss, this approach still falls short of Borio et al. (2014) and COVID-19 dynamics. Another possible approach is to use the International Financial Reporting Standard number 9 (IFRS 9) credit loss module[2].

Panic is a significant factor that can exacerbate a minor non-systemic crisis into a systemic crisis, underlining the need for an effective stress testing framework and risk management strategies. Credit dynamics and their potential interaction with other aspects of the banking system are not the only challenges. Risk amplification, propagation, and cross-border spillover are other challenges that must be included in any stress testing framework. The Global Financial Crisis shows us how a run-on Repo market could bring down almost the entire global financial system (Gorton & Metrick, 2012). Moreover, credit rationing by banks commonly happens in a time of crisis, and this could further worsen the economy (Barajas et al., 2010; Drehman et al., 2006). In this regard, Tirole (2011) argues that in a distress period, bank risk appetite drops significantly, thus reducing all liquidity and credit outlets to other banks. He continues that the impact of this risk aversion might cause harm not only to other banks but also to other sectors of the financial system.

2.2.1 Climate-change Scenarios and Their Drawback in Stress Testing Framework

Unlike crises induced by traditional financial mechanisms, those originating from climate change represent a phenomenon that has not yet been encountered. This distinction arises primarily from the inherent differences in the characteristics of financial and climate change-induced crises. Typically, financial turmoil manifests abruptly as a result of sudden shocks, which interact with an already vulnerable financial system, precipitating a crisis. Although vulnerabilities may accrue over time, the shocks can occur within a relatively brief time frame. In contrast, the shocks induced by climate change are likely to unfold over an extended

[1] Based on the Indonesia Financial Service Authority Regulation, the bank has to assess its potential losses from restructured credit. The assessment considers depositor repayment capacity in the current condition (COVID-19 environment) and analyses depositor credit structure. Although this regulation helps the bank assess expected credit loss from restructured credit, this assessment still has its issues. One issue is how accurately the bank could assess the depositor's repayment capacity.

[2] This module considers expected loss from performing and underperforming loans. The loss counted as lifetime losses; the loans will have a potential credit loss every time horizon until they mature.

temporal horizon. While existing vulnerabilities may persist within the financial framework, financial agents and regulatory authorities possess the capacity to respond to such shocks, as they can often foresee their occurrence.

Climate change scenarios lasting longer than 3 years and peaking longer than the first 3 years are common. While this practice is normal and likely close to real-world dynamics, it is insufficient to create a severe but plausible scenario. Various NGFS scenarios indicate that the development of climate change shock can happen in three to 25 years, which is longer than the stress testing periods.

In the stress testing framework, the test is conducted to assess the financial system's resilience in the face of an abrupt and severe shock. Hence, most of the literature does not provide the needed scenarios. Given the climate-change shock nature, this approach may seem impossible to implement. However, learning from historical crises reveals that all crises are caused by something that was deemed “impossible” to happen during the period of the crisis. This phenomenon is pointed out by Reinhart and Rogoff (2010)[3].

A later session provides more detailed information on how this paper argues that the stress testing framework is better off using a strong assumption that the climate change shock occurs abruptly and severely. Furthermore, the abrupt climate change shock scenario considers all previous historical crisis characteristics, capturing the shock transmission fully.

2.3. Climate Change – Disaster and Financial Turmoil

Climate change is increasingly recognised as a critical driver of disaster risk, with profound implications for economic stability. Rising global temperatures and shifting weather patterns amplify the frequency and severity of extreme events, such as floods, droughts, and storms, while compounding existing vulnerabilities in exposed economies (Fernando et al., 2024; Roson & Sartori, 2016). As Cappelli et al. (2021) highlight, these climate-induced disasters can trigger economic turmoil by destroying physical capital, disrupting labour markets, and depressing asset prices. Such dynamics create feedback loops that further erode environmental resilience and elevate disaster probability.

The economic costs of disasters materialise through both direct and indirect channels. Directly, disasters destroy productive assets and infrastructure, resulting in the loss of human

[3] In the recent NGFS scenario, NGFS proposed a similar situation in which severe physical and transition risks emerged unexpectedly. The scenario involves extreme weather events in 2026 and 2027 that cause financial instability (in the scenario design, NGFS base year was 2025).

lives. Indirectly, they cause wage declines, supply chain disruptions, and persistent output losses that weigh on medium-term growth (Hochrainer, 2009; Okuyama, 2003). The combined impact on labour and capital translates into broad productivity shocks, weakening public finances and undermining economic resilience.

This paper bases its scenario design on the causal link between climate change, disasters, and economic losses, positing that failures in climate mitigation and adaptation will intensify natural disasters, thereby amplifying economic damage over time.

Indonesia provides a compelling case study of these dynamics. Geographically situated within the Pacific Ring of Fire, the country faces elevated risks from both geological and climate-related hazards (The World Bank, 2019). Over the past eight years, disasters have affected at least 1 billion people and damaged 3.8 million hectares of landscapes and infrastructure. The cumulative economic losses are staggering, equivalent to 26% of Indonesia's average nominal GDP from 2015 to 2023, or more than twice the country's current GDP when aggregated over that period.

2.3.1 Provincial Exposure and Disparities in Disaster Losses

The geographic concentration of economic activity amplifies Indonesia's vulnerability. As shown in Figure 1, cumulative losses from 2015 to 2023 reveal that disaster impacts are particularly acute on the island of Java, which alone contributes 80% of Indonesia's GDP. The clustering of infrastructure and population in high-risk areas turns localised hazards into systemic economic shocks.

