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Climate change, macroprudential policy responses and their distributional consequences in South Africa

Aditya Khemka,* Christina Laskaridis† and Dimitrios P. Tsomocos‡

Abstract

In transitioning from coal-dependent growth to a low-carbon economy, South Africa faces intertwined environmental, macro-financial and distributional risks. We build a two-period computable general equilibrium model with heterogeneous households, firms and a dual-tier banking system, embedding endogenous default, brown and green capital markets and a pollution-damage feedback. After calibrating to South African data, we compare three instruments – downstream carbon taxes, brown risk-weighted capital surcharges and green capital discounts – individually and jointly. Carbon taxation most sharply curbs emissions and, when revenues are rebated to workers, also narrows wealth and consumption inequality. Brown penalising factors restrain leverage and reduce default probabilities but raise energy prices and widen wage inequality; green supporting factors lower financing costs yet trigger a Jevons-type rebound that can increase coal demand. Welfare decompositions show that no single tool dominates; the optimal approach involves pairing a carbon tax with prudential tweaks that balance climate gains, stability and equity for South Africa.

JEL classification

D63, G21, G28, Q56

Keywords

Green capital requirements, carbon taxes, wealth inequality, heterogenoeous agent general equilibrium

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1. Introduction

In this paper we study how climate-related prudential tools – green and brown capital requirements – and carbon taxes influence inequality, welfare, output, pollution and financial stability in South Africa.

Addressing the financing needs of the green transition is a primary policy challenge if South Africa is to achieve its net zero goal by 2050 and its Nationally Determined Contribution target by 2030.[1] Following the influential remarks of Valdis Dombrovskis (Dombrovskis 2017) and the Network for Greening the Financial System's (NGFS's) Guide on prudential supervision (NGFS 2020), central banks have begun to study the viability of using 'green capital requirements' (i.e. climate-specific risk weights for banks) as a tool to incentivise financing of the green transition. These tools have also been discussed in South Africa, in a speech by Governor of the South African Reserve Bank (SARB) Lesetja Kganyago (Kganyago 2023), as well as in Arndt, Loewald and Makrelov (2020).

Proponents of these tools argue that they are a means to manage the exposure of bank balance sheets to adverse climate shocks, thus contributing towards a more stable banking sector. Additionally, the objective is to create cost-of-capital disadvantages for polluting firms thereby creating the incentives necessary for polluting firms to transition.

Existing research has focused on trade-offs created between climate-related and prudential objectives. Oehmke and Opp (2022) find that the effectiveness of policy in incentivising investment in green lending depends crucially on the marginal loan, which may also be a brown loan, leading to unintended outcomes. Dafermos and Nikolaidi (2021) show that green differentiated capital requirements by themselves can only generate quantitatively small reductions in emissions, while potentially leading to some transition risks, which lead to increased bank leverage or increased loan defaults. The European Banking Authority (EBA 2023) covers the discussion on green capital requirements from the policy perspective, arguing that notwithstanding

[1] Estimates by the Climate Policy Initiative (De Aragao Fernandes et al. 2023) suggest that South Africa needs to increase financing of the climate transition by at least three- to fivefold.

the undisputed importance of climate-related risks for banking and finance, such risks are best managed within the current risk-based framework rather than by introducing dedicated treatments. Castren and Russo (2024) find that green capital requirements can induce banks to channel more lending to green projects, but create a trade-off with higher bank vulnerability to credit risk in green projects. Thus the trade-offs of pollution reduction and financial stability have been well studied.

However, broader implications for price stability and equity have not been studied. As argued by Kganyago (2023), using prudential policy tools to artificially change relative prices to favour the green sector might undermine financial stability. Similarly, transitioning companies are likely to generate significant distortions in the labour market. Moreover, the impact on inequality is ex-ante ambiguous, especially if low-income (more vulnerable) households are the largest participants in the sectors of the economy most susceptible to such regulations. Hence, in South Africa and more generally in the Global South, such policies are likely to lead to increasing inequality, which poses further implications for output, inflation, the political economy of support towards climate policies, the resilience of household balance sheets to future shocks and ultimately the necessity of fiscal transfers and/or debt restructuring of the Global South's sovereign debt. This is particularly relevant to South Africa considering the findings of Dasgupta, Emmerling and Shayegh (2023), who estimate that the Gini coefficient in South Africa could increase by 3–6 points by 2100 because of global warming, resulting in large welfare losses.

Therefore, policy interventions aimed at mitigating the impact of climate change are likely to give rise to a number of trade-offs, necessitating a study of how optimal policy can be designed. It is crucial to analyse the consequences of such policy responses in the context of South Africa's large financing needs to facilitate a green transition, its exposure to transition risks and the potentially large second-order effects of physical or transition shocks of climate change.

In this paper, we employ a richly specified two-period computable general equilibrium (CGE) model with uncertainty to study three policies – brown capital requirements (brown penalising factor), green capital requirements (green supporting factor) and carbon taxes. The model features a household sector, a production sector and a banking sector. Households are heterogeneous with respect to their incomes and occupations, which helps us match inequality of wealth and income. The production sector features intermediate producers of non-renewable energy (such as coal plants) and renewable energy (such as wind farms), as well as a final goods producer (such as a manufacturer of automobiles). Pollution is a byproduct of the coal extraction process and reduces future productivity across all sectors. Finally, the banking sector comprises heterogeneous banks engaging in retail and commercial lending. We allow for endogenous default across households and banks.

The policymaker (the central bank or the government) has an array of policy tools at its disposal, including fiscal policy (carbon taxes) and macroprudential policy (brown and green capital requirements). We assume that the policymaker's objective function is to achieve multiple goals, namely aggregate efficiency, lower pollution, higher equity or redistributive justice, lower financial instability and higher welfare. We study the design of optimal policy while incorporating the trade-offs among multiple objectives.

We use estimates from the literature on environmental economics, data sources from South Africa and previous studies of the South African banking sector to carefully calibrate the key parameters of our model. Then, for our key policies, we study the impact of the policy change on inequality, welfare, output, pollution and financial stability. To our knowledge, this is the first comprehensive study which addresses the potential side-effects and trade-offs of climate-focused policies and the design of optimal policy.

We find that the three policy levers behave very differently. Raising the downstream carbon tax directly shifts demand away from coal; even after accounting for banking frictions, it delivers the largest fall in brown output and hence emissions. Because the tax revenue is recycled to labour households, the post-transfer income distribution tightens – producing the paper's 'divine coincidence' of lower pollution and lower inequality. Tightening brown-capital risk weights, by contrast, works through credit prices: investment in coal shrinks only modestly while energy prices jump, squeezing brown wages and widening the income gap. Loosening green risk weights cheapens finance for renewables, but the resulting drop in aggregate energy costs drives a Jevons-style rebound that actually lifts coal demand and can raise emissions.

Our analysis of effects on productive capital reveals that tighter brown risk weights shift some lending towards renewables but do not induce a one-for-one substitution; total investment shrinks, brown-loan premia rise and aggregate capital stock falls, limiting the abatement gain. On the financial stability front, the same surcharges lower system-wide leverage – delivering the intended prudential benefit – but they also erode bank profitability and push up non-performing loans as borrowers face higher rental spreads, so the net effect is a trade-off between resilience and earnings. Comparative statics underline how strongly these outcomes hinge on deeper parameters: greater energy substitutability, for example, can perversely raise emissions in a coal-dominant economy, while a lighter energy share or reduced coal efficiency cuts pollution yet may widen inequality or spur inflation. Together, these show that both policy effectiveness and its side-effects are highly contingent on the economy's evolving fundamentals, reinforcing the need for calibrated and adaptive regulation, as well as a broader welfare function.

A welfare decomposition that weighs efficiency, climate damage and redistribution shows why no single tool is sufficient. Carbon taxation scores highest on environment and equity yet temporarily raises energy price inflation and default risk; moderate brown-capital add-ons buttress bank solvency but exacerbate wage inequality; broad green discounts boost output while undermining climate goals. The joint-policy surface therefore peaks when a robust carbon tax is deployed first and prudential tweaks are added only to contain the financial side-effects – an ordering that nudges every planner type, from labour-focused to anti-pollution, towards the same neighbourhood of the welfare map. These results motivate the paper's core recommendation: South Africa's transition strategy should be built on a 'tax first, finance second' sequence, calibrated and coordinated across agencies to respect the trade-offs revealed by the model.

1.1 Relevance to South Africa

Why is the study of the welfare consequences of climate policy particularly relevant to South Africa? The country lies in an area that is particularly affected by climate variability and experiences droughts, floods and other extreme weather events with increasing intensity. The World Bank's Climate Risk Country Profile for South Africa recognises the country as vulnerable to climate change impacts, ranking 92 out of 181 countries. Therefore, the country faces a high degree of physical risk from climate change.

Moreover, South Africa is highly dependent on coal for its power generation – 92% of energy generation is through cheap and abundantly available coal.[2] The coal industry directly employed around 93 000 people in 2021 (Bhorat et al. 2024). The government has set an objective of transitioning the power sector to 42% non-fossil fuel sources by 2030 in line with its UNFCCC Paris Agreement targets. This also makes the country vulnerable to the transition risks of climate change.

At the same time, South Africa is one of the most unequal countries in the world. The World Bank's 2022 estimate of South Africa's Gini coefficient, 66.5, is the highest of the 164 countries it measures. Meanwhile, the share of income held by the richest 20% of the country's population is estimated to be 70%, 20 percentage points higher than the median for emerging economies. This situation has remained stagnant, suggesting that inequality has remained a persistent problem. Recent estimates of the unemployment rate – 32% – are also in the top percentile of the world. As discussed in the *Framework for a just transition in South Africa* (Presidential Climate Commission 2022), climate change exacerbates South Africa's triple challenges of poverty, unemployment and inequality.

South Africa completed implementing Basel III risk-based capital regulations between 2013 and 2019. As discussed in Makrelov, Davies and Harris (2021), South Africa's regulatory regime tends to be stricter than Basel III in terms of speed of implementation and size of the ratios, such as implementing a risk-weighted capital adequacy ratio that is higher than the recommended

[2] From the IEA's profile on South Africa: https://www.iea.org/countries/south-africa

8%. Monnin, Sikhosana and Singh (2024) conduct one of the first assessments of the exposure of the South African banking sector to transition risks. They find that South African banks are more exposed to transition risks than the European banking sector. They also find evidence to suggest potentially significant second-order effects and amplification of climate shocks. They note that relative to countries with similar transition risks, households and sovereign economic weakness in South Africa add to risks for the financial system. They use this analysis to justify using capital requirements to absorb climate shocks and prevent the build-up of climate-related risks, while remaining flexible to the economy's transition path.

The rest of the paper is organised as follows: section 2 sets out the model, its components, structure and timeline; section 3 describes the calibration strategy; section 4 lays out the key mechanisms and predicted outcomes of the model; section 5 conducts our main quantitative analyses, including discussing trade-offs, capital investment outcomes, financial stability measures and comparative statics; section 6 lays out our welfare measure and discusses the design of optimal policy, individually and jointly; section 7 considers a few model extensions and variations relevant to South Africa; section 8 summarises the key policy takeaways from our analysis; and section 9 concludes.

2. Model

Our CGE model incorporates key features of Khemka and Tsomocos (2025) and Beyers et al. (2020). The Khemka-Tsomocos model features heterogeneous households across four sector-occupation pairs, where households are exposed to a pollution externality created due to the production of non-renewable energy. We augment this with a richly specified banking sector as in Beyers et al. (2020), which incorporates heterogeneous, interconnected banks subject to capital adequacy ratios and endogenous default. This setup allows us to capture the effect of changing climate-specific capital requirements on financial stability, interbank contagion, price levels and welfare. In the following section we describe the key features of the model before defining equilibrium.

2.1 Model description

The model consists of three agents on the production side – a non-renewable energy producer (a coal plant) that emits greenhouse gases, a renewable energy producer (a wind farm) and a consumption goods producer (an automotives producer) that uses an energy composite as intermediate input.

There are four types of households. Households are pre-assigned to be labourers or entrepreneurs, in the brown or the green energy sector. Entrepreneurs have a claim to all profits of their sector's energy producer, while labourers earn wages in exchange for supplying labour to their chosen sector's energy producer. This implies that the four household types based on occupation-sector, indexed by h, are $h \in \{Bl, Gl, Be, Ge\}$.

There are two banks – a retail bank (RB) and an investment bank (IB). The retail bank lends to and takes deposits from labour households, but cannot finance investment projects (capital). The investment bank lends to and takes deposits from entrepreneur households, finances investment by the three production firms and lends to the retail bank in an interbank market.

Households and banks are finitely lived over two periods. The first period consists of a single initial state and the second period consists of $S = 2$ possible states. Each state denotes a realisation of productivity shocks in the brown and green energy sectors, which are perfectly negatively correlated and take two values, up (u) and down (d), with probability defined by the probability density function as $P(S = s) = \mu(s)$. At the baseline, we consider a setup where both sectors are equally risky. Wherever possible, we suppress the state notation and instead represent uncertainty by using the expectations operator.

The structure of the model is given in Figure 1. The timeline is given in Figure 2.

Figure 1: Structure of the model

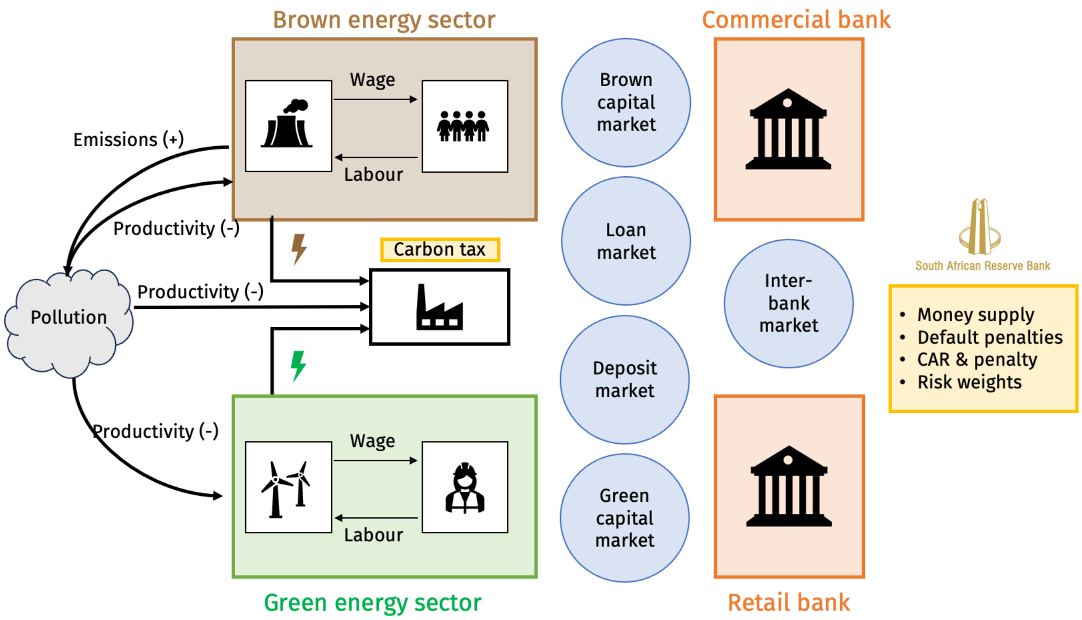
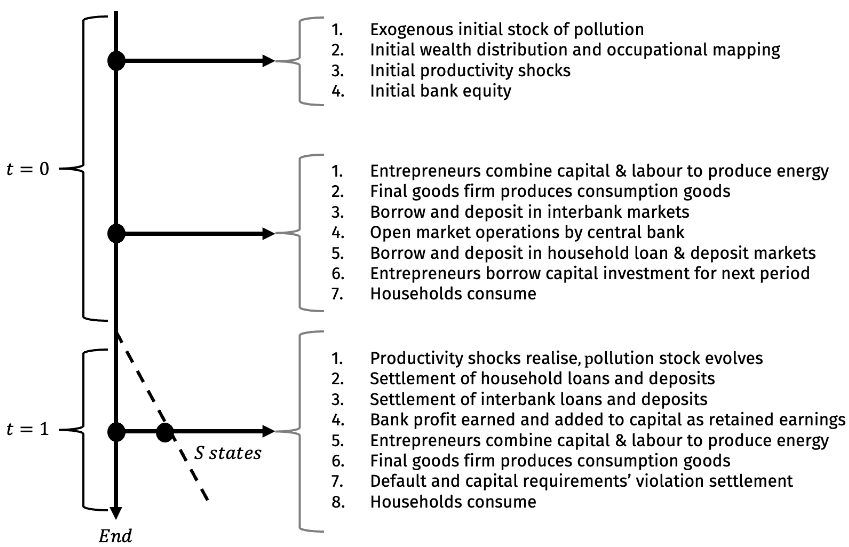


Figure 2: Timeline of the model



2.2 Producers

Pollution. We allow for a climate variable P to affect output. P is a proxy for pollution and measures the current carbon concentration in the atmosphere. The stock of pollution P increases endogenously through polluting activities – the production of brown energy. This mapping, called the carbon cycle, is an increasing function of brown energy output and depends on the depreciation function $(1 - d_n)$. The carbon cycle impacts the economy by reducing productivity through the damage function $D(P)$, which is an increasing function of P. Damages due to pollution cause productivity losses across all three sectors, implying that productivity is lowered by a factor of $1 - D(P_t) = e^{-\sigma(P_t - \bar{P})}$, where $\bar{P}$ are pre-industrial levels of pollution.

