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ABSTRACT

This study examines the macroeconomic dynamics under the recently announced intensity-based Carbon Credit Trading Scheme (CCTS) in India using an Environmental Dynamic Stochas¬tic General Equilibrium framework. The policy freely allocates carbon certificates in the primary carbon market and aims to incentivize their trading by monetizing emission intensity reductions in the secondary carbon market. Distinguishing between thermal power and green electricity, we find that the incentive mechanism of this policy promotes the adoption of green electricity and reduces emissions in the long term. Although phasing out the use of fossil fuels remains a challenge in the short term, an ambitious intensity target, coupled with cheaper green electricity, can accelerate the energy transition. In addition, it stabilizes the economy against volatility in fossil fuel prices. Our results highlight that the rate-based CCTS outperforms the price-based carbon tax policy in promoting the energy transition while sustaining the growth objectives.

Keywords: E-DSGE, Secondary carbon market, Intensity target, Free allocation

JEL Code: E32, Q48, Q58, D47

Carbon Credit Trading and India's Green Transition[1]

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Abstract

This study examines the macroeconomic and environmental implications of India's newly introduced Carbon Credit Trading Scheme (CCTS), an intensity-based emissions trading system that incentivizes target-achieving firms through free allocation of carbon certificates tradable in secondary carbon markets. We employ an Environmental-Dynamic Stochastic General Equilibrium model with a secondary carbon market and two energy sectors (thermal power and green electricity). Unlike conventional models, the model captures firms' endogenous abatement and green electricity adoption responses to the incentive mechanism. We find three key results. First, CCTS policy promotes energy transition and reduction in emissions in the long term by lowering the marginal cost of production. Second, while fossil fuel phase-out remains a challenge in the short term, a stricter target and cheaper green electricity can accelerate the transition. Third, the incentive effect of the CCTS acts as a macroeconomic stabilizer against fossil fuel price volatilities, converting real shocks into financial adjustments through the certificate market mechanism. Finally, the CCTS outperforms the price-based carbon tax in transition while sustaining the growth objectives. Thus, intensity-based emissions trading with free allocation enables green transition while avoiding the high output costs of carbon taxation, making it the preferred policy choice for developing economies like India.

JEL Codes: E32, Q48, Q58, D47

Keywords: E-DSGE, Secondary carbon market, Intensity target, Business cycle, Energy transition

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1 Introduction

India ranked third in total CO2 emissions in 2023 (International Environmental Agency (IEA), 2024) and is projected to increase its annual emissions by nearly 30% by 2050 (IEA, 2023). It is also one of the most vulnerable[2] countries to climate change (Intergovernmental Panel on Climate Change (IPCC), 2023)[3]. The dual challenge of rapidly rising emissions and high climate vulnerability presents a policy dilemma in balancing economic growth with the transition to a low-carbon economy. Unlike developed economies that industrialized prior to climate constraints, India must decarbonize while maintaining a sustainable growth.

In response to this challenge and its commitment to a net-zero target by 2070 in the United Nations Climate Change Conference in Glasgow COP26)[4], the Indian government notified the Carbon Credit Trading Scheme on 28 June 2023[5]. The CCTS targets the emission intensity (emissions per unit of output) rather than an absolute cap. This policy aims to develop a unified secondary carbon market[6] called the India Carbon Market (ICM) for trading carbon certificates. A firm that outperforms the mandated target is allocated certificates proportional to the difference between the target and the achieved emission intensity[7]. It can then sell certificates to underperforming firms in the secondary carbon market and earn revenue. Thus, the CCTS creates an incentive mechanism.

To examine the macroeconomic and environmental implications of this market-based emission trading scheme (ETS), this paper develops an Environmental-Dynamic Stochastic General Equilibrium (E-DSGE) model of India's CCTS. We address three critical

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[2] The IPCC decomposes vulnerability into three components: exposure, sensitivity, and ability to cope with climate change.

[3] Climate change has ecological and economic impacts (Nordhaus, 2019). As a result, it has led to a growing global call for environmental policies (Barnett et al., 2022) and countries committing to net-zero.

[4] `https://pib.gov.in/PressReleasePage.aspx?PRID=1795071` *Accessed on August 19, 2025*

[5] See the Government of India notification S.O. 2825(E), dated 28th June 2023 and amendment notification S.O. 5369(E), dated 19th December 2023. *Accessed on August 19, 2025*

[6] In a secondary carbon market, firms trade certificates among themselves.