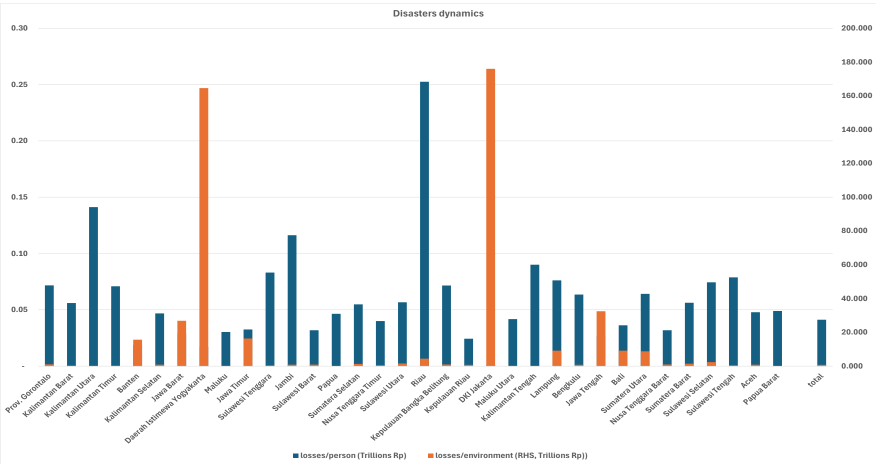

Figure 1 *Indonesia's provinces' disaster dynamics – cumulative losses from 2015 to 2023*

Disasters disrupt economic activity through multiple, reinforcing channels. The destruction of infrastructure and productive assets halts business operations and reduces working hours. Damage to transport and energy networks delays supply chains, extending output losses beyond the directly affected provinces. Crucially, disasters also degrade human capital through injury, displacement, and livelihood loss, shrinking the effective workforce and dragging on productivity.

These disruptions have tangible financial consequences. Over the past eight years, disaster-related losses in business hours and labour capacity are estimated at 0.7% of Indonesia’s total workforce. The associated financial toll exceeds double the nation’s current GDP, underscoring the compounding nature of disaster shocks.

Looking forward, climate change is expected to intensify these risks. Global temperatures exceeding 2°C would significantly increase the likelihood of severe climate-related disasters in Indonesia, further straining its economic heartlands. Without robust adaptation and disaster risk management measures, these shocks threaten to erode Indonesia's economic resilience and undermine long-term growth.

This paper’s empirical estimates of the macro-financial impacts of climate shocks aim to inform policy design. Quantifying the economic toll of disasters underscores the urgency of integrating climate risk into economic planning and financial stability frameworks to safeguard Indonesia's development trajectory.

In sum, the escalating risks of climate change and natural disasters pose not only humanitarian and environmental challenges but also profound macro-financial threats to Indonesia. The evidence presented highlights how these shocks simultaneously disrupt labour markets, destroy physical capital, and erode productivity, leading to persistent economic and financial losses. As climate change intensifies, these risks will compound, heightening vulnerabilities in key economic regions—particularly in Indonesia’s industrial heartlands—and threatening to derail the country’s long-term development trajectory.

This growing exposure underscores the urgent need for climate risk to be systematically integrated into economic planning, financial regulation, and resilience-building strategies. Against this backdrop, the next chapter introduces the empirical framework developed in this paper to quantify the macro-financial impacts of climate-related shocks on Indonesia’s economy and financial system. By rigorously measuring these effects, the analysis aims to provide actionable insights for policy interventions that can strengthen climate resilience and safeguard economic stability.

3. Methodologies – Scenario, Climate Change and Stress Testing

3.1. Overall framework

This paper develops an integrated framework that links climate change shocks to macroeconomic disruptions and financial system stress, as summarised in Figure 2. The framework combines three key components: (i) macroeconomic scenario design using the G-CUBED model, (ii) a climate damage function that translates environmental risks into productivity and labour shocks, and (iii) a simplified solvency stress-testing module to assess banking sector resilience.

Each component plays a critical role in capturing how severe climate shocks propagate through the economy and the financial system. Climate scenarios are mapped into economic shocks affecting labour, total factor productivity (TFP), and asset prices. These shocks are then simulated using the G-CUBED model to generate adverse macroeconomic scenarios. The resulting economic downturns put pressure on the banking sector by increasing the non-performing loan (NPL) ratio, as reduced household wealth and repayment capacity translate into credit losses. This, in turn, necessitates the drawdown of capital buffers and the internalization of financial losses by banks, revealing systemic fragilities.

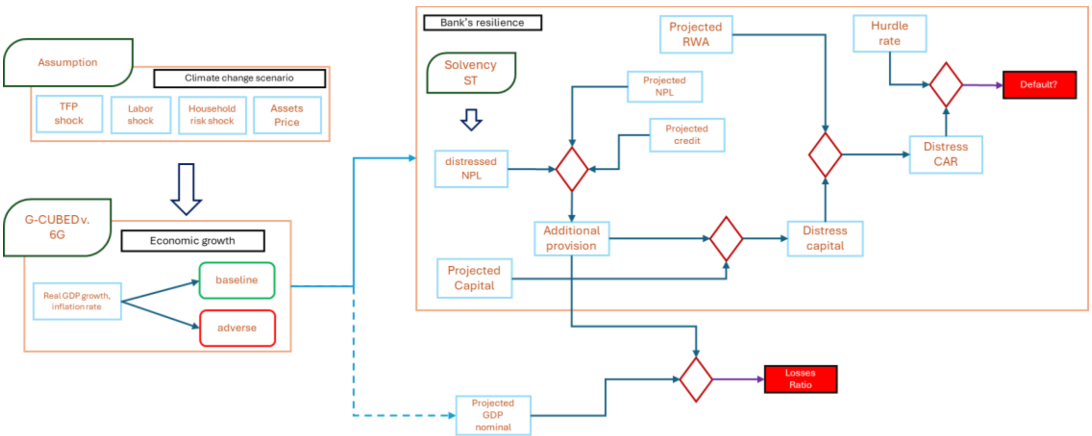

Figure 2 *overarching framework*

The first stage focuses on scenario design, linking climate risks to macroeconomic outcomes. This is operationalised through two modules:

- The *productivity channel* models how environmental damage reduces labour productivity and capital efficiency, using NGFS projections and established damage functions (Fernando et al., 2024; Roson & Sartori, 2016).

- The *financial channel* captures how climate risks erode investor confidence, leading to asset price corrections and tighter financial conditions. This approach adapts McKibbin and Stoeckel's (2009) method to sectoral and household risk.

This paper employs the G-CUBED model (version 6Gv176) due to its unique strengths. It not only tracks sectoral and regional dynamics but also provides policy-relevant variables commonly used by central banks for stress testing. Unlike models that apply uniform shocks, G-CUBED captures the uneven sectoral and geographic impacts of climate change, which is critical for countries like Indonesia with concentrated regional vulnerabilities.