Combining the carbon cycle with the damage function, we obtain:

$$1 - D(P_t) = e^{-\sigma(P_t - \bar{P})} = \exp\left[-\sigma\left\{\sum_{n=1}^{t+T}(1 - d_n)E_{1t-n}\right\}\right] \tag{1}$$

The damage function takes the form defined in the Khemka-Tsomocos model, which in turn derives it from Golosov et al. (2014).

Final goods. The consumption good acts as the numeraire. Output in the final goods sectors is described by a constant returns to scale nested Cobb-Douglas specification with four inputs (indexed by subscript 0) and multiplicative pollution damages. The final goods producer takes its capital and labour endowments K_{0t}, N_{0t} as given and chooses inputs to maximise its per-period profits:

$$\max_{E_{01t}, E_{02t}} \Pi_{0t} = Y_t - (p_{1t} + \tau)E_{01t} - p_{2t}E_{02t} \ \forall \ t$$

where

$$Y_t = e^{-\sigma(P_t - \bar{P})} K_{0t}^{\alpha} N_{0t}^{1-\alpha-\nu} E_{0t}^{\nu} \tag{2}$$

where E_{0t} represents an energy composite (of brown energy and green energy) defined by the following constant elasticity of substitution (CES) structure:

$$E_{0t} = (\psi E_{01t}^{\rho} + (1 - \psi)E_{02t}^{\rho})^{\frac{1}{\rho}}$$

E_{01t} denotes demand for brown energy, while E_{02t} denotes demand for green energy, with p_{1t}, p_{2t} denoting the respective prices of inputs. τ is carbon tax, assumed to be downstream (i.e. levied on the buyer of energy). α is the capital elasticity of substitution and ν is the composite energy elasticity of substitution. $\rho < 1$ is the elasticity of substitution parameter between different energy sources (implying that energy sources are imperfect substitutes) and ψ measures the relative energy efficiency of brown energy. Given the South African economy's relatively high reliance on coal and relatively low reliability of current established non-renewables capacity, we calibrate ψ to be high, while ρ is smaller. This allows us to conduct a counterfactual exercise where the South African power sector transitions to 42% non-fossil fuel sources by 2030 in line with its UNFCCC targets.

Energy production. Each energy sector has its own decreasing returns to scale Cobb-Douglas production specification using capital and labour as inputs,[3] productivity shock z_{it} and productivity damages due to pollution. Denote energy sectors with $i \in \{1 = Brown, 2 = Green\}$. Then sector i energy output is:

$$E_{it} = e^{-\sigma(P_t - \bar{P})} z_{it} K_{it}^{\alpha} N_{it}^{\beta}, \quad \alpha + \beta < 1 \tag{3}$$

where β is the labour elasticity of substitution.

2.3 Households

Households are ex-ante heterogeneous. They enter the economy with different initial endowments a_0^h in units of the consumption good. Entrepreneurs are endowed with initial, sector-specific capital – that is, capital is immobile.

Labour is imperfectly mobile. Worker households are endowed with one unit of labour, which they may choose to allocate between the brown and green energy sectors. Denote the time t allocation of labour household h to the brown sector by $\theta_t(h)$. The corresponding allocation to the green sector is then $1 - \theta_t(h)$. To incorporate heterogeneity between labour households, we assume that they enter the economy with different pre-period allocations of labour hours between sectors, denoted by $\theta^*(h)$. Brown and green labour households are therefore charac-

[3] While energy itself may be an intermediate input, we abstract away from such a specification for ease of exposition. Note that capital at time $t = 0$ is predetermined (i.e. an endowment).

terised by $\theta^*(h = Bl) > \theta^*(h = Gl)$. We assume that in order to deviate from their pre-period allocations, households need to incur quadratic adjustment costs denoted by χ_l, which capture upskilling costs, sectoral switching costs, losses due to unemployment in the transition between jobs or search costs.

All households choose consumption today and consumption in both states tomorrow. In addition, each household has access to both a deposit facility and a borrowing facility with their nature-selected bank, labour households with the retail bank ($Bl, Gl \to RB$) and entrepreneur households with the investment bank ($Be, Ge \to IB$). Households are allowed to default endogenously on their borrowings. Default is subject to utility costs parametrised by λ_h. Households also receive transfers in each period which they take as given. Transfers comprise tax revenues distributed based on the policymaker's redistributive weights and an equal share of profits in the banking sector at $t = 1$.

There is restricted participation in asset markets due to wage labour households not having access to the capital savings technology. Therefore, markets are incomplete as wage labour households cannot insure themselves perfectly by using the risk-free bond.

In what follows, we lay down the maximisation problems of all four types of household.

Brown labour households. Bl households receive wages from both sectors in proportion to their allocation of working hours. They choose consumption (C_t^{Bl}), deposits (d_1^{Bl}), borrowing (b_1^{Bl}), labour allocation to the brown sector (θ_t^{Bl}) and delivery rate on its borrowing in each state (D_s^{Bl}) to maximise intertemporal utility net of default costs:

$$\max_{C_0^{Bl}, C_s^{Bl}, d_1^{Bl}, b_1^{Bl}, \theta_0^{Bl}, \theta_s^{Bl}, D_s^{Bl}} \Pi^{Bl} = U(C_0^{Bl}) + \delta \mathbb{E}_0 \left[U(C_s^{Bl}) - \lambda_h \max\{b_1^{Bl}(1 - D_s^{Bl}), 0\} \right]$$

subject to:

$$C_0^{Bl} + d_1^{Bl} + \frac{\chi_l}{2}(\theta_0^{Bl} - \theta^{*,Bl})^2 = \theta_0^{Bl} w_{10} + (1 - \theta_0^{Bl}) w_{20} + a_0^{Bl} + b_1^{Bl} + t_0^{Bl} \tag{4}$$

$$C_s^{Bl}+(1+r_l^{RB})D_s^{Bl}b_1^{Bl}+\frac{\chi_l}{2}(\theta_s^{Bl}-\theta^{*,Bl})^2=\theta_s^{Bl}w_{1s}+(1-\theta_s^{Bl})w_{2s}+(1+r_d^{RB})D_s^{RB}d_1^{Bl}+t_s^{Bl},\ \forall s\in S \tag{5}$$

where r_l^{RB} is the lending rate offered by the retail bank, r_d^{RB} is the deposit rate offered by the retail bank and t_t^{Bl} are government transfers of tax revenue and equal share of banking sector profits. $D_s^{RB}\in[0,1]$ is an endogenous quantity that denotes the delivery rate of the retail bank on its deposits.

Green labour households. The problem for Gl households looks very similar to that of brown households:

$$\max_{C_0^{Gl},C_s^{Gl},d_1^{Gl},b_1^{Gl},\theta_0^{Gl},\theta_s^{Gl},D_s^{Gl}} \Pi^{Gl}=U(C_0^{Gl})+\delta\mathbb{E}_0\left[U(C_s^{Gl})-\lambda_h\max\{b_1^{Gl}(1-D_s^{Gl}),0\}\right]$$

subject to:

$$C_0^{Gl}+d_1^{Gl}+\frac{\chi_l}{2}(\theta_0^{Gl}-\theta^{*,Gl})^2=\theta_0^{Gl}w_{10}+(1-\theta_0^{Gl})w_{20}+a_0^{Gl}+b_1^{Gl}+t_0^{Gl} \tag{6}$$

$$C_s^{Gl}+(1+r_l^{RB})D_s^{Gl}b_1^{Gl}+\frac{\chi_l}{2}(\theta_s^{Gl}-\theta^{*,Gl})^2=\theta_s^{Gl}w_{1s}+(1-\theta_s^{Gl})w_{2s}+(1+r_d^{RB})D_s^{RB}d_1^{Gl}+t_s^{Gl},\ \forall s\in S \tag{7}$$

Brown entrepreneur households. Be households earn profits from producing energy net of wage costs. In addition to consumption (C_t^{Be}), deposits (d_1^{Be}), borrowing (b_1^{Be}) and delivery rate in each state (D_s^{Be}), they also choose how much capital to borrow from the investment bank to invest in the production of energy for the next period, K_{11}, as well as how much labour to use in the production process, to maximise intertemporal utility net of default costs (where default can be over their cash borrowings or capital borrowings):

$$\max_{C_0^{Be},C_s^{Be},d_1^{Be},b_1^{Be},D_s^{Be},K_{11},N_{10},N_{1s}} \Pi^{Be}=U(C_0^{Be})+\delta\mathbb{E}_0\left[U(C_s^{Be})-\lambda_h\max\{(b_1^{Be}+K_{11})(1-D_s^{Be}),0\}\right]$$

subject to:

$$C_0^{Be}+d_1^{Be}=p_{10}E_{10}-w_{10}N_{10}+a_0^{Be}+b_1^{Be}+K_{11}+t_0^{Be} \tag{8}$$

$$C_s^{Be}+(1+r^B)D_s^{Be}K_{11}+(1+r_l^{IB})D_s^{Be}b_1^{Be}=p_{1s}E_{1s}-w_{1s}N_{1s}+(1+r_d^{IB})D_s^{IB}d_1^{Be}+t_s^{Be},\ \forall s\in S \tag{9}$$

where r_l^{IB} is the lending rate offered by the investment bank, r_d^{IB} is the deposit rate offered by the investment bank, r^B is the rate at which capital is borrowed and t_t^{Be} are government transfers of tax revenue and equal share of banking sector profits. $D_s^{IB} \in [0,1]$ is an endogenous quantity that denotes the delivery rate of the investment bank on its deposits.

Green entrepreneur households. The only difference between the brown and green entrepreneur problem is the inclusion of exogenous markdowns κ_e in the sector. These capture both the scale differences between the two sectors, as well as lower bargaining power available to renewable energy producers in a coal-dominated economy:

$$\max_{C_0^{Ge},C_s^{Ge},d_1^{Ge},b_1^{Ge},D_s^{Ge},K_{21},N_{20},N_{2s}} \Pi^{Ge} = U(C_0^{Ge}) + \delta\mathbb{E}_0\left[U(C_s^{Ge}) - \lambda_h \max\{(b_1^{Ge} + K_{21})(1 - D_s^{Ge}), 0\}\right]$$

subject to:

$$C_0^{Ge} + d_1^{Ge} = p_{20}(1-\kappa_e)E_{20} - w_{20}N_{20} + a_0^{Ge} + b_1^{Ge} + K_{21} + t_0^{Ge} \tag{10}$$

$$C_s^{Ge} + (1+r^G)D_s^{Ge}K_{21} + (1+r_l^{IB})D_s^{Ge}b_1^{Ge} = p_{2s}(1-\kappa_e)E_{2s} - w_{2s}N_{2s} + (1+r_d^{IB})D_s^{IB}d_1^{Ge} + t_s^{Ge}, \ \forall s \in S \tag{11}$$

2.4 Banks

There are two types of banks that are ex-ante heterogeneous. Banks assume different levels of risk and therefore expect different returns. Banks are allowed to default on their borrowings but are subject to default penalties set by the regulator. Default can be either strategic or due to ill fortune. Strategic default occurs when institutions choose not to honour their obligations even though they have the means to do so, while ill fortune default occurs when a bank is genuinely unable to honour its obligations as a result of not having adequate funds. The investment bank is also subject to a capital adequacy requirement. This is calibrated such that it does not bind in equilibrium – however, any deviation is punished by the regulator.

Banks enter the economy endowed with initial capital (equity). They choose the amounts to offer in the different borrowing and lending markets as well as how much to default to maximise expected future profits. The retail bank is restricted from participating in the capital lending market (due to, for example, lack of relationships, lack of capital or differing business models). There is also an interbank market, where the retail bank may borrow funds from the investment bank. In what follows, we lay down the maximisation problem of both banks.

Retail bank. The retail bank chooses the amount to offer in the borrowing market to labour households ($\bar{m}^{RB}$), the amount to accept as deposits from labour households (μ_d^{RB}), the amount to borrow in the interbank market from the investment bank (μ^{RB}) and the delivery rate on its obligations in each state (D_s^{RB}) to maximise its payoff (which is a quadratic function of its expected profits π_s^{RB}) net of default penalties:

$$\max_{\bar{m}^{RB},\mu^{RB},\mu_d^{RB},D_s^{RB}} \Pi^{RB} = \mathbb{E}_0\left[\pi_s^{RB} - c^{RB}(\pi_s^{RB})^2\right] - \mathbb{E}_0\left[\lambda^{RB}\{\mu^{RB}(1-D_s^{RB})\} + \lambda^{RB}\{\mu_d^{RB}(1-D_s^{RB})\}\right]$$

subject to a balance sheet constraint:

$$\frac{\bar{m}^{RB}}{1+r_l^{RB}} + A^{RB} = \frac{\mu^{RB}}{1+\rho^B} + \frac{\mu_d^{RB}}{1+r_d^{RB}} + e_0^{RB} + Others^{RB} \tag{12}$$

where ρ^B represents the interbank borrowing rate, A^{RB} represents the market book of the retail bank, e_0^{RB} is the initially endowed equity and $Others^{RB}$ represents other items that act as a balancing figure; a liquidity constraint:

$$D_s^{RB}(\mu^{RB} + \mu_d^{RB}) + Others^{RB} + e_0^{RB} \leq \tilde{R}_s^l\bar{m}^{RB} + (1+r^A)A^{RB}, \ \forall s \in S \tag{13}$$

That is, the repayment of liabilities (left-hand side) is possible through the receipts from assets (right-hand side) in each state. r^A represents the retail bank's returns on its market book and $\tilde{R}_s^l$ denotes the repayment rate in the lending market (taken as given and determined in equilibrium).

Profits are given by:

$$\pi_s^{RB} = \tilde{R}_s^l \bar{m}^{RB} + (1 + r^A)A^{RB} - D_s^{RB}(\mu^{RB} + \mu_d^{RB}) - Others^{RB} - e_0^{RB}, \;\; \forall s \in S$$

that is, receipts from assets minus payments on liabilities.