[7] The CCTS distributes tradable carbon certificates to firms in a primary carbon market through a free allocation approach. A free allocation eases a firm's upfront cost of emissions while providing incentives to reduce emissions (World Bank, 2019), mitigating carbon leakage (Branger et al., 2015) and ensuring political acceptability, especially in the initial stages of the policy (Yoon and Oh, 2021).

gaps in the literature. First, existing E-DSGE models of ETS focus almost exclusively on primary carbon markets with market-determined prices (see Annicchiarico and Di Dio (2015); Xiao et al. (2018); Dubois et al. (2025)). The dynamics of secondary carbon markets with freely allocated certificates that are traded among firms based on their performance remain largely unexplored. Second, although Burgold et al. (2025) model the secondary carbon market using sectoral heterogeneity[8], they do not differentiate between energy sources[9]. Such models hinder the analysis of green energy transition[10] as energy substitutability is central to transition dynamics (Dissou and Karnizova, 2016). In contrast, green transition is one of the core features of this paper, as we allow firms to substitute emission-intensive energy with green energy. Third, the sparse Indian E-DSGE literature (see Reserve Bank of India (2023); Shah et al. (2025)) omits both the secondary carbon market and an explicit modeling of the energy sector. This limits the evaluation the macroeconomic and transition implications of India's emerging carbon market architecture and green energy policy, both of which are envisioned to be a cornerstone for India's low-carbon transition.

In this context, the paper addresses the following questions: What is the impact of a CCTS policy on macroeconomic variables and the energy sector in the presence of a secondary carbon market? How does this policy fare against a carbon tax and a no-policy scenario? What are the critical factors that can shape the effectiveness of the CCTS in promoting India's green transition?

To answer these questions, we develop a Real Business Cycle model augmented with emissions and environmental policy for India using Bayesian estimation. Following Khan et al. (2019), we categorize this as an E-DSGE Model. The model economy features (i) a disaggregated electricity sector with thermal power and green electricity (see Golosov

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[8] Some firms are target achievers (low emission intensity sector) and others are non-achievers (high emission intensity sector).

[9] Hence, a firm can only reduce its emission intensity through abatement efforts or by increasing the share of non-energy inputs in the production function.

[10] We define energy transition as the adoption of green electricity. The definition is in line with IRENA (see `https://www.irena.org/Energy-Transition/Outlook`).

et al. (2014); Dissou and Karnizova (2016)) to align with India's policy priority of expanding green electricity infrastructure[11], and (ii) a secondary carbon market where emission certificate trade (Burgold et al., 2025). We assume that fossil fuels serve as inputs for both thermal power generation and direct use in production. At the core of our model is a firm that is allocated carbon certificates at no cost when it outperforms the mandated target or purchases them in the ICM when it underperforms. A firm's performance is determined by its optimal decision on abatement efforts and green electricity adoption, contingent on the attractiveness of the incentive mechanism[12]. To keep the analytical framework simple, we model this choice using gains from selling certificates in the secondary market.

Our analysis yields several important findings. In line with the literature (see Annicchiarico and Di Dio (2015); Xiao et al. (2018)), our results suggest that environmental policies such as carbon tax and CCTS reduce emissions and macroeconomic variables, such as output, consumption, and investment in the long run, due to the additional cost of regulations borne by firms. However, the incentive provided by the CCTS reduces this cost. As a result, CCTS is more efficient than a carbon tax regime in reducing emissions and advancing the energy transition while mitigating the adverse impact of an environmental policy on growth. For example, our simulation exercise shows that, relative to the carbon tax, the CCTS reduces emissions by an additional 2.71% of baseline emissions, lowers the fossil fuel share by a further 11.3% of the baseline level, and preserves output by an additional 8.4% of the baseline level, thereby demonstrating its relative efficiency. Our result that intensity-based CCTS dominates alternative instruments aligns with Burgold et al. (2025), who demonstrate that intensity targets outperform cap-and-trade by lowering marginal costs through output-linked free allowances, in contrast to free lump-sum allowances under cap-and-trade which leave marginal production incentives unchanged.

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[11] see `https://www.pib.gov.in/PressNoteDetails.aspx?id=155063&NoteId=155063&ModuleId=3` for details on India's ongoing projects. *Accessed on 6 September 2025.*

[12] In an economy, some firms may find it optimal to buy certificates over reducing emissions due to high marginal abatement costs (Rekker et al., 2023), uncertainty about long-term benefits (Pommeret and Schubert, 2009), and knowledge and infrastructure limitations (Brown et al., 2008). Other firms may adopt costly energy-efficient technology (Gillingham and Sweeney, 2012; Lanteri and Rampini, 2025)and learn and adapt new technology (Pommeret and Schubert, 2009).

A subsidy that reduces the effective price of green electricity further amplifies the transition in the CCTS regime. However, as regulation cost decreases, firms find it optimal to increase output, leading to an increase in emissions. To give a perspective, the introduction of a 50% subsidy increases output by 5.6% and raises emissions by 7.1%, while reducing the fossil fuel share by 5.7% relative to the no subsidy CCTS benchmark.