In the second stage, the framework applies these macro shocks to a simplified solvency stress test for Indonesia's banking system. Using a quasi-static approach, the test links projected GDP growth and inflation to banking sector balance sheets and credit risk, with a focus on NPL dynamics. Here, the analysis adopts a macroprudential perspective, under the assumption that the economy ultimately internalizes the entirety of financial sector losses. The impact of banking distress is measured as a ratio to GDP, highlighting the systemic consequences of climate-induced financial stress.

Together, this integrated framework provides a comprehensive understanding of how climate change shocks can escalate into macroeconomic downturns and financial instability. It allows for a systematic assessment of resilience gaps and policy priorities for safeguarding Indonesia's financial system against escalating climate risks[4].

3.2. Macroeconomics Scenario Design

Scenario design forms the foundation of this paper's stress-testing framework, enabling simulation of macro-financial impacts stemming from climate change shocks. Effective scenarios must balance realism with severity: they must be extreme enough to test system resilience yet plausible enough to reflect real-world vulnerabilities. This paper's scenarios adhere to four key design principles:

(i) they are *extreme but plausible*,

(ii) shocks reflect historically relevant magnitudes (e.g., 3% GDP drop, as during the COVID-19 shock, rather than the extreme -13% seen in the 1998 crisis),

(iii) scenarios align with current system vulnerabilities,

(iv) shocks vary across sectors and regions to capture heterogeneous exposures.

[4] Assessing individual bank risk and potential failure remains crucial, as these factors can contribute to a systemic too-interconnected-to-fail risk.

This study employs the G-CUBED 6G model (version 6Gv176), a multi-country, multi-sector dynamic general equilibrium model that tracks 24 countries and six sectors—three of which (energy, mining, agriculture) are particularly sensitive to climate risks. Unlike simpler models, G-CUBED captures real-world transmission dynamics and addresses limitations associated with VAR models that rely on historical data (Blanchard, 2018).

3.2.1. Baseline Scenario

Baseline projections follow global trends in population, sectoral productivity, and technology adoption. This paper adopts parameters from Jaumotte et al. (2021), setting U.S. productivity growth at 1.4% and global technological catch-up at 2% per annum. Population growth is based on the United Nations World Population Prospects, with adjustments made for COVID-19 disruptions during 2020–2021.

3.2.2. Climate Shock Scenarios: Two Main Channels

This paper applies climate change shocks through two primary channels:

- Productivity Channel: Climate change reduces total factor productivity (TFP), labour supply, and household risk exposure. These are quantified using NGFS projections (2023–2024), damage functions from Fernando et al. (2024), and sectoral models from Roson & Sartori (2016). Shocks are sector-specific and regionally differentiated to reflect Indonesia's exposure.
- Financial Channel: Climate risks cause investor uncertainty, leading to rising risk premiums and equity price corrections. This finding aligns with McKibbin and Stoeckel (2009), who introduce equity risk premium shocks into their model to examine financial stress transmission.

All shocks will be applied only to Indonesia. The productivity channel follows a gradual increase for each subsequent time horizon. In contrast, the financial channel examines how failure to achieve net zero impacts investor appetite and, consequently, the price correction shock.

3.2.3. Damage Function Specification

The damage function quantifies the climate risks' impact on sectoral TFP growth using the following specification:

$$Y_{i,j} = \beta_0 + \sum_{k=1}^{10} \beta_k * X_{i,j,k} + \gamma_i + \delta_j + \varepsilon_{i,j} \qquad (1)$$

And the formula used to calculate TFP shocks is $SHY_{i,j} = \bar{Y}_{i,j} + \theta * \sigma_{i,j}$

Where: $Y_{i,j}$ is the annual growth of the sector i at year j, β are intercept and climate-related indicators coefficient ($X_{i,j,k}$); while the rest of the symbols are sector and year fixed effects and residuals.

The TFP shock reflects the deviation from baseline productivity growth, based on projected climate variables. Following SSP5 ("Fossil-fuelled Development") scenarios, which represent heightened climate risk, this paper assumes failure to achieve net zero by 2100, increasing disaster probability.

To calculate sectoral TFP shocks, projected independent variables are substituted to compute deviations from baseline output growth. The minimum projected growth rates from 2020 to 2100 are used to estimate the worst-case shocks applied in stress testing.

3.2.4. Labour Shock Estimation

Using Roson and Sartori's (2016) methodology, labour shocks are derived, which considers six climate-related factors. These factors are sea-level rise (affecting land rents), crop productivity changes, heat stress (reducing work capacity), health impacts (mortality, morbidity), tourism declines, and household energy demand volatility.

Labour shocks specifically account for heat stress, which is shown to significantly affect Indonesia. The aggregated impact is then disaggregated into sectoral shocks using weighted averages based on G-CUBED sector deviations.

3.2.5 Household Risk and Consumption Channel

Households adjust consumption based on wealth and risk perceptions. Climate shocks impact households via:

(i) partial wealth loss from reduced working hours,

(ii) total wealth and asset loss from job displacement and disasters.

Household consumption adjustment is captured through key G-CUBED variables, the household discount factor. This variable reflects increased household risk aversion and reduced consumption capability. The financial stress is reflected using the following household intertemporal consumption relationship where a rise in θ leads to reduced future consumption, triggering economic contractions.

3.2.6. Financial Market Shock

This paper uses Indonesian government bond yields (6–7%) as a reference to calibrate the financial channel. In times of distress, capital markets may fluctuate, causing severe liquidity losses. The household may lose a certain amount of its wealth, which may come from losses in financial assets. This condition forces the household to discount its consumption, leading to a loss in economic output.

Severe climate change scenarios may significantly distress the environment, businesses, labour, and capital, reducing economic output. Moreover, this condition can increase uncertainty in the capital markets. Investors will perceive higher risk in the capital market, leading to a significant decline in asset prices, which poses financial risk. It is important to note that panicked investor behaviour will affect the most affected sectors and similar-related sectors. Gorton and Metrick (2012) found evidence of this during the Global Financial Crisis (GFC) when panic in mortgage-backed securities (MBS) spread to other assets. Hence, a severe climate change scenario can undoubtedly affect many economic aspects.

3.2.7. Scenario Application

By applying these shocks to Indonesia through G-CUBED, adverse macroeconomic scenarios are generated. These scenarios feature sectoral TFP decline, labour force contraction, reduced household consumption, and financial asset price corrections. The resulting macroeconomic downturns are then fed into the banking system stress test in Section 3.3, enabling quantification of climate-induced financial stability risks.