Investment bank. The investment bank chooses the amount to offer in the borrowing market to entrepreneur households ($\bar{m}^{IB}$), the amount to accept as deposits from entrepreneur households (μ_d^{IB}), the amount to offer to the retail bank in the interbank market (μ^{IB}), the amount to offer as capital loans to the brown and green entrepreneurs (A^B and A^G) and the delivery rate on its obligations in each state (D_s^{IB}) to maximise its payoff (which is a quadratic function of its expected profits π_s^{IB}) net of default penalties and net of penalties for violating its capital adequacy requirement ($\bar{k}^{IB}$):

$$\max_{\bar{m}^{IB},\mu^{IB},A^G,\mu_d^{IB},D_s^{IB}} \Pi^{IB} = \mathbb{E}_0\left[\pi_s^{IB} - c^{IB}(\pi_s^{IB})^2\right] - \mathbb{E}_0\left[\lambda_k^{IB}\max\{0, \bar{k}^{IB} - k_s^{IB}\} + \lambda^{IB}\{\mu_d^{IB}(1 - D_s^{IB})\}\right]$$

subject to a balance sheet constraint:

$$\frac{\bar{m}^{IB}}{1 + r_l^{IB}} + \frac{A^B}{1 + r^B} + \frac{A^G}{1 + r^G} + \mu^{IB} = \frac{\mu_d^{IB}}{1 + r_d^{IB}} + e_0^{IB} + Others^{IB} \tag{14}$$

where e_0^{IB} is the initially endowed equity and $Others^{IB}$ represents other items that act as a balancing figure; a liquidity constraint:

$$D_s^{IB}\mu_d^{IB} + Others^{IB} + e_0^{IB} \leq \tilde{R}_s^e \bar{m}^{IB} + D_s^{Be}A^B + D_s^{Ge}A^G + D_s^{RB}\mu^{IB}(1 + \rho^B), \;\; \forall s \in S \tag{15}$$

That is, the repayment of liabilities (left-hand side) is possible through the receipts from assets (right-hand side) in each state. $\tilde{R}_s^e$ denotes the repayment rate in the lending market (taken as given and determined in equilibrium).

Profits are given by receipts from assets minus liabilities:

$$\pi_s^{IB} = \tilde{R}_s^e \bar{m}^{IB} + D_s^{Be} A^B + D_s^{Ge} A^G + D_s^{RB} \mu^{IB}(1+\rho^B) - D_s^{IB} \mu_d^{IB} - Others^{IB} - e_0^{IB},\ \forall s \in S$$

Bank equity e_s^{IB} follows the law of motion where current period profits are added to equity as retained earnings:

$$e_s^{IB} = e_0^{IB} + \pi_s^{IB},\ \forall s \in S$$

Violations of the capital adequacy ratio are determined based on the capital-assets ratio:

$$k_s^{IB} = \frac{e_s^{IB}}{\bar{\omega}\tilde{R}_s^e \bar{m}^{IB} + \omega D_s^{RB} \mu^{IB}(1+\rho^B) + \tilde{\omega} D_s^{Be} A^B + \hat{\omega} D_s^{Ge} A^G},\ \forall s \in S$$

where assets are weighed based on their risk profiles: $\bar{\omega}$ is the risk weight on loans to entrepreneurs, ω is the risk weight on interbank loans, $\tilde{\omega}$ is the **brown capital requirement** and $\hat{\omega}$ is the **green capital requirement**.

2.5 Government and central bank

The government is the fiscal authority that imposes and collects carbon tax. Carbon tax of τ is imposed on the purchase of brown energy by the final goods producer in each period. Its revenue from carbon tax collections is equal to $\Re_t = \tau E_{01t}$. It redistributes tax revenue (as well as bank profits) back to households based on the transfer vector $\mathbf{t_t} = \{t_t^h\}_{h \in H}$. Its objective is to maintain a balanced budget in each period:

$$\Re_s + \mathbb{I}_{t=1}(\pi_s^{RB} + \pi_s^{IB}) = \sum_h t_s^h\ \forall\ s$$

Therefore, the government's policy tool is a tuple of tax rates and household transfers $(\tau, \{t_s^h\}_{h \in H})$.

The central bank has four policy tools. First, it sets base money M, that is, money supplied into the interbank borrowing market through the SARB's repo window. Second, it sets default penalties for households λ_h, for retail banks λ^{RB} and for investment banks λ^{IB}. Third, it sets the capital adequacy requirement (CAR) $\bar{k}^{IB}$ as well as the penalty for violating the CAR λ_k^{IB}. Fourth, it sets risk weights $\bar{\omega}$ on loans to entrepreneurs, ω on interbank loans, $\tilde{\omega}$ on brown capital loans and $\hat{\omega}$ on green capital loans.

2.6 Market clearing conditions

There are 17 active markets in the economy: 4 energy markets, 6 labour markets, 2 household deposit markets, 2 household lending markets, 2 capital borrowing markets and the interbank market. The equalising of demand and supply in each of these markets determines the relevant price, wage or interest rate:

Energy markets:

$$E_{is} = E_{0is} \ \forall \ i \in \{0,1,2\}, s \in \{0,1,2\} \tag{16}$$

Wage markets:

$$N_{0s} = 1 \ \forall \ s \in \{0,1,2\} \tag{17}$$

$$N_{1s} = \theta_s^{Bl} + \theta_s^{Gl} \ \forall \ s \in \{0,1,2\} \tag{18}$$

$$N_{2s} = (1-\theta_s^{Bl}) + (1-\theta_s^{Gl}) \ \forall \ s \in \{0,1,2\} \tag{19}$$

Deposit markets:

$$1 + r_d^{RB} = \frac{\mu_d^{RB}}{d_1^{Bl} + d_1^{Gl}} \tag{20}$$

$$1 + r_d^{IB} = \frac{\mu_d^{IB}}{d_1^{Be} + d_1^{Ge}} \tag{21}$$

Borrowing markets:

$$1 + r_l^{RB} = \frac{\bar{m}^{RB}}{b_1^{Bl} + b_1^{Gl}} \tag{22}$$

$$1 + r_l^{IB} = \frac{\bar{m}^{IB}}{b_1^{Be} + b_1^{Ge}} \tag{23}$$

Interbank market:

$$1 + \rho^B = \frac{\mu^{RB}}{M + \mu^{IB}} \tag{24}$$

Capital borrowing markets:

$$1 + r^B = \frac{A^B}{K_{11}} \tag{25}$$

$$1 + r^G = \frac{A^G}{K_{21}} \tag{26}$$

Additionally, consumption markets clear in each state by Walras' Law.

We note that these interest rates are the ex-ante nominal interest rates that incorporate default premium since default is permitted in equilibrium. The effect of default is incorporated in ex-post repayment rates that are determined in equilibrium.

2.7 Equilibrium

For a full definition of equilibrium, refer to Annex 1. We say that the tuple of bank choices, household choices and prices is an equilibrium in the economy if and only if all banks optimise, all households optimise, all markets clear and all agents are correct in their expectations about the repayment rates they face.

3. Calibration

We lay out the calibrated values for exogenous parameters in Table 1.

Table 1: Exogenous variables

Parameter	Description	Value	Source
Production			
δ	Discount rate	0.9	Literature
α	Capital share of GDP	0.3	Golosov et al. (2014)
ν	Energy share of GDP	0.1	ISS (2025), Steenkamp (2018)
β	Labour share for energy production	0.4	Gouzoulis, Constantine and Ajefu (2023)
ρ	ES b/w brown & green energy	0.32	Lin and Atsagli (2017)
ψ	Brown share of total energy	0.91	IEA (2024)
Initial wealth			
$\{a_0^{Bl}, a_0^{Gl}, a_0^{Be}, a_0^{Ge}\}$	Household endowments	{5.4, 150, 250, 500}	Statistics SA (2024)
K_{10}	Brown capital endowment	33	Match Gini 0.68
K_{20}	Green capital endowment	33	Match Gini 0.68
Productivity shocks			
μ	Probability of up state	0.9	Assumed
(z_{11}, z_{21}^U)	$t = 1$ Up state shocks	(1.5, 0.5)	Assumed
(z_{12}, z_{22}^U)	$t = 1$ Down state shocks	(0.5, 1.5)	Assumed
Occupation costs			
κ_e	Markdown in renewable energy	0.2	Smarte Anekwe et al. (2024)
χ_l	Cost of labour adjustment	1.1	Cantelmo and Melina (2020)
$\theta^{*,Bl}, \theta^{*,Gl}$	Baseline labour allocation	0.8, 0.2	Definition
Environment			
$\{d_0, d_1\}$	Depreciation of emissions	{0.2, 0.5}	Golosov et al. (2014)
σ	Ex-ante damage cost	0.0003	Golosov et al. (2014)

$E_{1,base}$	Energy production from -T to 0	281	IEA (2024)
Banking parameters			
c^{RB}	Coeff. of risk aversion (retail bank)	0.26	Beyers et al. (2020)
c^{IB}	Coeff. of risk aversion (inv. bank)	0.31	”
A^{RB}	Market book (retail bank)	2.0913	”
r^{A}	Return on market book	0.0730	”
e_0^{IB}	Equity (inv. bank)	139.74	”
Regulator/Government			
M	Money supply	1	Normalised
$\lambda_h, \lambda^{RB}, \lambda^{IB}$	Default penalties	0.1, 0.9, 0.9	Beyers et al. (2020)
$\bar{k}^{IB}$	Capital adequacy requirement	0.13	”
λ_k^{IB}	CAR violation penalty	0.1	”
$\bar{\omega}$	Risk weight on household lending	1.0	BIS (2024) CRE 20.68
ω	Risk weight on interbank lending	0.5	BIS (2024) CRE 20.18
Baseline policy			
$\tilde{\omega}$	Brown capital requirement	1.5	Assumed
$\hat{\omega}$	Green capital requirement	1.5	”
τ	Carbon tax	2.5	”

Our calibration strategy involves a combination of relying on literature estimates, targeting moments of South African data and choosing calibrated parameters from previous studies on South Africa.

We choose a discount rate of $\delta = 0.9$, as is commonly assumed in the literature. For capital share of gross domestic product (GDP), we choose $\alpha = 0.3$, as assumed in Golosov et al. (2014). However, for the energy share of GDP ν, we choose a higher value compared to the number proposed in Golosov et al. (2014) (0.04) for two reasons. One, they calibrate their model to the United States (US) economy, which is less manufacturing-oriented than South Africa, which implies that South Africa is likely to have a larger share of GDP accounted for by the energy sector. This is confirmed in the data – the Bureau of Economic Analysis's (BEA's) estimates for value added by industry as a percentage of US GDP put utilities at 1.3%,[4] while Cilliers and le Roux (2025) from ISS African Futures estimate that South Africa's energy share of GDP is 5.6%.[5] The figure of 5.6% is also likely to underestimate the dependence of the manufacturing and mining sectors on energy. Similarly, it understates the short-term impact of high energy prices and high energy efficiencies currently prevalent in South Africa. Two, in order to match the labour share of final goods production/GDP ($1-\alpha-\nu$) to the value discussed in Steenkamp (2018) of 55%, ν needs to be calibrated to a higher value of 0.15. Both these values represent extremes of the calibration range; therefore, we calibrate ν to be the average of these extreme values, that is, 0.1.

[4] US Bureau of Economic Analysis,'Value added by industry as a percentage of gross domestic product'.
[5] https://futures.issafrica.org/geographic/countries/south-africa/?

Calibrating β, that is, the labour share of *energy* output, is challenging. For one, we cannot calibrate this to be the same as the labour share of final goods production, given the different structural differences between the sectors. We rely on estimates of the private sector wage share as a percentage of GDP from Gouzoulis, Constantine and Ajefu (2023), who estimate that this averages to 40% from 2010 to 2020. Therefore, we set $\beta = 0.4$.

We use Lin and Atsagli (2017) to calibrate the elasticity of substitution between brown and green energy. Specifically, we take the average elasticity of substitution between coal and electricity (which they define as being generated from renewable sources of energy) between 1980 and 2012 to set $\rho = 0.32$. This implies that brown and green energy are imperfect substitutes in South Africa.

The brown share of total energy is calibrated using the International Energy Agency's (IEA's) country profile on South Africa, focusing on its energy mix. As of 2022, 70.1% of South Africa's energy needs were being met by coal, while 19.9% were being met by oil. This implies a share of $\psi = 0.91$ of non-renewable energy sources.

In order to calibrate initial endowments for households as well as capital holdings by entrepreneurs, we use a combination of Statistics South Africa's *Monthly earnings in South Africa, 2017-2022* report[6] (in hundreds of South African rands) and the World Bank's estimate of the Gini coefficient. Specifically, we refer to "Table 1.1: Median monthly earnings by status in employment, 2017 and 2022" from the monthly earnings report. We focus on data from the year 2022. Brown labour endowment is calibrated to the median monthly earnings of employees. Green labour endowment is calibrated to the top 25 percentile of employee earnings. Brown entrepreneur endowment is calibrated to the top 25 percentile of employer earnings, while green entrepreneur endowment is calibrated to the top 10 percentile of employers earnings. When it comes to calibrating capital endowment, we assume equal capital endowment for simplicity. We choose the level of capital endowment such that the total endowment of households (which, for entrepreneurs, is the sum of their base and capital endowments) leads to a Gini coefficient of

6 Accessed at https://www.statssa.gov.za/publications/02-11-20/02-11-202022.pdf

0.68, matching the World Bank's estimates.[7] As discussed in Khemka and Tsomocos (2025), there exists a negative correlation between a sector's average earnings and its intensity of carbon emissions. Therefore, earnings of green sector participants are higher than earnings of brown sector participants. The assumption that entrepreneurs have higher endowment than labourers is fairly innocuous.

We assume that uncertainty in this economy is characterised by a negatively correlated increase or decrease in the productivity of non-renewable energies. We assume a 90% probability that productivity in the non-renewables sector increases by 50%, while productivity in the renewables sector falls by 50% and vice versa with 10% probability. Therefore, we start from a baseline calibration where brown energy is less risky than green energy – we argue that given the economy's dependence on non-renewable energy sources, this is the relevant present benchmark for the South African economy. In the down state, the productivity increase in renewables is designed to be higher than the compound annual growth rate in the renewables energy share to achieve a target of 42% by 2030.

Calibrating sectoral occupation costs is tricky. For the markdown in renewable energy, we use Table 1 from Smarte Anekwe et al. (2024) to note that the cost of generating energy from solar (US$ 0.068/kWh) is 66% higher than the cost of generating energy from coal (US$ 0.023/kWh). However, this is misleading because the lifespan of solar installations is 25–40 years, while that of coal installations is 200 years. Assuming that the cost of solar power generation would fall by 60% if its lifespan increased to 200 years, we note a 20% higher price of solar energy. We assume that in order to remain competitive, producers have to bear this additional 20%, hence the effective price they receive is 20% lower than the actual price, allowing us to set $\kappa_e = 0.2$. We set baseline labour allocations as a matter of definition – brown labour households are defined as those that work 80% of their hours in the brown energy sector and vice versa for green labour households. We calibrate labour mobility costs χ_l to directly match estimates from Cantelmo and Melina (2020), who estimate the parameter in a two-sector New Keynesian

[7] We assume that 60% of households are brown labour, 20% are green labour and 10% each are brown and green entrepreneurs.

setup.

To calibrate parameters in the environment module, we rely mostly on Golosov et al. (2014). As an initial condition on the carbon cycle, we calibrate energy production between 2020 and 2022 to be equal to 281 Mt CO2, based on the IEA's estimate of the trend of South Africa's CO2 emissions from fuel consumption. We set the ex-ante damage costs from Golosov et al. (2014) ($\sigma = 0.0003$) to be equal to the average of the high and low values of damage costs in their calibration. Finally, our calibration of the depreciation of emissions is based on Khemka and Tsomocos (2025), who adopt the three-parameter family carbon cycle described in Golosov et al. (2014). This results in depreciation estimates of 0.2 in the first year and 0.5 in the second year.