A CCTS regime may increase fossil fuel use in the short run if output expands faster than emissions, keeping firms within the mandated target. Additionally, the incentive mechanism in this regime may increase the abatement efforts and promote green electricity production. Hence, in the short run, an increase in emissions may coincide with green electricity expansion. It means that the economy can follow a transition path even if emissions increase initially. We show this by simulating the economy with a positive technology shock in the production and green electricity production sector. A stricter intensity target accelerates the transition by stimulating green efforts and disincentivizing the use of fossil fuels. However, it comes at the cost of reduced output since the incentive mechanism is weakened as the target becomes difficult to achieve and certificate trading reduces.

The CCTS policy also acts as a macroeconomic stabilizer against fluctuations in fossil fuel prices, converting a real shock into a financial event, and almost entirely neutralizing its macroeconomic impacts. The mechanism works as follows: when fossil fuel prices fall, firms would normally increase fossil fuel consumption, raising emissions and output. Under CCTS, however, any attempt to increase emissions immediately raises certificate demand and prices in the secondary market. This financial counter-shock constrains emissions and creates an investment opportunity where small green investments lead to high-value green electricity generation and therefore certificate trading. As a result, despite the energy price shock, macroeconomic variables (output, consumption, and investment) remain stable as the volatility is completely absorbed by the certificate market mechanism. This novel finding therefore makes a strong case for the establishment of an emission trading market in energy-importing economies like India.

We make several contributions that span methodological innovation and policy relevance. First, we develop a novel quantitative model that captures free allocation and secondary carbon market effects on firm decisions, well suited for transition and early-stage carbon market dynamics. Our study shows that an intensity target-based ETS can lead to transition at lower regulatory cost than carbon tax and no policy scenarios. Our framework clearly indicates that an economy can advance on a growth-consistent transition path even with rising emissions. Second, we propose an E-DSGE model for India that, in contrast to existing Indian E-DSGE literature[13], accounts for implications on the energy sector and align with recent policy initiative taken by the Indian government. Third, we establish that CCTS acts as an automatic macroeconomic stabilizer for energy-importing economies like India, which are subject to frequent fossil fuel price shocks, a property not previously identified for emission trading systems. Finally, we find that, while a stricter intensity target accelerates the green transition, it comes at a cost: firms must substitute for more expensive green electricity and divert resources from production to abatement efforts, resulting in lower output and consumption. Furthermore, as the target becomes more difficult to achieve, the incentive mechanism weakens, preventing certificate trading. Overly ambitious targets can thus undermine the market-based incentive structure that makes CCTS appealing in comparison to its alternatives, and target stringency should be gradually increased, if necessary.

Our paper has three important policy implications. (i) The findings of this paper suggest that transitions are more costly for developing economies than developed economies. However, developing economies can promote the transition without burdening firms through carbon taxation if governments focus on investing in green infrastructure through providing subsidy and providing market-based incentives that reduce the cost of regulations. (ii) Fossil fuels will remain in use, so policies should emphasize cleaner tech-

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[13] Reserve Bank of India (2023) addresses the impact of natural disaster on capital and Shah et al. (2025) compare carbon tax, cap-and-trade, and intensity target.

nologies and efficiency improvements. (iii) Our paper provides some insights on the impact of a national carbon market. Hence, the implication also extends to developing countries that are looking for policy frameworks that does not compromise growth, especially in the initial phase of the implementation.

2 Literature Review

Emission trading schemes (ETS) are increasingly being adopted as a key tool for reducing carbon emissions[14]. These schemes are a cost-effective strategy for controlling emissions (Rubin, 1996) and achieving a set environmental quality standard at a minimum possible abatement cost, where each firm minimizes its marginal abatement costs until it is equal to the permit price in the market (Montgomery, 1972). Thus, these schemes reveal the private marginal valuation for an additional permit for firms (Cason and Gangadharan, 2006).

ETS establishes two carbon markets: a primary carbon market where a government issues carbon certificates to the firms via free allocation or auctions and a secondary market where firms trade certificates among themselves. A free allocation approach is preferred in the initial phase of an ETS, as it reduces the financial burden of participating firms and leads to a lower reduction in output (Yoon and Oh, 2021).[15] The Indian CCTS follows the free allocation approach.