All the above approaches are depicted in Figure 3.

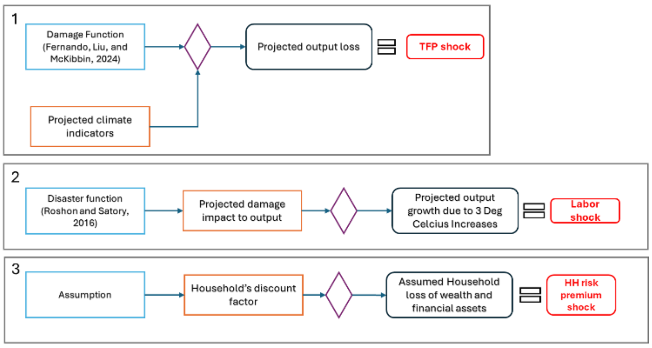

***Figure** 3 shock formulation using damage and damage functions*

3.3. Solvency Stress Testing

Using Catalan and Hoffmaister's (2020) quasi-static approach, this paper projects balance sheet growth as a one-to-one relationship with GDP and inflation rates. While this approach arguably may under-/overestimate the estimation, it is commonly used in stress testing frameworks. Moreover, Catalan and Hoffmaister (2020) argue that quasi-static is a better approach than "initial" projection, but not better than the "dynamic" approach[5].

This approach can be written as:

$$NPL_{i,t+1} = NPL_{i,t} + \left(\alpha g\widehat{GDP_{t+1}} + \beta\pi_{t+1}\right) \tag{3}$$

Where:

NPL_{t+1} : bank i non-performing loans at a time $t+1$

α : GDP coefficient for NPL, based on Catalan et al. (2020), $\alpha = 1.3$

$g\widehat{GDP_{t+1}}$: projected nominal GDP growth rate (scenario-wise) at the time $t+1$

β : coefficient of inflation, this paper follows the Catalan et al. (2020) value, which is 0.46

π_{t+1} : inflation rate at the time $t+1$

This paper approaches credit risk as an NPL ratio instead of the bank's probability of default point in time (PD PiT) due to data concern[6][7].

This paper assumes that a sudden increase in NPL forces a bank to reduce its capital due to additional provisions it should add. Given the shock applied, the additional provision can be described as follows:

$$adProv_{t+1} = (\widehat{NPL}_{t+1} - NPL_{t+1}) * \hat{L}_{t+1} \tag{4}$$

Since the bank has not put a provision in place, the additional provision is assumed to impact its capital:

$$\widehat{Cap}_{t+1} = (Cap_{t+1} - adProv_{t+1}) \tag{5}$$

Moreover, following BASEL accordance to check whether the distressed capital adequacy ratio is above its hurdle rate. If the distressed capital falls below the hurdle rate[8], the bank is considered a default.

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[5] The "Initial" approach uses its starting (initial) balance sheet value throughout testing periods, while the "dynamic" balance reprojects macro variables using the bank's distressed variables at t+1 and uses them to project the balance sheet at t+2.
[6] PD PiT is a better credit risk indicator based on IFRS 9. This indicator considers risks that may come from expected and incurred losses.
[7] Along with NPL, other bank-related indicators are projected similarly (quasi-static approach).

$$\widehat{CAR}_{t+1}\begin{cases}\geq \ hurdle\ rate : resilient \\ < hurdle\ rate : default\end{cases} \tag{6}$$

In which CAR (Capital Adequacy Ratio) is calculated as the following:

$$\widehat{CAR}_{t+1} = \left(\frac{\widehat{Cap}_{t+1}}{RWA_{t+1}}\right) \tag{7}$$

The projected capital adequacy ratio ($\widehat{CAR}_{t+1}$) also reflects the banking sector's capacity to internalise potential economic shocks. In this sense, it serves as a proxy for overall bank performance.

3.4. The Data

The banking data utilized in this paper spans from 2010 to 2020 and encompasses comprehensive bank-by-bank balance sheet information. The banking data is obtained from the Bank Indonesia data warehouse. Macroeconomic variables are sourced from multiple data warehouses, including Badan Pusat Statistik (BPS), Bank Indonesia, the World Bank Group, and G-CUBED data sources. Climate-related data is obtained from the data warehouses of NGFS and BNPB. The data covers the period from 2010 to 2020, except G-CUBED, which pertains specifically to 2018.

The paper covers individual banking to calculate the stress testing for 2022. When this paper was written, there were 107 active banks, including conventional and Shariah banks. The data used in this paper is sourced from the Bank Indonesia data warehouse.

The simulation period can be differentiated into two phases:

1. The G-CUBED simulation runs from 2019 to 2100. The period from 2019 to 2022 counts as a tranquil period. Post-distress periods are counted as recovery periods.
2. Stress testing sees 2023 to 2024 as its distressed periods. These are the stress periods when the economy is hit by a climate change shock, economic performance declines, and subsequent solvency distress is felt in the banking system.

Previous studies have found evidence that macroeconomic conditions correlate with banks' credit risk (Louzis et al., 2010). Usually, when the real GDP growth rate increases, the credit growth rate also tends to rise. Conversely, the credit growth rate typically falls when the real GDP growth rate declines. This relationship highlights how economic conditions and overall

[8] Each bank has a different hurdle rate depending on its risk level, capital buffer, and conservation buffer. In the result session, I consider 10.5% and 8% as two complementary thresholds for the stress testing approach. The 10.5% comes from 8% (the BASEL II regulation threshold value) and an additional 2.5% for the conservation buffer.

wealth influence credit growth. Agreeing with the quasi-static assumption by Catalan et al. (2020), Figure 4 illustrates that the credit growth rate moves in alignment with the real GDP growth rate. While this movement is not a perfect one-to-one ratio, both variables generally trend in the same direction.

Generally, banks' NPL exhibit a similar pattern to the broader economy. When the economy slows, financial agents' repayment capacity decreases, leading to increased NPL. However, given the policy responses applied during the COVID-19 pandemic, banks' NPL have remained stable. In crisis times, NPL tend to increase, and vice versa. Notably, Figure 4 shows no increase in NPL during the COVID-19 pandemic in 2020. In this period, the central bank's policy on loan restructuring has helped maintain a steady level of non-performing loans (NPL) and mitigated the risk of bad loans[9].