To calibrate parameters in the banking sector, we rely extensively on Beyers et al. (2020), who set up a CGE model for banking sector risk assessment in South Africa. They rely on annual account data for the banking sector in South Africa, constructed using balance sheet data provided by individual South African banks. In their study, they cover the six largest banks by assets in South Africa, which account for most of the country's banking activity. They then consider three heterogeneous banks in their model – the largest bank, the second largest bank and the four smaller banks as a combined entity. While the identities of the banks are kept confidential in their paper, we can map the banks to be Standard Bank and FirstRand as the two larger banks and Absa, Nedbank, Investec and Capitec combined into a third bank (using data on total assets from The Banker database).

Given their sizes, Standard Bank and FirstRand Bank are both significant players in the investment banking and commercial lending markets. Meanwhile, Absa, Nedbank, Investec and Capitec are either well established or growing rapidly within the retail banking market. Therefore, it is natural for us to assume that the investment bank in our model is a combination of Standard Bank and FirstRand (the two large banks in Beyers et al. (2020)), while the retail bank is a combination of the other four banks (the third bank in Beyers et al. (2020)).

With this mapping, we are now in a position to calibrate parameter values using Beyers et al.

(2020). Coefficients of risk aversion for both banks are set using the average of the expected value of risk aversion coefficients from Table 6 in Beyers et al. (2020). The market book of the retail bank and returns on the market book are directly calibrated from the same table, using assets of bank τ in their paper. Equity of the investment bank is the average of equity endowments of banks γ and δ in their setup.

Default penalties for banks are set at 0.9 following Table 5 in their paper, while the default penalty for households of 0.1 is calibrated from Goodhart, Sunirand and Tsomocos (2005), who first lay out the base model used in Beyers et al. (2020). Both the capital adequacy requirement and the CAR violation penalty are set using values for the bigger banks in Table 5 in Beyers et al. (2020). To set risk weights on household lending and interbank lending, we rely on the Bank for International Settlements' (BIS') latest note on the calculation of risk-weighted assets for credit risk,[8] published in December 2024. CRE 20.68 lays out that retail exposures should be weighed at 100%, which sets ω. CRE 20.18 lays out the risk weight for bank exposures as a function of the counterparty's external rating. We choose a risk weight of 50% corresponding to a counterparty external rating of BBB+ to BBB-.

Other parameters, namely money supply (M), brown risk weight ($\tilde{\omega}$), green risk weight ($\hat{\omega}$) and carbon taxes (τ), are the focus of our analysis and therefore subject to an extensive comparative statics analysis.

4. Mechanisms

Before we proceed to solve the model numerically and given its complexity, it is useful to first consider the mechanisms through which different policy tools function in the model. This section considers our three primary policy tools – tightening brown capital requirements, loosening green capital requirements and increasing carbon taxes. For each tool, we answer the following three questions qualitatively: i) Which policy delivers the biggest decrease in pollution?, ii) Which policy leads to the largest increase in inequality? and iii) Which policy reduces financial

[8] Accessed at https://www.bis.org/basel_framework/chapter/CRE/20.htm?inforce=20230101&published=20221208

stability the most? Under each question, we trace how a perturbation in the policy parameter flows across the system and note which parameters or exogenous quantities determine magnitudes of effects.

4.1 Brown capital requirements

Let us first consider the brown capital requirement, $\tilde{\omega}$. This enters the investment bank's capital-assets ratio. For simplicity and to set intuition, consider a simpler version of the bank's balance sheet, which looks like the following:

$$\underbrace{A^B + A^G}_{\text{Loans to entrepreneurs}} = \underbrace{ND^{IB}}_{\text{Net deposits}} + \underbrace{e^{IB}}_{\text{Equity}}$$

and a simplified CAR condition:

$$e^{IB} \geq \bar{k}^{IB} \underbrace{(\tilde{\omega}A^B + \hat{\omega}A^G)}_{\text{Risk-weighted assets (RWA)}}$$

Consider the bank's decision to offer an extra rand of capital loans to the brown entrepreneur. The brown entrepreneur promises to repay $1 + r^B$ on the additional rand. However, they can default endogenously, choosing to deliver $\mathbb{E}(D_s^{Be}) \in [0, 1]$. Therefore, the bank's expected inflow is $\mathbb{E}(D_s^{Be})(1 + r^B)$. The bank has two costs associated with this additional lending. First, it can use net deposits to fund the additional rand, at a price of $1 + r_{ND}^{IB}$, where r_{ND}^{IB} is the net deposits funding cost, a function of the deposit rate, the household lending rate and the interbank lending rate. Second, it must raise $\bar{k}^{IB}\tilde{\omega}$ rand of new equity, at an associated shadow price of Λ (the Lagrange multiplier on the CAR condition). Assuming that the bank is perfectly competitive, it prices the loan at r^B which solves for equating the expected inflow with the funding cost:

$$1 + r^B = \frac{1 + r_{ND}^{IB} + \Lambda\bar{k}^{IB}\tilde{\omega}}{\mathbb{E}(D_s^{Be})}$$

Clearly, the steepness of this brown capital loan supply curve is determined by the amount of endogenous default (which is higher for higher r^B) and the regulatory lever (the risk weight and the amount of equity slack).

4.1.1 Effect on pollution

Now, consider a policy change that increases $\tilde{\omega}$. This makes the CAR condition tighter or reduces equity slack ($e^{IB} - \bar{k}^{IB} RWA$). From the above pricing equation, the supply curve of brown loans tilts upwards – r^B rises while A^B falls. There is an additional round of adjustments which is determined by entrepreneurs reaching the point of indifference between defaulting and not defaulting on more costly loans – if default penalties are low, equilibrium delivery rates are low, pushing r^B further up. As the cost of capital increases, brown entrepreneurs reduce investment in brown capital, the size of which is determined by production elasticities α and β. With lower capital investment, the brown energy supply curve shifts leftwards, with the magnitude being determined by a combination of production elasticities and costs of labour adjustment (χ_l). If the supply curve is relatively more inelastic, the drop in brown energy production is larger, otherwise the price of brown energy adjusts upwards and bears the brunt of the adjustment. The effect on brown entrepreneur profits is ex-ante unclear, but lower profits further increase default rates. Faced with higher prices, the final goods producer substitutes away from brown energy towards green energy, the magnitude of which is determined by the elasticity of demand governed by ρ and ψ. This raises green energy prices (but not necessarily green energy production).

With perfectly functioning capital markets, an inelastic brown energy supply curve (due to imperfect factor mobility) and elastic brown energy demand (due to ease of substitution to green energy), the drop in brown energy production would have been substantial in magnitude. However, banking frictions moderate the effect of the drop. Once the bank's CAR binds, every extra rand of brown lending needs new equity. Given the scarcity of equity, loan supply becomes steep, leading to moderate drops in A^B but large price adjustments. Second, because entrepreneurs can default with limited liability, it makes them less sensitive to rate hikes, making loan demand inelastic. These frictions already ensure that the drop in brown capital investment is not very large. In addition, the South African economy is characterised by low substitutability of brown energy demand, which implies that the demand curve is also inelastic. Therefore, the likely outcome is a large price increase in the brown energy market (and simultaneous increase in green energy prices leading to energy price inflation), but a moderate decrease in brown energy production (and hence pollution).

4.1.2 Effect on inequality

For the same thought experiment as above, we study the effects on household incomes across the four types. Brown entrepreneurs' profit from productive activities (dropping state subscripts for simplicity) is $\pi^{Be} = p_1 E_1 - w_1 N_1 - D^{Be}(1 + r^B)K_1$. As we noted above, we expect p_1 to increase, E_1 to decrease and financing costs r^B to increase. Further, given lower output, marginal product of labour is lower, which lowers w_1. In sum, the effect on brown entrepreneur profits is ambiguous, but likely to leave them at the same income level or make them slightly better off.

Brown labourers, however, unambiguously suffer. If labour adjustment costs are high, the labour supply curve is relatively steeper, resulting in even larger wage drops.

Green entrepreneurs' profit is $\pi^{Ge} = p_2 E_2 - w_2 N_2 - D^{Ge}(1 + r^G)K_2$. Due to substitution in the CES energy bundle, demand for green energy increases, pushing up p_2 and E_2. On the cost side, as marginal product of labour is higher, wages w_2 increase. The effect on the cost of financing capital is ambiguous – on one end, higher demand for capital investment pushes r^G upwards, but on the other end, the bank might tilt its loan portfolio towards greater supply of green capital loans, putting downward pressure on r^G. In sum, green entrepreneur profits are expected to increase slightly.

Finally, green labourers fare better. However, if labour adjustment costs are low, higher wages in the green sector attract more brown labourers to move to the green sector, somewhat negating the increase in wages.

With entrepreneur households faring better but brown labour households (which, in our calibration, account for the largest share of households) faring worse, the distribution gets pulled outwards and inequality is expected to increase.

4.1.3 Effect on financial stability

Traditionally, the role of higher capital requirements is to increase resilience of the financial system to unexpected shocks. Does an increase in brown capital requirements lead to higher financial stability?

First, risk-weighted assets increase, pushing equity slack lower, which is ex-ante positive. As credit supply is re-priced, the bank substitutes away from brown capital loans towards safer green capital loans, household lending or interbank lending. This diversification may be positive or negative – while the bank is now increasing its holdings of green assets, thereby reducing diversification and increasing risk, it might be holding *safer* assets, reducing its value-at-risk. However, in order to negate the increase in r^B, the brown entrepreneur is likely to increase its default rate, especially if this is also accompanied by lower profits. The total exposure to default risk is ambiguous and depends on the green entrepreneur's lower default risk. The reduction in default by green entrepreneurs is likely to be small, especially if they face higher capital financing costs r^G. The magnitude of these effects is regulated by the size of the policy change, the default sensitivity of entrepreneurs, the substitution elasticity to green loans and capital shares in energy production.

The effect on the investment bank's profitability is also ambiguous – it may improve slightly, given a higher net interest margin, that is, the spread between deposit funding cost and brown capital loan rate, or decrease if the volume drop in brown capital loans is large enough. Brown entrepreneurs increase net borrowing on the household borrowing line ($b^{Be} - d^{Be}$) if the substitution effect dominates; this is likely to be the case as income drops and deposits become less rewarding.

How does systemic risk evolve? As brown labour incomes drop and deposit rates decrease, brown labour households borrow more from the retail bank, which the retail bank may fund through greater interbank borrowing, driving up interbank rates (though the effect is likely to be small given the investment bank substituting from brown capital lending to other forms of lending). The retail bank's profitability is likely to increase, making it more stable. However, overall household leverage in the economy is expected to increase.

Clearly, the effect on financial stability is ex-ante unclear and depends on how policymakers manage trade-offs between different measures of financial stability.

4.2 Green capital requirements

Next, consider a loosening of green capital requirements, $\hat{\omega}$. Continuing from the balance sheet equation and capital adequacy condition above, we can express the green capital supply curve as follows:

$$1 + r^G = \frac{1 + r^{IB}_{ND} + \Lambda \bar{k}^{IB} \hat{\omega}}{\mathbb{E}(D^{Ge}_s)}$$

4.2.1 Effect on pollution

Consider the effect of lowering $\hat{\omega}$. This frees up equity for the bank, increasing equity slack and allowing the shadow value of green lending Λ to fall. This tilts the green capital loan supply downwards, increasing A^G and decreasing r^G. Once again, this effect is scaled by the green entrepreneur's expected delivery rate, which increases, further reducing r^G.

As the rental rate decreases, green capital stock rises, leading to an investment boom. The magnitude of the increase is controlled by factor elasticities α and β, as well as how much r^G falls in equilibrium. Higher capital investment pushes green energy supply rightwards – E_2 rises while p_2 falls. By itself, this does not have an effect on pollution.

At the final step, however, the final goods producer's energy demand comes in, moderated through the CES energy composite. As p_2 falls, total energy becomes cheaper, which increases the demand for energy. This *increases* the demand for brown energy. The magnitude of this increase is likely to be large in our calibration – when ψ is high and ρ is low, cross-elasticity is high. In other words, the expansion effect dominates the substitution effect, leading to an increase in brown energy production. Thus, unintuitively, lowering green capital requirements increases pollution.

4.2.2 Effect on inequality

Green entrepreneurs unambiguously benefit from an increase in demand (even though prices fall) as well as a reduction in the rental rate of capital. Therefore, Ge income increases, pulling the distribution rightwards. As marginal product of labour increases, wages in the green sector rise, thereby benefiting green labour households.

Due to demand spillovers, brown entrepreneurs are also likely to benefit – profits increase due to higher output. However, r^B might increase if banks skew lending towards the green sector. Additionally, higher output translates into higher wages for brown labourers. Combined, this has the effect of mildly shrinking the income distribution. The ultimate outcome on inequality, therefore, is ambiguous and depends on the relative magnitudes of α, β, χ_l, ψ and ρ.

4.2.3 Effect on financial stability

The regulatory ratio increases as green capital requirements fall, pushing CAR above its floor and increasing equity slack. Due to an increase in both A^G and A^B, the asset base of the bank increases, hence leverage, defined as equity divided by assets, falls. However, as the share of green loans increases, sectoral concentration risk increases. On the other hand, stranded asset risk, that is, the risk of brown assets getting severely and suddenly repriced, drops.

Effects on bank profits are ambiguous; while lending volume increases, margins (i.e. green spreads) decrease. Ultimately, the effect on profits depends on how other deposits and loan rates react in equilibrium. As the policy largely delivers a boom in the economy, it is likely that households substitute away from saving and borrowing towards consumption, which reduces household leverage.

4.3 Downstream carbon taxes

Finally, we consider the effects of levying downstream carbon taxes. Taxes enter the final goods producer's profit maximisation problem and affect demand for brown energy. Intuitively, taxes do not work through the financial sector. By affecting production directly and avoiding passing through financial sector frictions, taxes are likely much more potent. Solving for the optimal brown-to-green energy mix by minimising the final goods producer's energy cost function, we get:

$$\frac{E_{01}}{E_{02}} = \frac{\psi}{1-\psi}\left[\frac{p_1+\tau}{p_2}\right]^{\frac{-1}{1-\rho}}$$

Then, solving the profit maximisation problem of the final goods producer, brown energy demand can be expressed as:

$$E_{01} = E_0\psi\left[\frac{p_1+\tau}{p}\right]^{\frac{-1}{1-\rho}}$$

where E_0 represents total energy demand (controlled by ν) and p denotes the CES price index of the energy bundle. Clearly, brown energy demand is a decreasing function of carbon taxes.

Additionally, taxes feature in the form of government transfers to households, t_t^h. For simplicity's sake, we assume that tax revenues are equally distributed to *labour* households. This is not a self-evident tax redistribution scheme; indeed, we can consider a large variety of complex tax redistribution schemes. However, given that spending on social welfare schemes was South Africa's third largest line item in its annual budget spend (2022–23), we think a labour-focused redistribution scheme represents a good baseline for our analysis.

4.3.1 Effect on pollution

Consider the effect of increasing τ. The user price of brown energy increases, which shifts the demand curve leftwards. Due to low substitutability and high dependence on brown energy, the demand curve is relatively inelastic. However, the supply curve is relatively more elastic, as brown entrepreneurs have the ability to reduce brown energy production by substituting increased net borrowing on the household line for brown capital borrowing. Therefore, the effect of the leftwards demand curve shift is a small drop in p_1 and a large drop in E_1. Evidently, the carbon tax delivers the biggest decrease in pollution.

Due to limited substitution, green energy demand rises, but not one-for-one. This implies that total energy output falls, hence total final goods output also falls.