To capture the CCTS policy, we develop an Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model which has gained substantial attention due to its ability to integrate environmental policies with structural micro-founded DSGE models. It is important to study the interplay because the costs and benefits of environmental regulations fluctuate throughout the business cycle (Annicchiarico et al., 2022). A DSGE model can

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[14] See `https://icapcarbonaction.com/en/ets`

[15] However, Hahn and Stavins (2011) and Fowlie and Perloff (2013) argue that the final allocation of certificates, i.e., after trading on the secondary carbon market, does not depend on the initial allocation method if certain conditions are met. The conditions include zero transaction costs, full information, perfectly competitive markets, and cost minimization behavior.

improve the analysis of policymakers concerning systematic changes in a policy, such as the switch from one policy to another (Christiano et al., 2018). In this spirit, Fischer and Springborn (2011), Heutel (2012), and Angelopoulos et al. (2013), the pioneers of E-DSGE literature, establish that economic agents adjust their utilities/profits to accommodate and optimally respond to additional regulation costs imposed by different environmental policies. Our paper is related to the burgeoning literature that focuses on climate issues, environmental policies and DSGE models, as we compare ETS with a carbon tax regime.

Although these works are a benchmark in the E-DSGE literature, their ETS framework, if considered, only includes a competitive primary carbon market[16]. A secondary carbon market framework is largely missing in this literature. Burgold et al. (2025) capture the secondary carbon market using the sectoral heterogeneity where some firms have higher than target intensities and others have lower than target intensities. This difference creates the trading channel. In their paper, they compare Europe's cap-and-trade with China's Tradable Performance Standard. We add to this literature by developing an E-DSGE framework for India.

More recent contributions have extended these models to include energy sectors (see Golosov et al. (2014); Dissou and Karnizova (2016)). A transition from fossil fuels to green energy is necessary to demonstrate the dynamics of environmental regulations, as economic agents can adjust to changing energy prices by substituting between different energy sources (Dissou and Karnizova, 2016). Golosov et al. (2014) include polluting energy sources like oil and coal, and non-polluting green energy in a global E-DSGE model.[17]

Following Dissou and Karnizova (2016), we develop a nested structure to model different energy sources. They follow a nested structure where the first level nests different

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[16] Some other works that include a primary carbon market are Xiao et al. (2018); Dubois et al. (2025), etc., to name a few.

[17] They are the first to derive a simple formula for the marginal externality damage of CO2 emissions that is based on assumptions on discounting, expected damages, and carbon depreciation.

fossil fuels, and the second level nests the fossil index with electricity. In comparison, we first nest fossil fuels and electricity, followed by thermal power and green electricity. This framework allows us to capture India's effort to promote green electricity by analyzing the substitutability of different energy sources when the economy is moving on a transition path.

Another benefit of having an energy sector separately is that it facilitates a study on the impact of fossil fuel prices on the economy. An increase in fossil fuel prices reduces the output (Känzig, 2021; Peersman and Van Robays, 2012; Coenen et al., 2024; Chafwehé et al., 2025). The possibility of a recession increases if fossil fuel prices increase in energy-importing economies (Känzig, 2021; Auclert et al., 2023). In line with these works, we introduce an exogenous fossil fuel price shock in the economy to assess the impact of fluctuations in fossil fuel price within a secondary carbon market framework.

In addition to environmental policies, a subsidy of different forms has emerged as a major environmental policy to accelerate the transition process. Chen et al. (2017) find that the clean-production innovation subsidy performs better than a quantity subsidy[18] in agricultural sector in China. Argentiero et al. (2018) find that a subsidy in green R&D pushes renewable energy production more than a price subsidy for both demand and supply shocks in final output. In comparison, we study a subsidy on green capital purchase to align with the Indian government scheme to subsidize the cost of installation of solar cells[19].

An E-DSGE model is largely absent for India. Reserve Bank of India (2023) develops an NK-DSGE model for a climate shock that cause physical damage to capital. They find that these shocks have contractionary effects on output. Shah et al. (2025) develops an NK-DSGE model for India to assess the effectiveness of various environmental policies. They find that cap-and-trade is better than other policies in terms of reducing emissions

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[18] It subsidizes the quantity of agricultural production

[19] While these subsidies are mainly given in the agricultural sector or to households. We extend it to green electricity producers to understand the impact of a wider coverage through subsidy on green capital.

with favorable macroeconomic dynamics. However, these papers do not consider any energy sector or a secondary carbon market in their model. In comparison, our quantitative model focuses on energy substitution for transition. Additionally, our framework have important implications for the evolution of the India Carbon Market in initial phase of the CCTS.

This review identifies three gaps that our paper addresses. First, existing ETS models focus mainly on primary markets. Second, only Burgold et al. (2025) comes close to capturing the secondary carbon market using the sectoral heterogeneity, but they do not distinguish between energy sources, preventing the analysis on green transition. Third, the sparse Indian E-DSGE literature (Reserve Bank of India, 2023; Shah et al., 2025) omits either energy sectors or secondary carbon markets, which limits transition analysis. Our paper bridges these gaps by combining: (i) intensity-based targets with free allocation, reflecting India's CCTS; (ii) secondary carbon market dynamics where certificate prices and trading volumes emerge endogenously from firms' abatement and green electricity choices; and (iii) disaggregated thermal and renewable electricity to capture energy substitution.