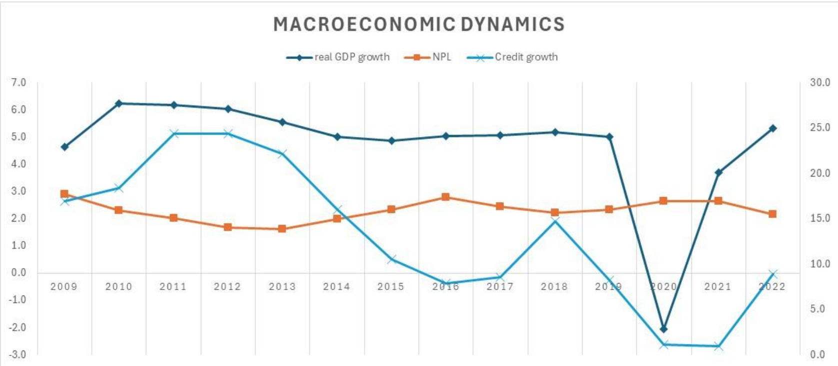

Figure 4 macroeconomic dynamics

4. Simulation Results

4.1. Climate change scenario results

Table 1 utilises the damage function outlined by Fernando et al. (2024) to provide an overview of the productivity and financial shock values for each sector. These values account for the effects of extreme climate change conditions on various economic sectors. The table illustrates how extreme climate change indicators can either enhance sectoral output (indicated as a positive shock, marked as "max") or impede sectoral performance (shown as a negative shock, marked as "min").

[9] Despite the different movement between real GDP growth and banking NPL in COVID-19 pandemic periods, quasi-static assumption is still valid to estimate banking solvency related

Table 1 *sectoral shocks estimation*

	Energy	Mining	Agriculture, fishing, and hunting	Durable	non-durable	Services
TFP Shock						
MIN	-1.90%	-0.69%	2.34%	0.000	-2.38%	-0.38%
MAX	1.11%	1.40%	1.00%	0.000	1.06%	0.38%
AVG	-0.08%	0.05%	-0.15%	0.000	-0.16%	-0.003%
Standard deviation	0.59%	0.40%	0.66%	0.000	0.71%	0.11%
Labour Shock						
MIN	-0.585	-0.334	-0.624	-0.903	-1.803	-2.720
MAX	-0.545	-0.271	-0.613	-0.781	-1.754	-2.645
AVG	-0.566	-0.301	-0.618	-0.854	-1.776	-2.685
Standard deviation	0.015	0.021	0.003	0.045	0.016	0.023
Household Risk Shock						
Discount factor (sector 1 to 6)	6%					
Equity Risk Premium Shock						
Sectoral (1 to 6) risk premium	8%					

Each sectoral shock value is applied to the respective shock variables, which include labour shock, TFP, and household risk premium shock variables for Indonesia. Based on their vectors, labour and TFP shocks have negative vectors, indicating a decline in performance. In contrast, household and equity risk premiums have positive vectors, indicating an increase in distress value.

4.2. Banking resilience estimation results

4.2.1. Scenario Variations

This paper presents a perspective on climate change that differs from many studies on gradual impacts. As explained in the previous chapter, climate change can lead to abrupt economic and financial shocks. One key factor in this distinction is that gradual changes allow the economy to adapt over time, whereas sudden shocks do not. If externalities trigger a sudden climate change event, it could catch the economy and financial sectors off guard. This situation underscores the need for analysis of such abrupt events[10].

Through macrofinancial transition analysis, we investigate the impact of productivity and financial risks on banks' balance sheets. Our exploration focuses on three specific scenarios: one-time (single shock), permanent shock, and stochastic shocks, addressing both types of risks.

The shock is applied only to a designated year in the one-time simulation. For instance, if the shock occurs in 2024, it will shock the economy in the applied year and the year after. This is important because the G-CUBED model specification assumes that a shock in year t will persist into the following year (t+1). On the other hand, the permanent shock scenario involves all relevant years, including 2023 and 2024. In this case, the economy cannot recover, as the shock continues in subsequent years.

In the stochastic scenario, the shock occurs in 2023 and is expected to be temporary—it then unexpectedly occurs again in 2024. Unlike the permanent shock, we permit the G-CUBED model to estimate the economic downturn in 2023, project the recovery for 2024, and then reapply the shock. This approach captures the element of unpredictability inherent in such events. Additionally, the stochastic scenario reflects the dynamics of policy responses, allowing financial authorities to react to the 2023 shock before being caught in another unexpected shock in 2024.

Table 2 illustrates four variations of climate change shocks. A significant climate change shock that impacts all plausible risk channels severely reduces Indonesia's real GDP growth rate, as shown by permanent and stochastic shocks. Unlike permanent and stochastic shocks, a one-time shock scenario exhibits a distinct economic impact. Specifically, a one-time shock scenario influences household consumption behaviour in a manner that diverges from longer-term scenarios. In longer-term scenarios, household consumption experiences a decline at the onset of the shock, persisting until the effects of the shock dissipate. This reduction in consumption precipitates an economic downturn, which further adversely affects household wealth and assets, resulting in an additional decline in consumption. Conversely, in a short-term scenario where the shock is confined to a single year, households tend to increase their consumption in anticipation of the economic decline. As a result, their wealth and assets

[10] Please refer to Appendix A For a more detailed explanation of the differences between gradual and abrupt climate change shocks.

available for consumption at time t+1 may fall short of their needs. This phenomenon is consistent with the model of intertemporal consumption behaviour, which posits that consumption at time t influences consumption at time t+1.

Table 2 distressed real GDP growth rates (level)

	2023	2024
Baseline	5.05%	5.2%
One-time shock in 2023	3.93%	5.03%
One-time shock in 2024	4.81%	3.64%
Permanent Shock	1.64%	0.92%
Stochastic shock	3.93%	1.71%

Note: Real GDP growth rate for Baseline 2024 is calculated using G-CUBED.

The simulation result analysis indicates that the economy consistently declines regardless of the financial asset shock values applied in the simulation. Therefore, this study utilises an 8% shock to financial assets as a scenario input for stress-testing calculations[11].