4.3.2 Effect on inequality

The effects on inequality are relatively straightforward, especially when we consider the labour-focused redistribution scheme. Brown entrepreneurs unambiguously earn lower profits as both p_1 and E_1 fall. Due to lower marginal productivity of labour, w_1 also falls, implying brown labour households suffer, at least pre-redistribution. Both green profits and green wages increase, benefiting green entrepreneurs and green labour households. Considered thus, carbon taxes stretch the income distribution and increase inequality.

However, carbon taxes also raise revenue, which can be redistributed back to households, providing a cushion against negative inequality impacts that capital regulation tools lack. By redistributing to brown labour households in particular, the income distribution becomes more equitable, even when green entrepreneurs towards the right of the distribution get richer. While total inequality is expected to fall, the distribution becomes more positively skewed as the gap between green and brown entrepreneurs increases, thereby leading to increased top income shares.

4.3.3 Effect on financial stability

The tax increase reduces brown capital loan demand. Hence, A^B shrinks (while A^G rises though less than one-for-one), leading to less use of bank equity. As the bank's portfolio share tilts towards green capital loans, stranded asset risk falls.

As brown entrepreneur profits drop, default rates are likely to increase in the brown sector, leading to higher default risk across the economy.

Lastly, when the tax rebate hits labour households, their demand for deposits is likely to increase, driving down deposit rates. This increases margins, especially for the retail bank, driving up profitability and return on equity.

Overall, the effect on financial stability is ambiguous, but seems to be neutral to mildly positive.

5. Analysis

Armed with our qualitative predictions, we are now in a position to solve the model and study policy scenarios. We solve the model numerically. Armed with the initial equilibrium, we conduct a number of analyses. First, we define our key measures of interest, including our preferred measures for pollution, inequality, inflation and financial stability. Second, we study how endogenous quantities of interest evolve when we vary the three central policy parameters, to uncover the trade-offs that arise from implementing policies. We study how capital investment varies and banking sector quantities evolve. Third, we conduct a comparative statics exercise, where we evaluate how outcomes change when we vary the main structural parameters of the model, in an economy where all three policy tools are simultaneously active (but fixed). This throws light on the relative usefulness of policy in an economy transitioning to a 'greener' regime where the transition can be described in terms of these time-varying parameters.

5.1 Quantities of interest

We first define our preferred measures of environmental damages, inequality, inflation and financial stability.

We measure pollution as expected future damages, $\mathbb{E}_1[D(P_2)]$. This is the appropriate and relevant measure because it is determined at $t = 1$ once the brown entrepreneur's period-1 production decisions are locked in. Hence, it allows for policy (especially capital regulation, which reduces future damages instead of current damages) to have an impact. It also takes into account the relevant depreciation occurring between $t = 1$ and a hypothetical $t = 2$.

We use two measures of inequality. First, we calculate the wealth Gini coefficient for the economy. Wealth A_t^h for household h is defined as the sum of their time-t income and their net returns on their bond positions. For entrepreneurs, this also accounts for capital endowments and borrowings. We then calculate the wealth Gini coefficient, maintaining the assumption of household split across the economy as in our initial calibration.

Second, following the discussion in Attanasio and Pistaferri (2016), we calculate consumption inequality as the variance in the natural log of consumption across households. Recent evidence (such as Gaillard et al. (2023)) shows that consumption and wealth or income inequality differ meaningfully from each other. Income or wealth inequality might not account for certain price effects and non-market-based consumption smoothing mechanisms for which consumption inequality accounts. Moreover, under certain conditions (if shocks to income are transitory), consumption inequality might offer a clearer picture of welfare implications. Therefore, we consider consumption inequality as an additional measure of redistribution.

Our preferred measure of inflation is energy price inflation. This considers the CES price index of energy, which comprises a basket of time t and state s energy inputs. Inflation is calculated as the percentage change between the (expected) price index at $t = 1$ and the price index at $t = 0$.

We consider a number of banking sector measures to study financial stability. Inspired by Tsomocos (2003), we create an average of three quantities to measure financial stability, which account for default risk and banking sector risk. First, we measure economy-wide default by constructing the ratio of non-performing loans (i.e. any borrowing which is defaulted) to total lending, as per the following:

$$NPLRatio = 1 - \mathbb{E}_0 \left[\frac{\sum_h D^h b^h + D^{Be} K_{11} + D^{Ge} K21 + D^{RB}(\mu^{RB} + \mu_d^{RB}) + D^{IB} \mu_d^{IB}}{\sum_h b^h + K_{11} + K21 + (\mu^{RB} + \mu_d^{RB}) + \mu_d^{IB}} \right]$$

Second, for each bank individually, we construct a 'distance to default' measure (z-score) in the

Merton style by scaling the bank's equity-assets ratio by the variance of its asset portfolio:

$$ZScore^{Bank} = \frac{\mathbb{E}_0(e^{Bank}/Assets^{Bank})}{Var(Assets^{Bank})}$$

A higher z-score implies a safer bank (bigger distance from default). Our index of financial stability calculates an equal-weighted average of the non-performing loans ratio, the z-score for the retail bank and the z-score for the investment bank.

In addition, we construct measures for spreads to study how rates evolve in the face of policy. Specifically, we calculate the brown-green spread, $r^B - r^G$, the brown premium, $r^B - r_d^{IB}$ and the green premium, $r^G - r_d^{IB}$. We construct a measure of banking sector leverage as the following:

$$BankingLeverage = 1 - \mathbb{E}_0\left[\frac{e^{IB} + e^{RB}}{Assets^{IB} + Assets^{RB}}\right]$$

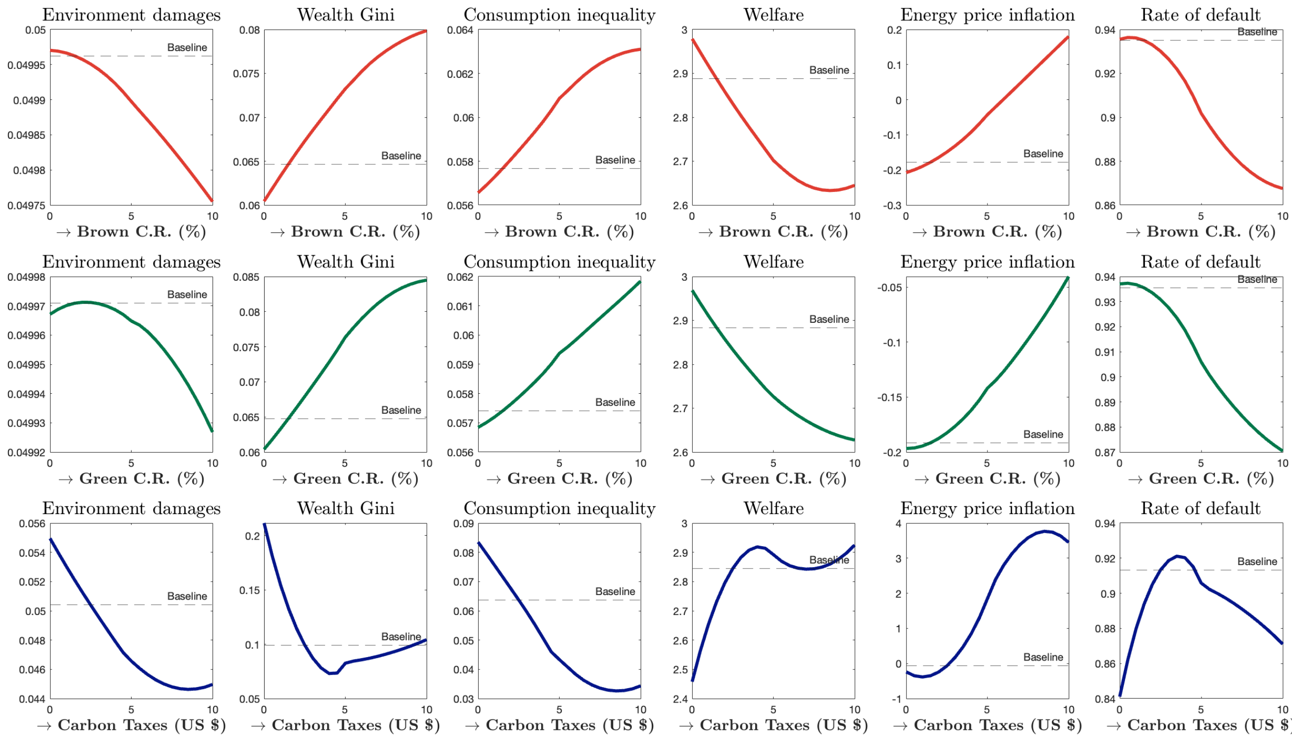
To measure bank profitability, we plot return on equity for banks, defined as profits divided by period-0 equity. Lastly, we measure portfolio concentration by studying the share of brown capital loans as a percentage of total capital loans, $\frac{A^B}{A^B + A^G}$.

Our preferred measure for welfare is DS-welfare (Dávila and Schaab 2022), which we define and discuss in more detail in section 6.

5.2 Trade-offs

As capital regulation becomes tighter (or carbon taxes increase), is the policymaker forced into trading off between objectives of lower pollution damages, lower inequality and better financial stability? Figure 3 plots wages, inequality measures, welfare, energy price inflation and rate of default (percentage of non-performing loans) as the policy tool is varied. The first panel (red) considers changing brown capital requirements while keeping green capital requirements and carbon taxes fixed. Panel two (green) and three (blue) do similar exercises for green capital requirements and carbon taxes.

Figure 3: Trade-offs



Note: The panels in the first row plot brown capital requirements $\tilde{\omega}$ on the x-axis, going from looser (0) to tighter (10). The panels in the second row plot green capital requirements $\hat{\omega}$ on the x-axis, going from looser (0) to tighter (10). The panels in the third row plot taxes τ on the x-axis, going from lower to higher. The y-axis in each panel plots the measure specified in the panel title. Each panel plots the evolution of the specified measure with respect to changes in policy. In each row, policy tools not being varied are still active but remain fixed at their baseline calibration. The black dotted line in each panel plots the level of the measure under the baseline calibration, $\tilde{\omega} = \hat{\omega} = 1.5, \tau = 2.5$. Tax revenues are redistributed equally to labour households.

First, note that brown capital requirements create a reduction-redistribution trade-off: making policy tighter achieves lower pollution but at the cost of higher inequality, as qualitatively predicted. This translates into lower welfare. For green capital requirements, the direction of interest is from right to left, that is, when green capital requirements are reduced in the form of a green supporting factor. This ensures lower inequality, but environmental damages are higher due to the scale effect resulting in higher brown energy production. This is a manifestation of the famous Jevons Paradox. Meanwhile, higher carbon taxes in this economy achieve a 'divine coincidence' of improving the environment while reducing wealth inequality, delivering higher welfare in the process.

If we consider magnitudes in addition to directions, carbon taxes deliver the lowest pollution, as expected.

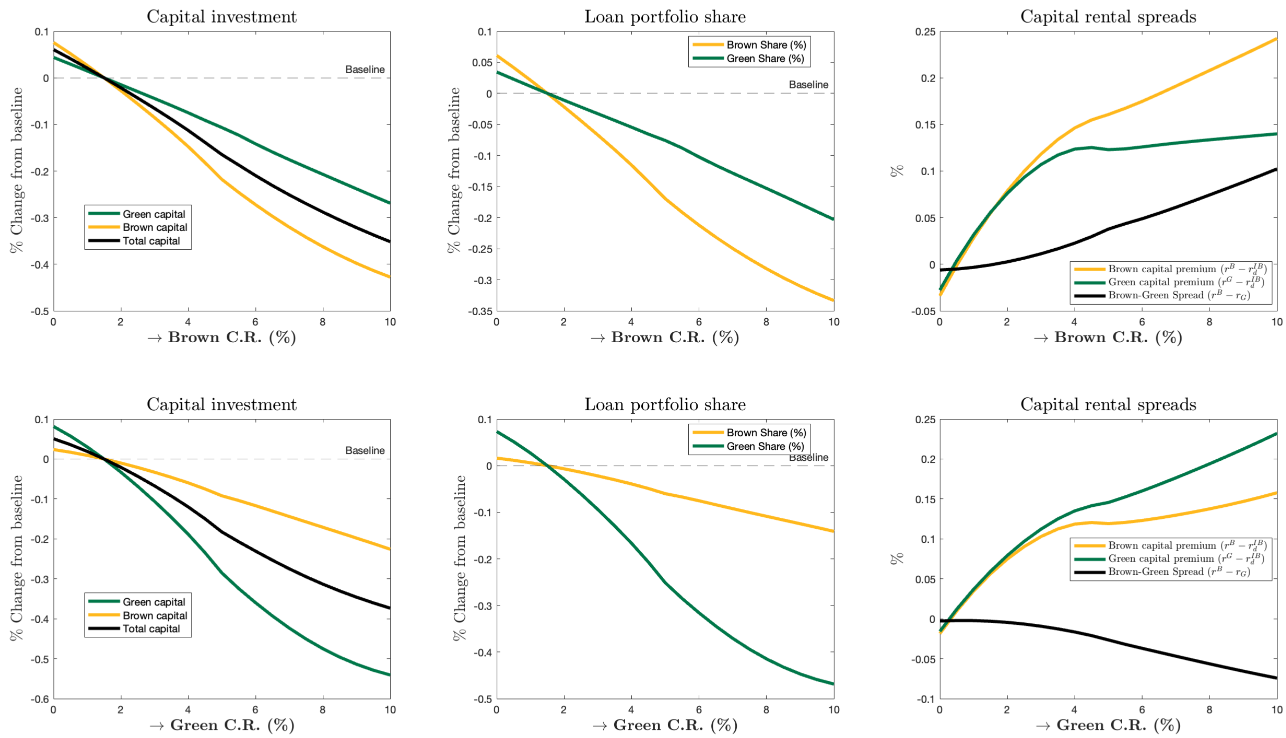
However, when the picture is expanded to include effects on energy inflation and rate of default, an additional set of trade-offs emerge. Both forms of capital regulation lead to higher energy price inflation, as expected. However, the highest magnitude of inflation is under the carbon tax regime. This demonstrates how the increase in green energy price due to substitution, plus the higher user cost of brown energy (incorporating the effect of tax), dominates strongly. Simultaneously, both capital regulation policies deliver better financial stability (at least when measured as the percentage of non-performing loans), delivering their expected result. However, increasing carbon taxes initially creates higher financial instability as brown entrepreneurs (and brown labour households) struggle to repay their obligations and choose to endogenously default more instead. This demonstrates that no policy is free from trade-offs; carbon taxes improve the environment and equity, but at the cost of higher inflation and financial instability. Looking ahead, this necessitates that our choice of optimal policy consider these trade-offs carefully across a range of policymaker preferences.

5.3 Productive capital

What is the effect of bank capital regulation on the (level of) productive capital investment in the economy? Do tighter brown capital requirements result in crowding in of green capital investment or incentivise banks to substitute towards green capital lending? In Figure 4, we study how capital investment from entrepreneurs, loan portfolio shares of banks and capital rental spreads evolve as capital requirements vary.

The headline result is that brown capital requirements do not crowd in green capital investments; some amount of brown capital gets substituted by green capital, but this substitution is not one-for-one and total capital investment in the economy falls. Returning to the mechanisms discussed in section 4, this happens because energy demand falls due to higher energy prices, which knocks down green investment as well.

Figure 4: Capital crowd-out



Note: The panels in the first row plot brown capital requirements $\tilde{\omega}$ on the x-axis, going from looser (0) to tighter (10). The panels in the second row plot green capital requirements $\hat{\omega}$ on the x-axis, going from looser (0) to tighter (10). Each panel plots the evolution of the specified measure with respect to changes in policy. The first column plots K_{11}, K_{21} and their sum in percentage changes from the baseline level. The second column plots A^B, A^G in percentage changes from the baseline level. The third column plots rental rate spreads in per cent. In each row, policy tools not being varied are still active but remain fixed at their baseline calibration. The black dotted line in each panel plots the level of the measure under the baseline calibration, $\tilde{\omega} = \hat{\omega} = 1.5, \tau = 2.5$.