The remainder of the paper is organized as follows. Section 3 describes the model. Section 4 reports data, estimation and calibration of parameters. Section 5 discusses the IRFs. Section 6 concludes along with policy implications and future scope.

3 Model

The economy is described by a Real Business Cycle (RBC) model, extended to account for emissions and environmental policies in India. The environmental policies in consideration in this paper are the Carbon Credit Trading Scheme (CCTS) and subsidies on purchasing green energy input. The economy is made up of 5 economic agents. A unit mass of identical and infinitely lived households that consume goods, provide labor, participate in the bond market, and rent capital. A good producer uses labor, capital,

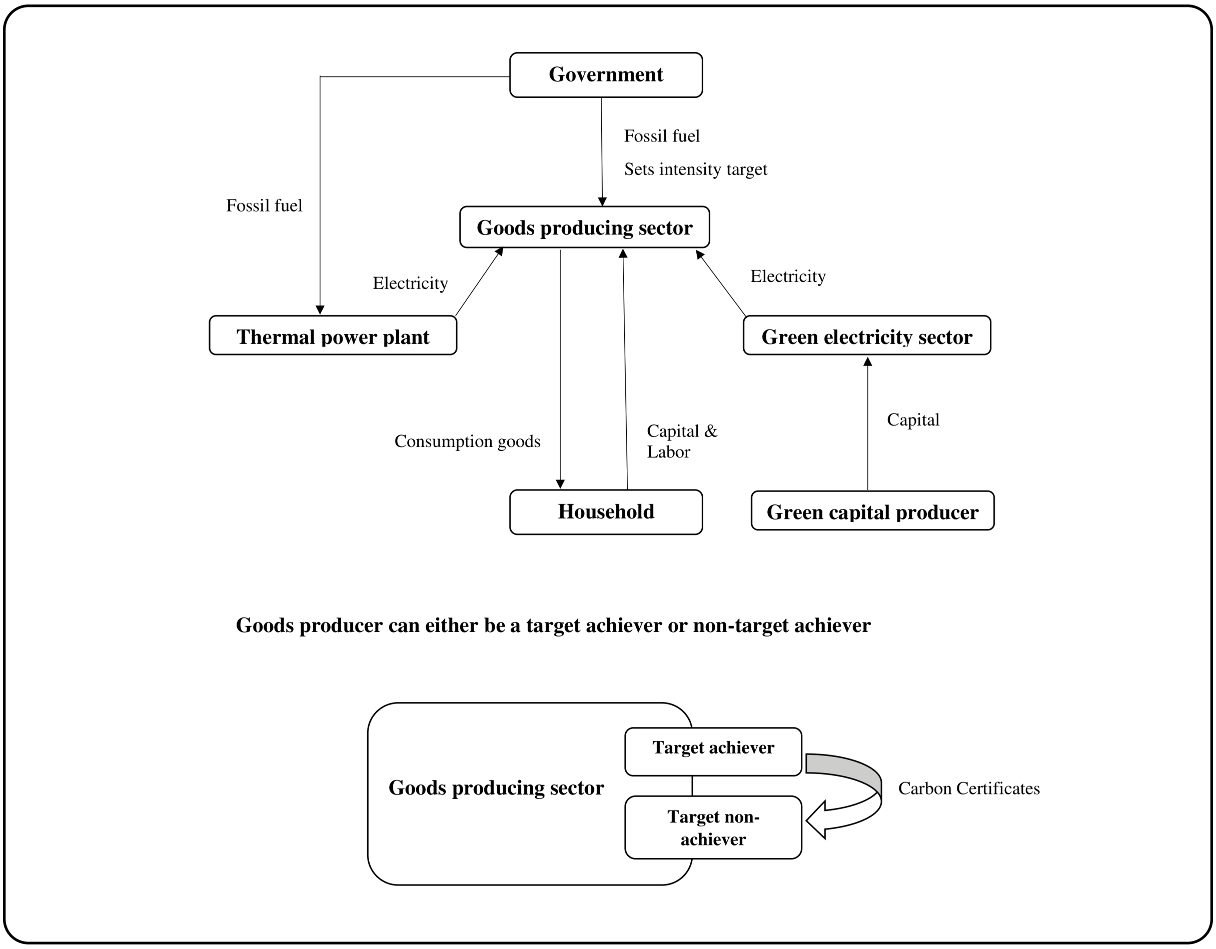

Figure 1: Energy sector augmented RBC model

and energy inputs to produce output. It generates emissions that are proportional to the output and share of fossil fuels. There exists a disaggregated electricity sector composed of thermal power plants that generate thermal power and green electricity sector that produces green electricity. A regulatory authority (or government) announces an intensity target to limit emissions produced by the good production sector. It allocates certificates to the good producer at no cost that outperforms the target. These certificates can be traded in the secondary carbon market.