The above simulation results are an interaction between long-term shock conditions and climate change-dependent sectors' output, heightened energy needs, financial agents' wealth losses, reduced national productivity, and a drop in repayment capacity. Based on Indonesia's Dewan Energi Nasional (2019), Indonesia's energy demands will increase at an 11-12% annual growth rate every year until 2025. This energy demand includes all sorts of energy: brown, yellow, and green. Any disruptions in energy-related sectors mean disruption in all sectors and the economy in general. Given that massive shocks were applied to energy and mining, both sectors' labour (demand) and capital were affected significantly. Furthermore, the impact of climate change on the environment and business has led to a significant drop in capital for both the mining and energy sectors. This decline in capital has also affected labour and repayment capacity, resulting in a downward shift in economic output.

Armas et al. (2012) concluded that agriculture is a vital component of Indonesia's economy, contributing 11.63% to the country's GDP by 2022. The loss of this contribution would pose significant challenges to the economy. A subsequent study by Fernando et al. (2024) indicates that climate change may seriously shock the agricultural sector. They emphasise that this shock affects several key factors, such as crop yields, animal dynamics, and habitats. Disruptions in these areas lead to a decline in agricultural productivity, decreasing overall

[11] Other financial asset shock values have less impact on the economy; hence, this paper will not show any results of the simulations.

economic output, including in the energy and mining sectors. These insights are further corroborated by Roson and Sartori (2016). Thus, not only does increased energy demand contribute to productivity losses, but the economy also faces additional strain from setbacks in agriculture and its associated sectors.

The externalities applied to the economy significantly increase core and aggregate inflation rates. Climate change has diminished the output capacity of these sectors, thereby raising the prices of associated products and services despite notable wage increases across all sectors. The rising inflation rate indicated that the bank's interest rate was also at its peak. This is intriguing as it suggests the potential for reduced bank loan approvals. The increased demand for credit is expected to be impacted as well. Furthermore, this signals a significant decrease in the repayment capacity of financial agents despite wage increases across all sectors.

Since a severe climate change shock causes panic in the capital market, it will affect investment in every sector. As a result of the inadequate liquidity supply, the cost of accessing energy has significantly escalated, leading to a marked increase in the inflation rate. The necessity of energy in all business operations, irrespective of origin, has given rise to this circumstance. According to Indonesia's Dewan Energi Nasional projections, Indonesia is anticipated to experience a staggering 550% surge in energy demand from 2018 levels under the "business as usual" scenario. The difficulty in acquiring energy has propelled prices upwards, consequently contributing to the inflation rate hike.

4.2.2. Stress testing results

The impact of climate change shocks on labour, productivity, and household wealth can have profound implications for the financial system. Although a one-time climate shock may not accurately reflect the dynamic between climate change and output deterioration, it remains crucial to acknowledge its relevance. The significance may be minimal for banks equipped with sufficient capabilities to mitigate such shocks. However, the scenario indicates concerning issues that may occur after the shock. This interesting result points out how household intertemporal consumption behaviour can trigger subsequent shocks to the economy. This is demonstrated by the fact that economic output is relatively higher than it should be when a permanent shock hits. Moreover, there is a decline in consumption at time t+1, where the economic output is significantly impacted. The results show that climate change has a significant impact on household consumption and worsens economic dynamics.

In severe yet plausible permanent and stochastic shock scenarios, financial agents may struggle to meet their obligations, leading to a rise in credit risk (represented by the NPL ratio).

Figure 5 illustrates how each bank's credit risk changes during climate change shock scenarios. In all scenarios, the NPL ratio for banks shifts due to the shock caused by climate change. In the one-time shock scenario, financial agents, especially households, experience a surge in liability repayment, causing the bank's NPL to decline. However, financial agents will have reduced repayment capacity when the shock lasts over a year. Unlike the one-time scenario, the longer-term scenario will cause the banking industry's credit risk, as represented by the NPL ratio, to increase. Notably, the permanent shock scenario shows the most significant increase in NPL ratios.

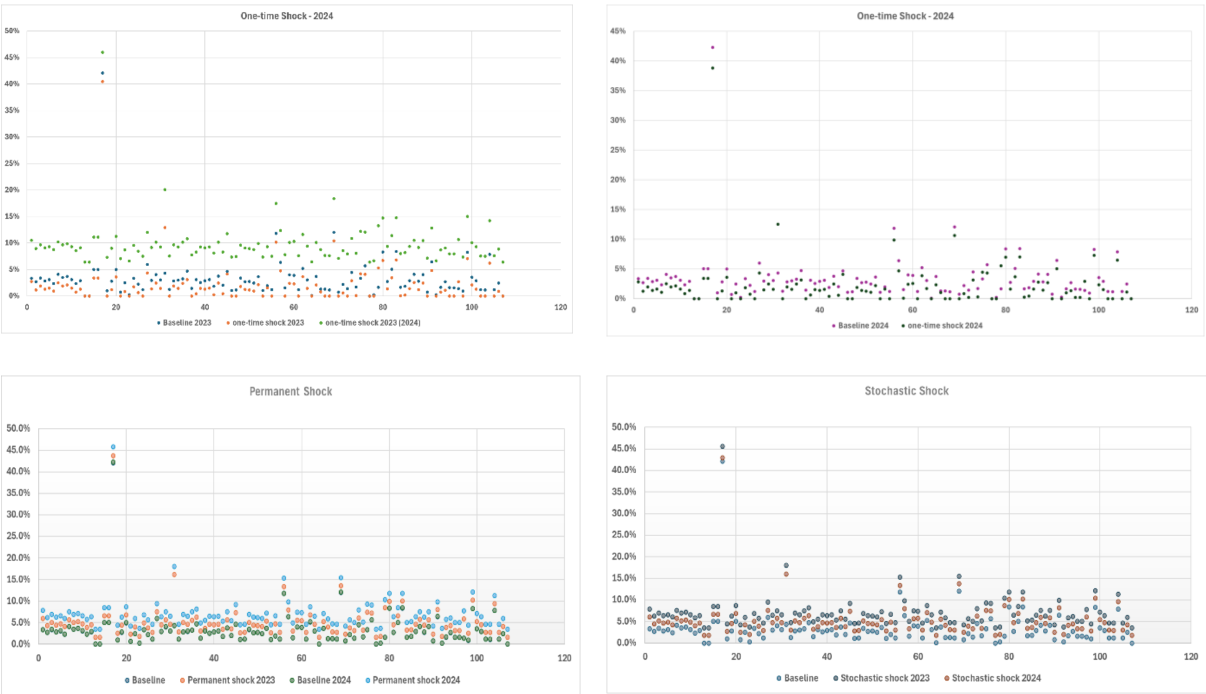

***Figure** 5 individual banks' credit risk dynamics*

However, it is worth noting that the impact of these shocks is not expected to decrease the aggregate banks' CAR below 10.5% (Table 3)[12]. The CAR declined by approximately 1.5% in 2023 and 2.5% in 2024, referring to permanent and stochastic scenarios. If the shock persists, the aggregate bank CAR will decline even further in the permanent shock scenario. In the permanent shock scenario, the financial system cannot recover since it is hit again in the following year. This condition causes banks' CAR to decline further compared to a one-time shock. The financial entities, households, and financial authorities do not have sufficient time to respond, causing further NPL (solvency risk) to increase.