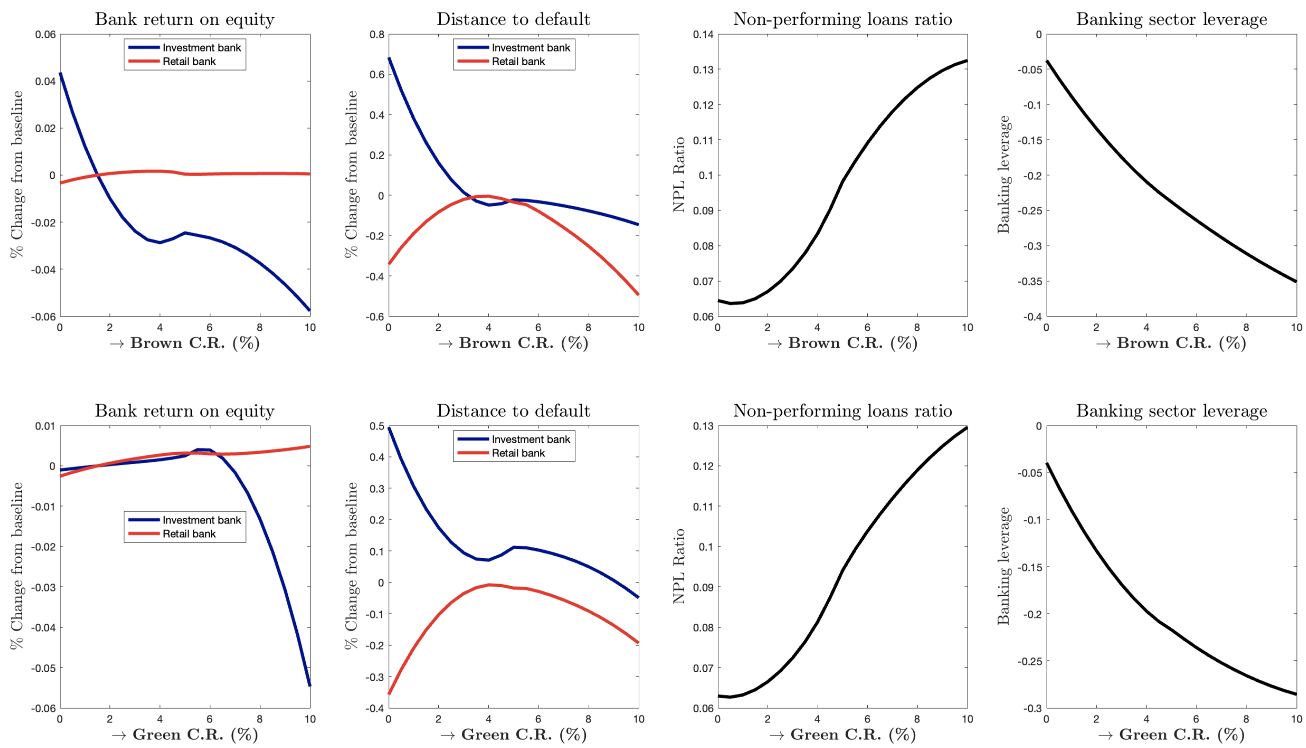
Unsurprisingly, the same phenomenon is visible for the bank's loan portfolio as well – when brown capital requirements tighten, the fall in brown capital loans outstrips the fall in green capital loans, but green capital loans also fall. Interestingly, capital investment demand falls faster than capital loan supply, implying that rental rates must be increasing. This is what we notice in the third column – brown capital carries higher premia than green capital and the spread widens (vice versa when green capital requirements increase). We interpret this as being driven by increased default risk of the borrower, who can endogenously choose to deliver fewer units of the capital loan in equilibrium.

The larger implication here is that capital regulation is likely not going to lead to increased green investments. In addition, even the reduction in absolute levels of brown capital investment is likely to be small as risk premia do most of the heavy lifting.

5.4 Financial stability

Do capital requirements reduce macroprudential risk and if so, through what channel? In Figure 5, we plot financial stability measures as a function of the level of capital requirements.

Figure 5: Financial stability



Note: The panels in the first row plot brown capital requirements $\tilde{\omega}$ on the x-axis, going from looser (0) to tighter (10). The panels in the second row plot green capital requirements $\hat{\omega}$ on the x-axis, going from looser (0) to tighter (10). The definitions of each measure can be found in section 5.1. Each panel plots the evolution of the specified measure with respect to changes in policy. The first two columns plot percentage deviations from baseline on the y-axis while the last two columns plot the specified ratio. In each row, policy tools not being varied are still active but remain fixed at their baseline calibration, $\tilde{\omega} = \hat{\omega} = 1.5, \tau = 2.5$.

Banking sector profitability is hit as a result of tightening capital regulations – the investment bank's return on equity decreases non-monotonically, primarily as a result of reduced capital lending (despite higher rental rates), which eats into profits. Similarly, the investment bank's distance to default reduces as capital regulation is tightened, while the ratio of non-performing loans in the economy increases. This is consistent with affected entrepreneurs choosing to increase endogenous default when faced with higher capital rental rates.

Total leverage in the banking sector, however, falls as policy is tightened. This finally gives us the ability to resolve the ambiguities of our qualitative predictions on financial stability. Capital requirements reduce macroprudential risk by preventing the build-up of *future* leverage within the system. However, this comes at the cost of bank profitability, while existing loan portfolios face larger delinquency rates in equilibrium.

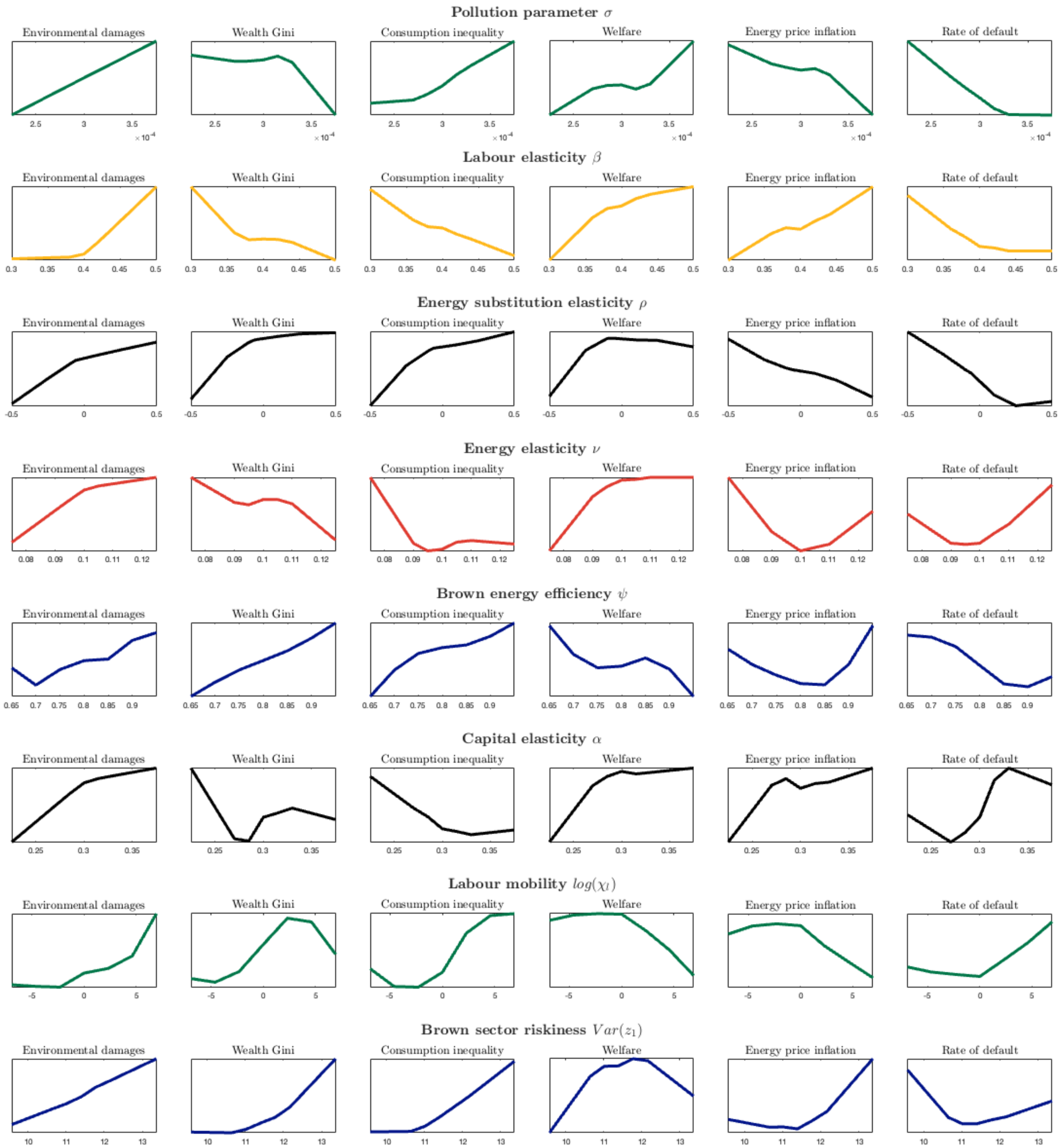
5.5 Comparative statics

Our discussion so far has uncovered how key outcomes (especially magnitudes) depend heavily on the economy's baseline calibration of structural parameters. To wrap up our analyses, we consider the effects of varying these parameters. This acts as a counterfactual simulation exercise where we consider outcomes in an economy that starts from, for example, a lower dependence on brown energy. Without referring to time dynamics, this is the closest the model can get to simulating how outcomes evolve when the economy undergoes a green transition – where transition is defined as a combination of structural parameter changes. Policy remains active but fixed at its baseline calibration.

We define transition as some permutation of the following – the damage function sensitivity to pollution (σ) reduces (higher resilience), energy sources become more substitutable (ρ increases), energy share of total output (ν) decreases or brown energy efficiency (ψ) decreases. In addition, we can also consider more general structural changes in the economy, such as changing labour and capital shares (β and α), better labour mobility (lower χ_l) or the brown sector becoming riskier (variance of z_1 increases). In Figure 6, we plot the results of these exercises.

Consider first the parameters that govern the economy's green transition. As sensitivity of economic damages to pollution (σ) decreases, environmental damages are lower by definition,

Figure 6: Comparative statics



Note: Each row presents movement in six measures of interest (identical to measures plotted in Figure 3) when the structural parameter in the row title is perturbed. In each case, policy tools are still active but remain fixed at their baseline calibration, $\tilde{\omega} = \hat{\omega} = 1.5, \tau = 2.5$.

but inequality remains largely stable. Counterintuitively, both inflation and default rates increase. As productivity is higher, the brown energy supply curve shifts downwards, which should reduce energy prices. Crucially, however, productivity is also higher in the final goods sector, which pushes up demand for energy inputs. The demand increase dominates the cost reduction, leading to higher inflation. Faced with higher demand, entrepreneurs borrow more, which, given higher exposure to risk, results in higher rates of default.

What happens when energy sources become more substitutable (ρ increases)? Counterintuitively again, environmental damages increase – if the final goods firm can more easily substitute between energy sources, it will prefer to use more of the cheaper source, which is brown energy in our baseline calibration. This results in gains for the brown entrepreneur, but small losses for the green entrepreneur, which is why inequality measures rise slightly, while welfare falls slightly. Brown entrepreneurs are safer with higher profit margins, hence the default rate falls. Even though demand is higher, inflation is lower as the energy price index loads more on the cheaper, more abundant source of energy. This reveals that making energy sources more substitutable cannot by itself generate transition if the economy's base is heavily reliant on brown energy.

When the economy becomes less energy intensive (ν falls), demand for both energy types goes down, but demand for brown energy goes down more in absolute terms, which leads to lower environmental damages. Lower energy production hits entrepreneur profitability, but the subsequent drop in wages is felt more prominently by labour households – wealth Gini and consumption inequality increase, which drives down welfare even though pollution is lower. Inflation does not move monotonically – when energy intensity is lower, price in the first period drops, but with lower environmental damages, productivity (and hence energy demand) rebounds in period 1, pushing inflation higher. Lower energy production (and lower capital investment) reduces exposure to lending, which reduces default rates.

When the economy's reliance on brown energy reduces (ψ falls), outcomes are straightforward – pollution falls, the economy becomes less unequal and welfare increases. Inflation first falls as the brown energy price falls, but as the economy's demand for green energy increases, further decreases in ψ imply the economy loads more on green prices, pushing inflation up. The default rate increases as brown sector households are exposed to higher risk.

Lastly, when the brown sector becomes riskier, it creates negative outcomes across the board – higher pollution, higher inequality, lower welfare, higher inflation and lower financial stability. This offers perspective on the joint usage of policy tools, which might be more relevant and pressing as brown sector risk increases.

In summary, policy that promotes the green transition must target multiple underlying parameters – focusing on one (such as promoting a higher usage of green energy) can create additional trade-offs.

Finally, consider an increase in the labour share of income (higher β) or better labour mobility (lower χ_l). Both are better for inequality and welfare. However, both are inflationary in nature, while going in opposite directions for environmental damages. Once again, this points to a reduction-redistribution trade-off; policies that are equitable might not necessarily be good for the environment.

6. Welfare

In this section, we explore the welfare implications of our setup. First, we need to choose an appropriate welfare concept suited to our analysis. We argue for the use of a modified version of Dynamic Stochastic weights (DS-weights) (Dávila and Schaab 2022), which we derive in more detail in Annex 2. Here, we simply state the welfare function:

$$W = \underbrace{\mathbb{E}_h\left[\omega^h \sum_{t=0}^{1} \omega_t^h \sum_{s=1}^{2} \omega_t^h(s) C_t^h(s)\right]}_{W^{DS}} - \omega^P \underbrace{\mathbb{E}_0[D(P_2)]}_{\text{Expected future pollution damages}}$$

where $\omega^h, \omega_t^h, \omega_t^h(s)$ denote household-specific individual, dynamic and stochastic weights respectively and ω^P denotes weight on welfare loss due to future pollution damages. The second term is our addition to the DS measure, to address the concern that the DS measure only takes into account consumptions during the life of the model, but policymakers might reasonably care about the present value of future environmental damages as well.

We prefer using DS-weights as our normative criteria instead of using conventional utilitarian welfare approaches because DS-weights allow us to break down how the social planner weights gains and losses across individuals, across time and across states of nature. In our model, therefore, a policy will be termed desirable only if its (net) effect – taking into account objectives of protecting the environment, ensuring equity and improving aggregate efficiency – is positive. Using DS-weights also allows us to make fair comparisons between different policy tools such as carbon taxes and capital requirements.

6.1 Mapping the welfare function onto South Africa

How does this welfare function compare to the (implicit or explicit) objective function(s) of the SARB and other policy institutions? Note that the welfare function above values household consumption across people, time and states of the world (and in addition considers disutility from future carbon externalities). The SARB's objective function, which exclusively focuses on price stability, is both a *special case* of the welfare function above and is part of the welfare function (indeed, our discussion hitherto has included energy price inflation as a key measure). The DS-based welfare aggregator nests price stability as a key sub-goal – via its role in stabilising consumption levels, distribution and risk – so the SARB's narrow mandate is entirely compatible with the broader social objective we employ; it is simply one instrument assigned to one slice of the same welfare function.

Moreover, the welfare function is flexible enough to capture the effects of lower financial stability, both through its effect on consumption (because default and default penalties affect total consumption) and through incorporating consumption risk. Therefore, it is also consistent with a macroprudential policy objective.