3.1 Households

A representative infinitely lived household maximizes intertemporal utility by choosing consumption (C_t), labor hours (L_t) and renting capital to the production sector (K_t^Y). The household earns a real wage (w_t) on labor and rent ($r_{k,t}$) on capital. It purchases riskless government bonds (B_t) in period t and earns an interest r_t.

The lifetime utility of the household is given by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\ln C_t - \mu_L \frac{L_t^{1+\eta}}{1+\eta} \right) \qquad \eta > 0,\ \mu_L > 0,$$

subject to a period-by-period budget constraint:

$$C_t + B_t + I_t^Y \leq w_t L_t + (1 + r_{t-1}) B_{t-1} + r_{k,t} K_{t-1}^Y + \Pi_t + \mathcal{T}_t$$

where $\mathbb{E}_0$ denotes the expectation operator at time $t = 0$, $\beta \in (0, 1)$ is the constant discount factor, μ_L is the labor disutility parameter, η is the inverse of Frisch elasticity of labor, I_t^Y is investment in production sector, Π_t is payouts from the ownership of production, energy, and capital sectors and $\mathcal{T}_t$ is the lump-sum transfers/taxes to the household.

The capital accumulation equation is given by:

$$K_t^Y = (1 - \delta_k) K_{t-1}^Y + \left[1 - \frac{\phi_c}{2} \left(\frac{I_t^Y}{I_{t-1}^Y} - 1 \right)^2 \right] I_t^Y \tag{3.1}$$

where δ_k is the capital depreciation rate and ϕ_c is the investment adjustment cost parameter.

3.2 Goods Producing Sector

The production sector is perfectly competitive. A representative producer produces output (Y_t) using labor (L_t), capital (K_t^Y), and energy mix (J_t). The production function is given by a Cobb-Douglas production function:

$$Y_t = A_t^Y (\Lambda_t L_t)^{\alpha} (K_t^Y)^{\gamma} J_t^{1-\alpha-\gamma} \tag{3.2}$$

where A_t^Y is the total factor productivity and Λ_t is the damage function due to emissions.

A_t^Y follows an AR(1) process

$$\log A_t^Y = \rho_Y \log A_{t-1}^Y + \epsilon_{Y,t} \tag{3.3}$$

where ρ_Y is the autocorrelation coefficient and $\epsilon_{Y,t} \sim \mathcal{N}(0, \sigma_Y^2)$ is an idiosyncratic shock. σ_Y is the standard deviation of the shock.

We model the damage function (Λ_t) as

$$\Lambda_t = 1 - (\eta_0 + \eta_1 M_t + \eta_2 M_t^2) \tag{3.4}$$

where M_t is the pollution stock. Following Annicchiarico and Di Dio (2015), the law of motion for the pollution stock is

$$M_t = (1 - \delta_M) M_{t-1} + Z_t + Z_t^* \tag{3.5}$$

where Z_t is the domestic emission in the economy and $Z_t^* = \left(\frac{1-e}{e}\right) Z_t$ is the emission produced by the rest of the world. e represents the share of domestic emissions in global emissions.

The energy mix (J_t) is a bundle of energy sources, fossil fuels ($R_{1,t}$) and electricity (El_t), used in the production process. We assume that these energy sources are imperfect substitutes given by a CES function (see Golosov et al. (2014)):

$$J_t = \left[(\omega_1)^{\frac{1}{\varepsilon_1}} El_t^{\frac{\varepsilon_1 - 1}{\varepsilon_1}} + (1 - \omega_1)^{\frac{1}{\varepsilon_1}} R_{1,t}^{\frac{\varepsilon_1 - 1}{\varepsilon_1}} \right]^{\frac{\varepsilon_1}{\varepsilon_1 - 1}} \tag{3.6}$$

where ω_1 is the weight of electricity and ε_1 is the elasticity of substitution between fossil fuel and electricity. A firm uses two types of electricity - green electricity (E_t^G) and thermal power (E_t^F). They are imperfect substitutes for each other. The electricity mix follows a CES function given by:

$$El_t = \left[\omega_2^{\frac{1}{\varepsilon_2}}(E_t^F)^{\frac{\varepsilon_2-1}{\varepsilon_2}} + (1-\omega_2)^{\frac{1}{\varepsilon_2}}(E_t^G)^{\frac{\varepsilon_2-1}{\varepsilon_2}}\right]^{\frac{\varepsilon_2}{\varepsilon_2-1}} \tag{3.7}$$

where ω_2 is the weight of thermal power and ε_2 is the elasticity of substitution between thermal power and green electricity.