[12] A threshold of 10.5% is used for aggregate banks since they do not have a specific individual risk value.

Shocks often occur unexpectedly. In a stochastic scenario, we estimate that the distress within the financial system is more severe than in other scenarios. The stochastic results indicate that financial authorities and institutions are again caught off guard by an unexpected shock.

Table 3 climate change impact on banks' CAR

estimated CAR	2023	2024
Initial	24.33%	24.62%
Single shock in 2023	22.84%	24.62%
Single shock in 2024	24.33%	22.14%
Permanent shock	19.87%	18.87%
Stochastic shock	22.84%	19.52%

This paper digs deeper into individual bank dynamics to understand the dynamics of smaller banks not captured in the table above. Table 4 demonstrates how even a seemingly insignificant decrease in the aggregate bank-level CAR can push individual bank CAR below a certain threshold. It is estimated that at least two banks fall below two thresholds. This trend is even more pronounced in the permanent results, with the number of affected banks ranging from two to three, depending on the threshold used. This underscores the critical importance of timely policy responses, reducing vulnerabilities, and building buffers. The stochastic scenario mirrors the findings in the permanent scenario with slightly lower CAR and higher NPL. In the stochastic scenario, the recovery phase causes the dynamic before being affected by a subsequent shock.

When permanent damage is inflicted upon the economy and financial system, financial authorities and institutions struggle to recover from subsequent shocks due to their ongoing nature, leaving them with inadequate resources for recovery. The number of banks that defaulted significantly increased compared to the stochastic scenario. In 2023, the financial system incurred losses estimated at approximately Rp 0.4 trillion, alongside an additional Rp 200 trillion in apprehended losses.

Table 4 distressed banks based on several thresholds

Estimated CAR	2023			2024		
	fail? (CAR <=10.5%	fail? (CAR <=8%	fail? (CAR <=HR	fail? (CAR <=10.5%	fail? (CAR <=8%	fail? (CAR <=HR
Single shock in 2023	-	-	-	-	-	-
Single shock in 2024	-	-	-	-	-	-
Permanent shock	-	-	1	2	1	2
Stochastic shock	-	-	1	1	-	1

The aforementioned losses may also exert a macroeconomic impact. Assuming the economy fully internalises these losses, the estimated permanent output losses amount to 0.50% of GDP in 2023 and accumulate to 1.04% of GDP by 2024[13].

4.4. Policy Implications

This paper explores the role of central bank policies in addressing climate change and green-related issues. Despite the absence of a direct mandate to tackle these issues, central banks can leverage their existing policies to mitigate the impact of distress scenarios on the financial system. Specifically, the paper focuses on calculating solvency risk, or credit risk, within the financial system. It suggests that other policies within the central bank's purview can compensate for the lack of authority in green-related policy.

Typically, central banks employ monetary and macroprudential policies, which can directly and indirectly impact the potential risks associated with climate change. For example, monetary policy can help alleviate interest rates for sectors affected by climate change-related shocks and prevent capital outflow due to interest rate parity or investor sentiment. However, it is essential to recognise that while monetary policy can target specific issues, it also affects the overall economy and can lead to unintended consequences for other sectors and aspects of the economy.

According to the estimations derived from the G-CUBED model, based on one-time (2023 and 2024) and stochastic scenarios, financial authorities must mitigate the decline in consumption capacity of financial agents, which has resulted from the erosion of their wealth and assets. Therefore, these authorities need to consider reducing the policy interest rate. This measure also addresses the inflationary pressures indicated by the escalating inflation rate. Moreover,

[13] Similar calculation of losses absorption to GDP has been done in various IMF's FSAP.

extreme scenarios related to climate change are contributing to a decrease in product availability and an increase in demand.

In contrast to a one-time stochastic scenario, a permanent scenario precipitates product scarcity, leading to a subsequent increase in demand. Despite diminished wealth and financial assets, this situation catalyses a price rise, consequently contributing to heightened inflation rates (as illustrated in Table 5). However, any response may result in unintended consequences, specifically distress in non-distress sectors and capital outflows (Bruno & Shin, 2015; Gödl-Hanisch et al., 2024). The underlying dynamics are further detailed in Table 6.

Table 5 monetary policy responses

deviation from baseline projection	Policy rate (%)		Inflation rate (%)	
	2023	2024	2023	2024
One-time shock in 2023	-0.33	-	0.30	-
One-time shock in 2024	0	-0.32	0.31	0.25
Permanent Shock	0.97	-2.46	2.11	4.72
Stochastic shock	0.33	0.32	0.30	0.25

We are now delving into the second policy that a central bank may employ, the macroprudential policy. This policy assists banks and other financial institutions prepare for challenging economic periods. It can also stimulate credit disbursements by adjusting credit down payment levels. However, due to the nature of the macroprudential policy, actively adjusting its level can pose challenges for the central bank. Misjudging the timing and prolonged implementation of the policy may lead to unintended consequences for the financial system. Furthermore, as indicated in this paper, evaluating the financial stability risk associated with climate change can be exceptionally complex and may add further intricacy to policy design.

Given its challenges and complexities, the central bank must consistently evaluate the impact of climate change daily while proactively collaborating with other financial authorities, notably the Minister of Finance, who has fiscal policy authority. Moreover, stochastic scenario results emphasise the importance of policy responses, especially those coordinated among financial authorities.