The DS block of the welfare function collapses into a typical central bank quadratic loss function (which considers inflation and output gap, such as the SARB's quarterly projection model) once households are treated as identical (individual weights are equal), utility is log-linearised around the steady state and only second-order terms are kept (akin to setting stochastic weights).

Secondly, the welfare function captures the objectives of a wider variety of policymakers, including National Treasury, the Department of Mineral and Petroleum Resources, the Department of Electricity and Energy, and the Department of Social Development, which care about inequity, climate damages and optimal capital allocation, in addition to the SARB caring about price stability.

6.2 Optimal policy in the baseline model

We now study the design of optimal policy in the baseline model. How do trade-offs between aggregate efficiency (which includes environmental damages, capital allocation, financial stability and inflation) and redistributional concerns manifest in setting the optimal level of capital requirements? How do optimal capital requirements change in the presence of carbon taxes? We address these questions here.

Optimising for a generic policy x requires us to calculate x^* such that $\frac{\partial W}{\partial x}|_{x=x^*} = 0$. To calculate this, in addition to marginal utilities of consumption, we need to define a set of weights $\{\lambda_h\}_1^4 > 0$ that act as an input to calculate the individual weights. We argue that for a normalised utilitarian planner (i.e. a planner who does not explicitly define their preference for aggregate efficiency, risk sharing or redistribution), the choice of these weights is determined by their policy mandate. Moreover, we need to define ω^P, that is, how much a policymaker cares about future environmental damages.

We consider four types of policymakers, who differ in terms of their mandate and therefore in terms of their vector of λ and ω^P.[9] Each of these policymakers has a mandate towards one or more sectors, or one or more occupations in the economy. We list their choice of λ and ω^P in

[9] Note that the level of ω^P does not hold significance; what matters is how relatively larger one type of policymaker's ω^P is relative to other types.

Table 2.

Table 2: Types of policy mandates

Mandate	Weights[10]	ω^P
Equal-weighted policymaker	$[0.25, 0.25, 0.25, 0.25]$	50
Anti-pollution policymaker	$[0, 05, 0, 0.5]$	200
Labour-focused policymaker	$[0.5, 0.5, 0, 0]$	50
Industry-focused policymaker	$[0, 0, 0.5, 0.5]$	50

We are now in a position to calculate different elements of the welfare decomposition (equation 29), as well as calculate $\frac{\partial W}{\partial x}$ for a generic policy parameter x. Importantly, however, the Dávila and Schaab (2022) decomposition allows us to go one step further – we can track how much marginal welfare is attributable to aggregate efficiency, risk sharing and redistribution for a particular value of x. This is useful because it allows us to answer the question at the very heart of this paper – what are the trade-offs to be made between aggregate efficiency and redistribution?

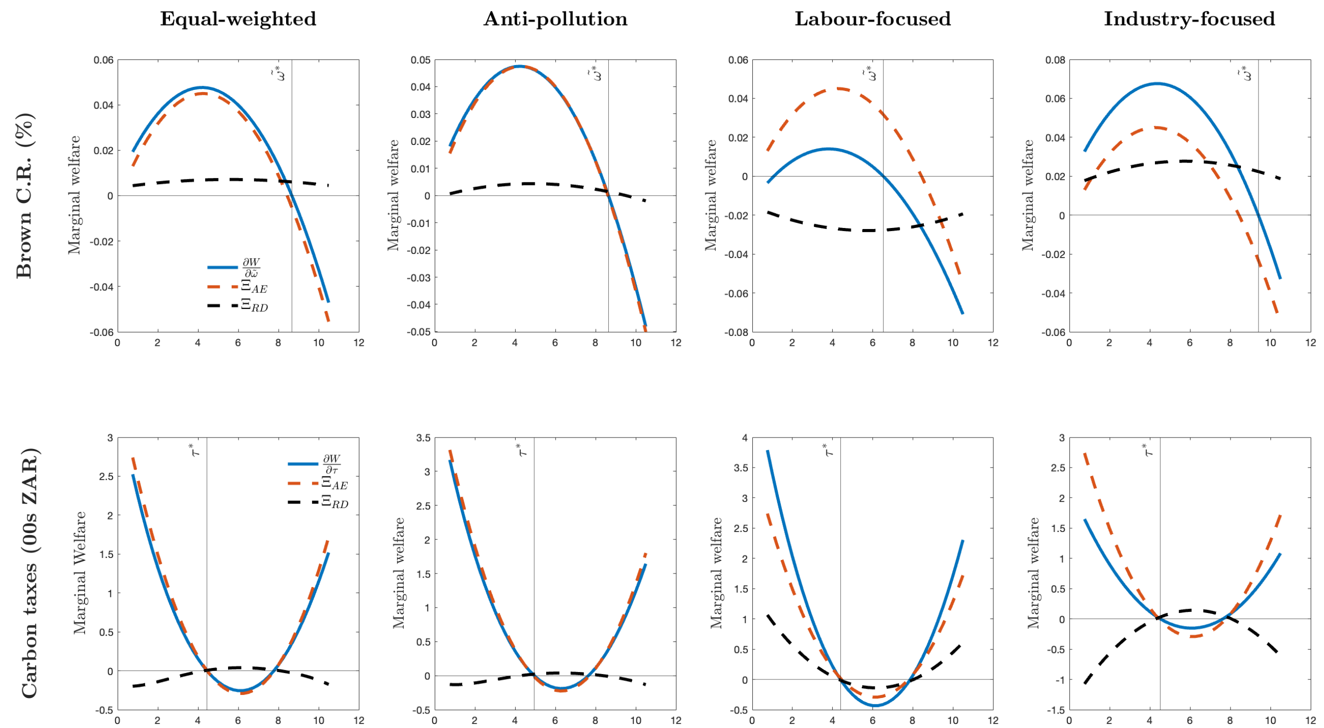
Our next analysis, therefore, does the following exercise. For each policy mandate listed in Table 2, we vary the underlying policy parameter and for each value, plot $\frac{\partial W}{\partial x}$ as well as its decomposition into Ξ_{AE} (marginal welfare from aggregate efficiency) and Ξ_{RD} (marginal welfare from redistribution). As we are plotting the marginal welfare against different values of x, the point at which the function intersects with the 0 line gives us the optimal value of x, where $x \in \{\tilde{\omega}, \tau\}$.[11]

First, as a benchmark, the equal-weighted policymaker sets a relatively high level of brown capital requirements at 8.25 and carbon taxes at 4.25. Given that they assign equal weight to households, most of their decision is based on aggregate efficiency considerations. Next, consider the anti-pollution policymaker, who sets marginally tighter brown capital requirements and higher carbon taxes. Given that most of their weight is assigned to preventing environmental damages, it is not surprising to see that their decision closely tracks marginal welfare derived from aggregate efficiency.

[10] Weights are defined in the order $\{Bl, Gl, Be, Ge\}$.

[11] For simplicity, we focus only on brown capital requirements and carbon taxes.

Figure 7: Optimal choice of policy



Note: Each column denotes a particular type of policymaker, defined by their preference towards sectors or occupations. Each panel plots $\frac{\partial W}{\partial x}$ (blue line) and its decomposition into marginal welfare from aggregate efficiency, Ξ_{AE} (red dotted line) and marginal welfare from redistribution, Ξ_{RD} (black dotted line). The panels in the first row plot the marginal welfare measure for where brown capital requirements are varied (x-axis) while $\hat{\omega} = 1.5$ and $\tau = 2$. The panels in the second row plot the marginal welfare measure for a model where carbon taxes are varied (x-axis) while $\tilde{\omega} = \hat{\omega} = 1.5$. The straight vertical line denotes the optimal choice of capital requirements conditional on the policymaker's preferences.

Consider now the labour-focused policymaker. They continue to set benchmark-level carbon taxes, given the benefit derived from using carbon tax revenues to redistribute to labour households even though higher taxes lower wages in the brown sector. However, they set the lowest brown capital requirements. Our decomposition proves to be useful here – had the policymaker not cared about redistribution, they would have continued to set high levels of brown capital requirements (at the point at which the red dotted line intersects the x-axis). Given that labour households are losing out under a capital requirement regime with no safety net, marginal welfare derived from redistribution is negative, which pulls down the optimal policy level.

Lastly, consider the industry-focused policymaker. Counterintuitively, this type of policymaker sets the highest level of capital requirements (but also the lowest level of carbon taxes). This happens for two reasons. First, given our mechanisms, brown entrepreneurs do not suffer much under capital requirements as profits may remain flat or fall very slightly. Therefore, redistribution between entrepreneurs is not of concern (and Ξ_{RD} is positive). Second, entrepreneurs care about lost productivity due to pollution damages affecting supply *and* demand – they are doubly exposed to environment-related losses. Hence, a policymaker who focuses on their welfare also sets a high level of capital requirements. The converse holds true for carbon taxes, where setting higher levels results in large profitability drops for brown entrepreneurs.

In summary, there is an active aggregate efficiency-redistribution trade-off, which creates different policy prerogatives based on preferences of the policymaker. In section 8, we discuss in more detail how this applies to the experience of South Africa.

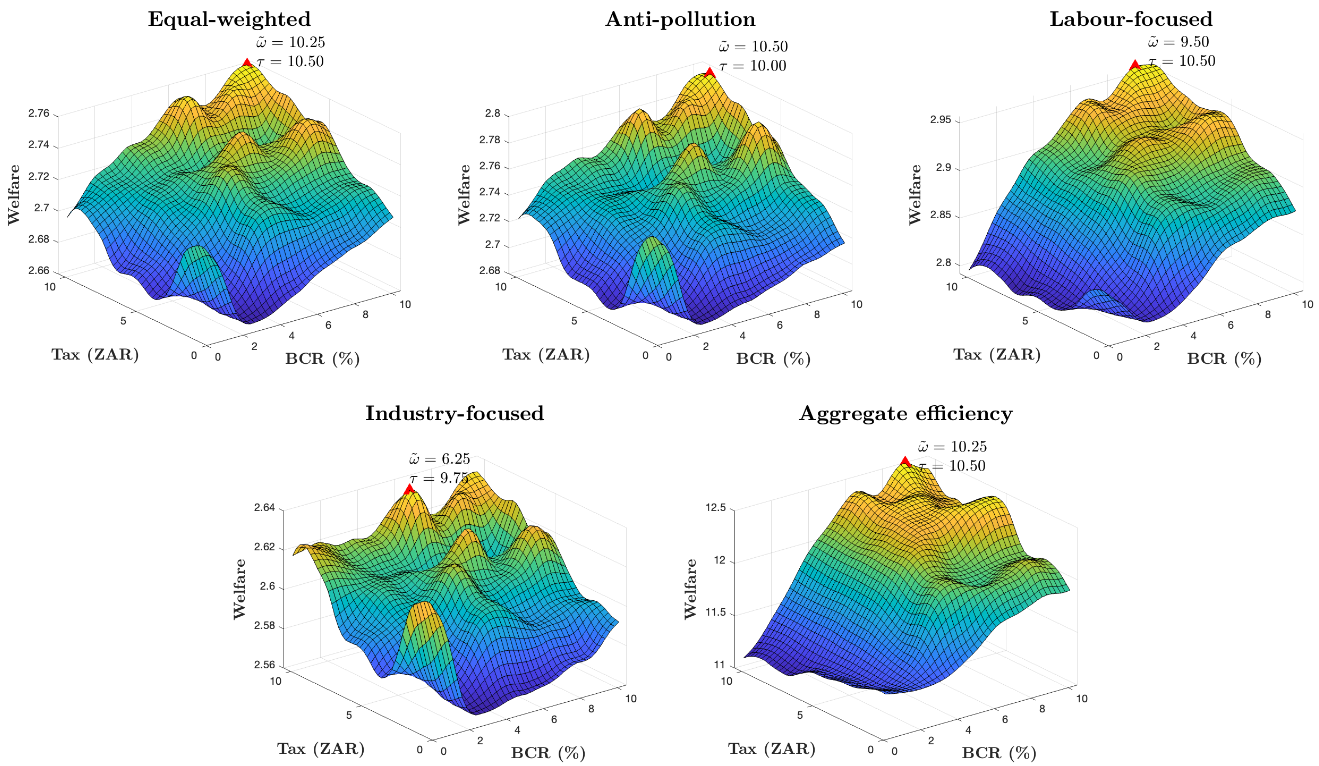
6.3 Optimal joint policy

The previous analysis considered optimal policy design under the assumption that the policymaker controls only one policy tool at a time. While this helps us examine the efficiency-redistribution trade-off, this is perhaps not very realistic. In reality, there is likely to be coordination between fiscal and macroprudential policy to some extent. Moreover, the Tinbergen principle requires multiple policy tools to be used to address multiple externalities. Given that policymakers control dual levers, how can they decide upon an optimal combination of carbon taxes and capital regulation? We focus on this question here.

Instead of focusing on marginal welfare as in the previous sub-section, our objective here is to choose the the level of policy that maximises total welfare under the DS-criteria. We continue to allow the policymaker's preferences to vary between the mandates listed in Table 2. In addition, we consider another type of policymaker who cares about aggregate efficiency only. For each type of policymaker, Figure 8 plots W against brown capital requirements and carbon taxes,[12] and marks the optimal level of policy.

[12] We consider this policy pair for simplicity, but the analysis can be carried out for another policy pair as well.

Figure 8: Optimal joint choice of capital requirements and carbon taxes



Note: Each panel denotes a particular type of policymaker, defined by their preference towards sectors or occupations. Each panel plots $\tilde{\omega}$ on the x-axis, τ on the y-axis and W on the z-axis. The red triangle denotes the point on the welfare surface that delivers the highest DS-welfare. Lighter (yellow) denotes higher welfare values on the surface, while darker (blue) denotes lower welfare values. We assume that tax revenues are equally distributed between brown and green labour households.

Observe that the joint setting of policy allows for tighter brown capital requirements as well as higher carbon taxes relative to optimising with respect to one tool. This is because carbon taxes help in alleviating the redistributive concerns that arise with capital requirements. Therefore, the policymaker can use capital requirements as an additional tool beside carbon tax for its positive effects on financial stability and pollution reduction.

Optimal policy levels, unsurprisingly, follow similar trends to the previous analysis. Anti-pollution policymakers set high capital requirements, while labour-focused policymakers set lower capital requirements (and higher taxes). The industry-focused policymaker, however, acts more intuitively this time by setting lower brown capital requirements and carbon taxes. This happens because at these levels, the carbon externality is already accounted for and the policymaker now trades off the lower consumption of entrepreneur households.

The shapes (peaks and troughs) of the surface, beyond simply the optimal point, also make for interesting reading. For the equal-weighted policymaker, peaks sit in the north-east corner; a balanced weighting pushes the planner to use both instruments heavily. The anti-pollution planner's brown capital requirements dimension is fairly flat, which implies that tax dominates when the sole concern is emissions, in line with our earlier analysis. An industry-focused policymaker witnesses large increases in welfare at very low levels of taxes and capital requirements, while a labour-focused policymaker's disutility at very low levels of taxes is evident. Interestingly, a small positive brown capital requirement still wins over none at all, suggesting that a bit of credit re-pricing shields banks/industry from future stranded-asset risk without hurting current profits too much. For the aggregate efficiency planner, the surface is much smoother because they do not care about distributional kinks.

Additionally, default and price-stability channels also hide in the topology. The ripples arise from nonlinear feedbacks in default probabilities and energy price inflation.

In sum, a pragmatic regulator (equal-weighted) ends up much closer to the anti-pollution optimum than to the industry-focused one, signalling that South Africa's welfare calculus – once climate and households are included – leans towards a sizeable carbon tax backed by prudential capital tweaks.