3.2.1 Carbon Credit Trading Scheme Modeling

The emissions are proportional to the output production (Annicchiarico and Di Dio, 2015) and the share of fossil fuels in the total energy production (Silva and Silva, 2024) in the economy. The government announces an emission intensity target ν and the production sector has to comply with it. The government follows a free allocation of certificates based on the difference between the mandated intensity target and the achieved intensity. The firm can trade these certificates on the secondary carbon market at a market-determined price. Emissions corresponding to this target (Z_t^{target}) are given by:

$$Z_t^{target} = \nu\theta_t Y_t \tag{3.8}$$

where θ_t is the target shock. θ_t follows an AR(1) process

$$log(\theta_t) = \rho_\theta log(\theta_{t-1}) + \epsilon_{\theta,t} \tag{3.9}$$

where ρ_θ is the autocorrelation coefficient and $\epsilon_{\theta,t} \sim \mathcal{N}(0, \sigma_\theta^2)$ is an idiosyncratic shock. σ_θ is the standard deviation of the shock. A positive target shock implies increase in emission intensity target leading to increase in permitted emissions.

Assumption 1. *A firm can be either a seller or a buyer of certificates. If the firm takes an abatement effort* (U_t) *with fixed probability* ϱ*, then it is allocated certificates and becomes a seller of certificates. If a firm does not take abatement, it becomes a buyer.*

Taking abatement represents the foresightedness of a firm. This means that the firm understands the incentive of the environmental policy (or the negative impact on the environment). Dickson and MacKenzie (2018) and Anouliès (2017) determine a firm's status as a net buyer or seller endogenously based on marginal abatement costs and productivity thresholds, respectively. We capture this heterogeneity in reduced form by modeling the trading position as a probability dependent on the firm's abatement effort. Hence, our modeling strategy is closer to Dickson and MacKenzie (2018). This assumption can also taken in the spirit of Calvo pricing, where a firm changes the price of goods with some fixed probability.

Following Annicchiarico and Di Dio (2015), the cost of abatement (CA_t) is given by

$$CA_t = \varrho\phi_1 U_t^{\phi_2} Y_t \tag{3.10}$$

where $\phi_1,\ \phi_2 > 0$ are technological parameters of the abatement cost. ϕ_1 measures the availability of existing technology alternatives, and ϕ_2 is the degree of non-linearity in costs.

Emissions are reduced when producers make abatement efforts or increase the proportion of green electricity in the energy mix. Hence, the total emission produced is the sum of emissions produced when abatement efforts are taken (Z_t^S) in the economy and emissions produced when abatement efforts are not taken (Z_t^B) is given by

$$\begin{aligned} Z_t &= Z_t^S + Z_t^B \\ &= \underbrace{\varrho(1-U_{t-1})\varphi E_t Y_t}_{\text{Emission produced when target achieved}} + \underbrace{(1-\varrho)\varphi E_t Y_t}_{\text{Emission produced when target not achieved}} \qquad (3.11) \\ &= (1-\varrho U_{t-1})\varphi E_t Y_t \end{aligned}$$

where $E_t = \left(\frac{E_t^F + R_{1,t}}{R_{1,t}+E_t^F+E_t^G}\right)$ (see Silva and Silva (2024)). The proportion $\left(\frac{R_{1,t}}{R_{1,t}+E_t^F+E_t^G}\right)$ represents direct and process-based emissions and $\left(\frac{E_t^F}{R_{1,t}+E_t^F+E_t^G}\right)$ represents indirect emissions, i.e., emissions produced during the production of electricity. φ is the emission intensity in 2005. φE_t represents the current emission intensity of Indian economy.

Departing from the prior literature, we assume that the abatement effort does not immediately reduce emissions. We model this delay by a one-period delay in U. This delay also represents the fact that when CCTS is announced, some foresighted firms take advantage of the policy by starting abatement efforts before the policy is even implemented in the country.

Assumption 2. *The production sector pays for emissions produced by the thermal power plants.*

The CCTS guidelines shared by the Bureau of Energy Efficiency do not cover thermal power plants under the intensity target policy. The emissions produced by these plants are captured as indirect emissions in the accounts of the production sector. Hence, Assumption 2 is in line with the Bureau of Energy Efficiency (2023) guidelines.

The number of certificates earned by a good producer depends on the abatement efforts, target, and probability ϱ. These certificates are then sold on the secondary carbon market. The number of certificates earned/sold is given by:

$$n_t^{sell} = Z_t^{target} - Z_t^S \tag{3.12}$$

$$= \varrho[\nu\theta_t - (1 - U_{t-1})\varphi E_t]Y_t \tag{3.13}$$

The number of certificates purchased on the secondary carbon market is given by:

$$n_t^{buy} = Z_t^B - Z_t^{target} \tag{3.14}$$

$$= (1 - \varrho)(\varphi E_t - \nu\theta_t)Y_t \tag{3.15}$$

Hence, the payoff (Π_t^T) of a representative producer from the trade is:

$$\Pi_t^T = p_t^C(n_t^{sell} - n_t^{buy}) \tag{3.16}$$

$$= p_t^C[\theta_t\nu - (1 - \varrho U_{t-1})\varphi E_t]Y_t \tag{3.17}$$

where p_t^C is the competitive price of the certificate in the market.