5. Conclusion and Recommendations

5.1. Conclusions

This study reveals that climate shocks are no longer distant threats but a plausible immediate and systemic risk for financial systems. By integrating macro-climate scenarios with bank-level stress testing, this research uncovers hidden vulnerabilities in Indonesia's banking sector that standard frameworks fail to capture.

The results show that severe climate shocks—sudden physical disasters or disorderly transitions—can swiftly erode GDP growth, spike inflation, and impair bank balance sheets. Rising NPL and declining capital buffers threaten individual banks and the financial system's stability. Even where aggregate resilience appears intact, the emergence of distressed banks signals contagion channels that could amplify systemic risk.

Crucially, this study underscores that climate risks are not just long-term structural issues. They can strike abruptly and trigger significant macro-financial disruptions in the short and medium term. Existing prudential frameworks, which are designed around idiosyncratic credit and market risks, are ill-equipped to address the multidimensional and dynamic nature of climate-related threats.

5.2. Recommendations

Policy actions are urgently needed:

- Embed climate risks into macroprudential stress testing by integrating physical and transition shocks into solvency and liquidity assessments.
- Mandate granular climate risk disclosures at the loan, sector, and portfolio levels to map vulnerabilities across the financial system.
- Activate countercyclical capital buffers and sectoral tools in response to climate shocks, preventing procyclical credit tightening and amplifying resilience.
- Strengthen cross-agency coordination among central banks, supervisors, and fiscal authorities to deliver cohesive responses to systemic climate shocks.
- Require financial institutions to conduct forward-looking climate scenario analysis and embed transition and physical risks into internal risk pricing and capital planning.

Looking forward, research must address critical gaps by modelling feedback loops between financial distress and climate shocks, particularly in vulnerable emerging markets where capital outflows, currency pressures, and sovereign risks can amplify initial disruptions. Integrating emissions metrics and transition pathways into credit risk models will be essential for building a climate-resilient financial system.

Climate risks are here, and they are systemic. Stress-testing frameworks and policy tools must evolve—urgently and decisively—to safeguard financial stability in the face of escalating climate threats.

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Appendix A. Gradual or Abrupt? The Dilemma of Severe Yet Plausible Climate Change and Disaster Scenarios

Climate change is often conceptualised as a gradual process. This perspective is reinforced by numerous studies and scenarios, including the latest scenarios from the Network for Greening the Financial System (NGFS), which portray climate change as a slow-moving shock. The economic effects of climate change are expected to intensify over the coming decades, with many analyses suggesting that substantial impacts—both global and domestic—will materialise over a 10 to 20-year horizon. Given the inherently gradual nature of climate change, this model is often viewed as the most appropriate for assessing potential risks.

However, achieving net-zero emissions requires robust policies, substantial capital investment, and coordinated incentives. If these requirements are not met, global temperatures are likely to continue rising, thereby increasing the likelihood of severe natural disasters. This could exacerbate existing risks, making climate change a critical factor for long-term economic stability.

Industries that are heavily dependent on fossil fuels—often referred to as "brown" industries—face the most significant challenge in transitioning to more sustainable practices. This transition demands significant capital outlays for new technologies and infrastructure, as well as the retraining of the workforce to operate the newly adopted technologies. Without a skilled labour force capable of operating these technologies, industries risk significant depreciation of their investments and a potential loss in capital value. This highlights a critical issue: the seemingly achievable targets for net-zero emissions could become significant financial and operational risks if not managed properly.

If the financing for these new technologies and labour force adjustments comes from the financial system, it introduces additional, potentially unknown, credit risks. Failure to meet financial obligations due to unforeseen circumstances, such as technological malfunctions, market volatility, or adverse climate events, could lead to solvency and liquidity crises. These challenges, compounded by the rising risks associated with climate change and its associated natural disasters, could result in significant disruptions across industries, whether fossil-fuel-based or otherwise. Existing literature underscores that climate change can severely affect both financial capital and labour, likely leading to a sharp decline in overall economic output.

What would these impacts look like in practice? They could have profound consequences not only for industries but also for financial systems and regulatory authorities. When financial entities fail to meet their obligations, the resulting losses ripple through the financial system, impacting counterparties and stakeholders. If these failures are exacerbated by uncertainties related to climate change, the effects could trigger a cascade of financial distress, ultimately leading to a full-blown economic crisis.

In light of this, it is crucial to evaluate both gradual and abrupt climate change scenarios. While gradual shocks are typically seen as the more suitable framework for assessing long-term impacts, the possibility of sudden, unexpected external shocks cannot be ignored. From the perspective of financial authorities, anticipating these unknown externalities is essential. Historical evidence suggests that the costs of recovery from a financial crisis often exceed the costs of preventing it. The gradual shock model allows authorities to prepare for the transmission processes that may unfold over time. However, the abrupt shock model is equally important for developing responsive, proactive policy frameworks.

A gradual climate change shock to the economy is likely to have a limited effect on the banking system, as illustrated in Figure 6, which projects the magnitude of such a shock in Indonesia by 2040. Given the 16-year time frame, the financial system should have sufficient time to adapt and adjust, meaning the overall financial landscape is unlikely to be significantly disrupted. However, if an extreme climate change event—one of the same magnitude—were to occur earlier than anticipated, the consequences could be markedly different. In this case, the financial system may not have had enough time to adjust, leading to potentially severe outcomes that could jeopardize economic stability.

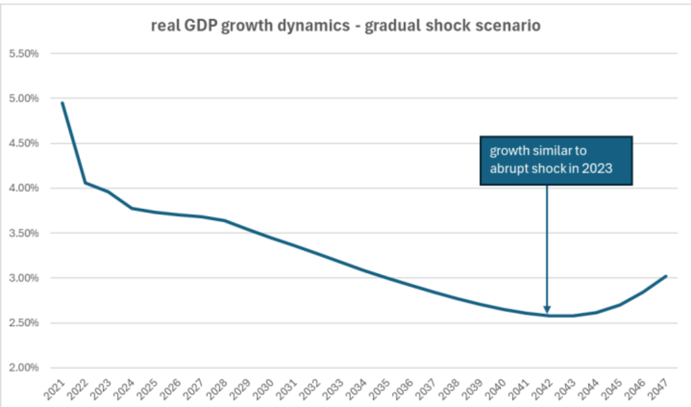

***Figure** 6 gradual shock real GDP growth dynamics*