Taken together, these results demonstrate how capital requirements and carbon taxes are *complementary* – the welfare gains from reduction of inequality are greater than the welfare gains from substituting between the two policies to reduce environmental damages. There are two key takeaways from our discussion on welfare: i) When policymakers care about redistribution, capital requirements need to be set at looser levels; ii) Taxes might help alleviate redistribution concerns – tighter capital requirements can be sustained with relatively higher carbon taxes.

7. Model variations

In this section, we briefly discuss how some policy-relevant model extensions might qualitatively affect our results and key insights.

Energy producers are monopolistic rather than perfectly competitive. In our analysis, we have assumed that both brown energy and green energy producers are perfectly competitive. However, in the case of South Africa, about 90%[13] of the country's electricity is provided by the vertically integrated state-owned monopoly, Eskom. How do our predictions change when we account for the presence of a large monopolist in energy production?

Let us assume that the brown energy producer in the model is a monopoly.[14] Then, they set the price as per the following:

$$p_1 = \frac{\epsilon}{\epsilon - 1} MC(K_1, N_1)$$

where MC is the marginal cost and ϵ is the price elasticity of demand for brown energy.

In turn, let us consider how our mechanisms change. When brown capital requirements are tightened, marginal cost increases, which raises the mark-up price less than one-for-one, which implies that the relative drop on E_1 would be smaller. The higher price cushions profits more while wages still fall, which improves the brown entrepreneur's profitability. With stable profits, lower leverage and stronger cash flows, default rates are lower. Therefore, the reduction in pollution is even less, the increase in inequality is even more, but financial stability is a bit more improved.

When carbon taxes are increased and demand shifts leftwards, the quantity reduction is proportionally higher than the perfect competition benchmark. Profits fall more as the higher margin shrinks. Extra profit squeeze raises default risk, but leverage also falls. Therefore, the reduc-

[13] Figure taken from: https://www.eskom.co.za/wp-content/uploads/2024/07/GX-0001-Generation-Plant-Mix-Rev-29.pdf

[14] The green energy sector is assumed to be perfectly competitive. For one, under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), a number of companies have begun supplying wind and solar energy. Additionally, Eskom itself is in the process of creating a separate renewables subsidiary, implying that the green energy market is likely to remain perfectly competitive.

tion in pollution is bigger, the fall in inequality is bigger and financial stability is not materially affected.

In sum, a monopoly dampens the effectiveness of supply-side credit tools because the firm can absorb cost shocks with mark-ups, but it amplifies the demand-side carbon tax. Distributional side-effects also grow: any policy that widens or narrows profits does so more starkly when a monopoly sits at the top of the income ladder.

Carbon taxes are redistributed with a different transfer scheme. The redistribution scheme of the carbon tax revenue merely affects inequality outcomes of the carbon tax. In our baseline, where taxes are equally redistributed to labour households, inequality decreases. If revenues were to be equally redistributed to all households, inequality would increase. If the redistribution covers brown households (entrepreneur and labour) only, inequality would remain stable or increase slightly.

Conventional instruments, such as money supply, are used. In our model, monetary policy is conducted in the form of changing money supply M. So far, we have not considered if this could be a potential policy tool to target the policymaker's objectives. Let us consider the effects of increasing the money supply; the effects of decreasing the money supply will be mirror images.

An easier monetary policy reduces r^B and r^G, allowing entrepreneurs to expand capital borrowing. Both energy supplies shift right, while the CES demand for the energy bundle also rises. With higher energy use and given the proportions of brown and green energy, brown demand increases, pushing pollution up. The first-round wage gains and easier household credit can compress consumption inequality, but wealth inequality is ambiguous: if entrepreneurial profits and asset prices balloon, the top tail may outpace the wage gains at the bottom. Cheaper funding lowers near-term default rates, yet at the cost of higher leverage and portfolio growth; the banking system looks healthier in the short run but is more exposed to a future negative shock. Additionally (and as expected), easier monetary policy is inflationary.

In this model money supply is a blunt instrument for climate or distributional goals. Expansionary monetary policy tends to raise emissions and shift risk into the future, while its inequality effects can go either way. If policymakers want to keep prices stable without worsening the carbon path or systemic risk, they need to combine the loose stance with a carbon tax (to neutralise the pollution bump) and/or tighter capital requirements (to lean against leverage growth).

8. Policy takeaways for South Africa

What are the key takeaways for policymakers in South Africa?

Shared mandate, coordinated action. Because the SARB centres its work on price and financial stability while fiscal and sectoral agencies hold explicit climate- and equity-oriented goals, their agendas inevitably overlap. The welfare framework in this paper nests price stability, financial resilience, climate damages and distribution in a single objective function, showing that the SARB's narrow mandate is just one slice of a broader social-welfare surface. A standing mechanism for routine coordination would allow each institution to pursue its own remit yet still move towards a common social-welfare benchmark, making trade-offs clearer to both policymakers and the public. Such routine dialogue makes it easier to explain why, for example, a move that raises headline inflation today may still advance aggregate welfare once future carbon damages and equity gains are considered.

Carbon tax with safety nets. Model simulations confirm that a downstream carbon levy delivers the sharpest cut in emissions: a one-rand increase in τ triggers a proportionally larger fall in brown output than in green because demand, not credit frictions, does the heavy lifting. Yet the same run also shows pre-transfer income losses for coal workers and entrepreneurs. Recycling the bulk of the receipts to labour households flattens that hump and even narrows the Gini, whereas a blanket rebate would widen it. Channelled through tariff discounts or targeted social grants, those transfers therefore turn a pure climate tool into a just transition instrument without distorting investment signals.

Inflation and financial stability. Because South Africa's energy bundle is 91% fossil fuels and substitution elasticity is barely a third, the model predicts a noticeable but temporary bump to energy price inflation when the tax is raised. It also shows that loan demand and default risk migrate away from brown borrowers, easing capital adequacy pressure on banks even as coal sector profits shrink. Publishing stress-test results that trace these channels would help markets price transition risk and let monetary policy lean pre-emptively against any second-round wage effects. Such transparency should help markets price risk more accurately and give researchers a firmer base for evaluating policy trade-offs.

Targeted prudential tools. Capital requirements can support, though not substitute for, carbon pricing. Tightening brown risk weights cuts emissions but does so mainly by hiking lending rates; wages in coal regions fall and inequality widens, while financial stability gains are modest. Loosening green weights, by contrast, cheapens total energy and – counterintuitively – raises brown demand through a Jevons rebound. The welfare surface therefore peaks at moderate settings: a small brown capital add-on is helpful where individual banks are heavily exposed or when carbon legislation stalls and a narrow green discount works only for REIPPPP-certified projects once brown reliance has already declined.

Guarding against a 'green rebound'. South Africa's coal-heavy energy mix means that cheaper green credit alone can depress overall energy prices and inadvertently lift demand for coal. Policymakers might therefore sequence reforms: prioritise measures that cut coal dependence – carbon taxes, grid upgrades, renewable deployment – before rolling out broader green finance incentives.

Equity thread through every instrument. Finally, the distribution blocks of the model show that any policy that narrows wage gaps but widens profits for the top tail can still reduce headline inequality if transfers are well targeted. Anchoring every climate measure to explicit, monitorable just transition support – whether through Eskom-to-household rebates, retraining funds or regional development grants – keeps the policy package aligned with the welfare-maximising path the analysis identifies.

9. Conclusion

This study links South Africa's climate challenge to its macrofinancial architecture and distributional realities within one coherent framework. The results underscore that an ambitious carbon price, when paired with well-targeted transfers, cuts emissions while also narrowing inequality – demonstrating that environmental and social goals need not be in conflict. Prudential measures can reinforce, but not replace, that core instrument: a modest surcharge on brown lending strengthens bank resilience, yet stronger surcharges dampen investment and jobs, while broad green discounts risk rekindling fossil demand through cheaper energy. The analysis therefore favours a 'tax first, finance second' sequence, with each lever calibrated to offset the externalities created by the other. Ultimately, a successful transition hinges less on any single policy than on clear trade-offs, transparent objectives and sustained coordination across monetary, fiscal and energy authorities.

Annexures

Annex 1: Equilibrium

Let $\sigma^{RB} = \{\bar{m}^{RB}, \mu^{RB}, \mu_d^{RB}, D_s^{RB}, \pi_s^{RB}\} \in R_+ \times R \times R_+ \times R_+^2 \times R^2$.

Let $\sigma^{IB} = \{\bar{m}^{IB}, \mu^{IB}, \mu_d^{IB}, A^B, A^G, D_s^{IB}, \pi_s^{IB}, e_s^{IB}, k_s^{IB}\} \in R_+ \times R \times R_+ \times R_+ \times R_+ \times R_+^2 \times R^2 \times R^2 \times R^2$

Let $\sigma^l = \{C_0^h, C_s^h, d_1^h, b_1^h, \theta_0^h, \theta_s^h, D_s^h\} \in R_+ \times R_+^2 \times R_+ \times R_+ \times R_+ \times R_+^2 \times R_+^2$ for $h \in \{Bl, Gl\}$

Let $\sigma^e = \{C_0^h, C_s^h, d_1^h, b_1^h, D_s^h, K_{i1}, N_{i0}, N_{is}\} \in R_+ \times R_+^2 \times R_+ \times R_+ \times R_+^2 + \times R_+ \times R_+ \times R_+^2$ for $h \in \{Be, Ge\}, i \in \{1, 2\}$

Let $\eta = \{p_{10}, p_{20}, p_{1s}, p_{2s}, w_{00}, w_{10}, w_{20}, w_{0s}, w_{1s}, w_{2s}, r_d^{IB}, r_d^{RB}, r_l^{IB}, r_l^{RB}, \rho^B, r^G, r^B\}$ denote the set of prices

Define the budget sets as

$B^l(\eta) = \{\sigma^l$: labour household budget constraints hold$\}$,

$B^e(\eta) = \{\sigma^e$: entrepreneur household budget constraints hold$\}$,

$B^{RB}(\eta) = \{\sigma^{RB}$: retail bank budget Constraints hold$\}$,

$B^{IB}(\eta) = \{\sigma^{IB}$: investment bank budget constraints hold$\}$.

We say that $((\sigma^l)_{h\in\{Bl,Gl\}}, (\sigma^e)_{h\in\{Be,Ge\}}, \sigma^{RB}, \sigma^{IB}, \eta)$ is an equilibrium in the economy if and only if:

1. All banks optimise, $\sigma^{RB} \in Argmax \Pi^{RB}(\pi^{RB})$ and $\sigma^{IB} \in Argmax \Pi^{IB}(\pi^{IB})$

2. All households optimise, $\sigma^l \in Argmax \Pi^h, h \in \{Bl, Gl\}$ and $\sigma^e \in Argmax \Pi^h, h \in \{Be, Ge\}$

3. All markets clear as per section 2.6

4. All agents are correct in their expectations about the repayment rates they face:

$$\tilde{R}_s^l = \frac{D_s^{Bl} b_1^{Bl} + D_s^{Gl} b_1^{Gl}}{b_1^{Bl} + b_1^{Gl}} \tag{27}$$

$$\tilde{R}_s^e = \frac{D_s^{Be} b_1^{Be} + D_s^{Ge} b_1^{Ge}}{b_1^{Be} + b_1^{Ge}} \tag{28}$$

Annex 2: DS-weights application

In this section, we lay out key propositions regarding our preferred welfare measure to analyse welfare implications of different policies using the concept of DS-weights (Dávila and Schaab 2022).

Aggregate additive decomposition. Based on Proposition 1 from DS, we decompose the change in total welfare (represented by W^{DS}) with respect to a change in a generic policy parameter, γ. Assume that states are $s \in \{1, 2\}$. We represent the individual, dynamic and stochastic weights as ω^h, ω_t^h and $\omega_t^h(s)$ respectively. Then, change in total welfare is:

$$\frac{\partial W^{DS}}{\partial \gamma} = \mathbb{E}_h \left[\omega^h \sum_{t=0}^{1} \omega_t^h \sum_{s=1}^{2} \omega_t^h(s) \frac{\partial C_t^h(s)}{\partial \gamma} \right]$$

In its decomposed form, this expression transforms into:[15]

$$\begin{aligned}
\frac{\partial W^{DS}}{\partial \gamma} = & \underbrace{\mathbb{E}_h(\omega_0^h)\mathbb{E}_h\left(\frac{\partial C_0^h}{\partial \gamma}\right) + \mathbb{E}_h(\omega_1^h)\left[\mathbb{E}_h(\omega_1^h(1))\mathbb{E}_h\left(\frac{\partial C_1^h(1)}{\partial \gamma}\right) + \mathbb{E}_h(\omega_1^h(2))\mathbb{E}_h\left(\frac{\partial C_1^h(2)}{\partial \gamma}\right)\right]}_{\Xi_{1t}\text{(Aggregate efficiency)}} \\
& + \underbrace{\mathbb{E}_h(\omega_1^h)\left[\mathbb{C}ov_h\left(\omega_1^h(1), \frac{\partial C_1^h(1)}{\partial \gamma}\right) + \mathbb{C}ov_h\left(\omega_1^h(2), \frac{\partial C_1^h(2)}{\partial \gamma}\right)\right]}_{\Xi_{2t}\text{(Risk-sharing)}} \\
& + \underbrace{\mathbb{C}ov_h\left(\omega_0^h, \frac{\partial C_0^h}{\partial \gamma}\right) + \mathbb{C}ov_h\left(\omega_1^h, \omega_1^h(1)\frac{\partial C_1^h(1)}{\partial \gamma} + \omega_1^h(2)\frac{\partial C_1^h(2)}{\partial \gamma}\right)}_{\Xi_3\text{(Intertemporal-sharing)}} \\
& + \underbrace{\mathbb{C}ov_h\left(\omega^h, \omega_0^h\frac{\partial C_0^h}{\partial \gamma} + \omega_1^h\left[\omega_1^h(1)\frac{\partial C_1^h(1)}{\partial \gamma} + \omega_1^h(2)\frac{\partial C_1^h(2)}{\partial \gamma}\right]\right)}_{\Xi_4\text{(Redistribution)}}
\end{aligned} \tag{29}$$

where $\mathbb{E}_h[\cdot]$ and $\mathbb{C}ov_h[\cdot, \cdot]$ denote cross-sectional expectations and covariances respectively.

Welfare weights. We consider DS-weights as assigned by a normalised utilitarian planner. The weights defined such that they satisfy certain desirable properties of 'proper weights' – that is, stochastic weights add up to 1 at every date, dynamic weights add up to 1 across all dates

[15] The proof leverages that $\mathbb{E}_h(\omega^h) = 1$.

and individual weights add up to 1 across all individuals.[16] Weights are defined as:

Stochastic:

$$\omega_1^h(1) = \frac{\mu U'(C_1^h(1))}{\mathbb{E}_0\{U'(C_1^h(s))\}} \quad \omega_1^h(2) = \frac{(1-\mu)U'(C_1^h(2))}{\mathbb{E}_0\{U'(C_1^h(s))\}}$$

Dynamic:

$$\omega_0^h = \frac{U'(C_0^h)}{U'(C_0^h) + \delta\mathbb{E}_0\{U'(C_1^h(s))\}} \quad \omega_1^h = \frac{\delta\mathbb{E}_0\{U'(C_1^h(s))\}}{U'(C_0^h) + \delta\mathbb{E}_0\{U'(C_1^h(s))\}}$$

Individual:

$$\omega^h = \frac{\lambda_h[U'(C_0^h) + \delta\mathbb{E}_0\{U'(C_1^h(s))\}]}{\sum_h \lambda_h[U'(C_0^h) + \delta\mathbb{E}_0\{U'(C_1^h(s))\}]}$$

where $\lambda_h > 0 \; \forall h$ is a collection of welfare weights assigned to each household.

[16] For the proof, refer to the appendix in Dávila and Schaab (2022).

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