3.2.2 Good Producer Problem and Aggregation

The representative firm solves the following discounted dynamic profit maximization problem:

$$\Pi_t = \mathbb{E}_t \sum_{t=s}^{\infty} \Omega_{t,t+s} \left[\begin{array}{r} Y_{t+s} - (w_{t+s}L_{t+s} + r_{k,t+s}K_{t+s} \\ +p^E_{F,t+s}E^F_{t+s} + p^E_{G,t+s}E^G_{t+s} + p^R_{t+s}(1+\tau^F)R_{1,t+s}) \\ -CA_{t+s} + \Pi^T_{t+s} \end{array} \right] \tag{3.18}$$

subject to eq (3.2) where $\Omega_{t,t+s} = \beta^s \frac{C_{t+s}}{C_t}$ is the stochastic discount factor that converts future payoffs to current values. τ^F represents the various indirect taxes paid by firms on their purchase of fossil fuels. Some examples of such taxes are VAT, excise duty, tariffs, cess, etc.

Proposition 1. *CCTS allows entities to increase their absolute emissions while remaining compliant, provided their output grows proportionally faster.*

Proof. Let the target emission intensity be $\left(\frac{Z}{Y}\right)$, where Z is emission and Y is output. Then a firm can produce (emission, output) $= (Zk, Yk)$, where $k \in \mathbb{R}$ is a constant. Let $k_2 > k_1 > k$. Then,

$$\frac{Z}{Y} = \frac{Zk}{Yk} > \frac{Zk_1}{Yk_2}$$

That means if emissions increase by k_1 times and output increases by k_2 times, the firm can still be within the limits of the target. □

The above proposition implies that a firm can earn certificates if the increase in output is greater than that of emissions.

3.3 Thermal Power Plants

This sector comprises perfectly competitive thermal power plants. The representative plant purchases fossil fuel ($R_{2,t}$) from the government at a given price p^R_t to produce electricity (E_t^F). The production follows a linear production function:

$$E_t^F = A_t^F R_{2,t} \tag{3.19}$$

A_t^F is the technology shock in this sector. It follows an AR(1) process given by

$$\log A_t^F = \rho_F \log A_{t-1}^F + \epsilon_{F,t} \tag{3.20}$$

where ρ_F is the autocorrelation coefficient and $\epsilon_{F,t} \sim \mathcal{N}(0, \sigma_F^2)$ is an idiosyncratic shock. σ_F^2 is the standard deviation of the shock.

Similarly to the production sector, this sector is also subject to indirect taxes τ^F on the purchase of fossil fuel.

3.4 Green Electricity Sector

This sector comprises perfectly competitive green power plants — solar power, hydroelectric plants, nuclear plants, etc. The representative plant uses non-polluting resources (for example, wind, sunlight, flowing water, biomass, hydrogen, etc.) to generate green electricity (E_t^G). The input for the production is green capital (R_t^G)[20]. It takes the price of resources p_t^G as given. The renewable electricity production function follows a linear function given by

$$E_t^G = A_t^G R_t^G \tag{3.21}$$

where A_t^G is a technology shock in this sector. It follows an AR(1) process given by

$$\log A_t^G = \rho_{AG} \log A_{t-1}^G + \epsilon_{AG,t} \tag{3.22}$$

where ρ_{AG} is the autocorrelation coefficient and $\epsilon_{AG,t} \sim \mathcal{N}(0, \sigma_{AG}^2)$ is an idiosyncratic shock.

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[20] For example, infrastructure and R&D. Argentiero et al. (2018) includes only R&D as input. However, looking at the financial reports of these firms, it is clear that their expenses are more on owning various equipment and improving infrastructure

The government finances this sector in proportion to the cost incurred in purchasing green energy resources in the form of a subsidy (f).

Assumption 3. *The government exempts the Green Electricity Sector from any tax.*

This assumption highlights the incentive given to promote the production of green electricity and also to keep the production process cheaper.

3.5 Green Capital Producer

This sector comprises of atomistic, perfectly competitive capital producer. It is incorporated to derive the equation of the market price of green capital demanded by the green energy sector similar to the capital sector in a traditional DSGE model. The green capital accumulation equation is given by

$$R_t^G = (1-\delta_G)R_{t-1}^G + \left[1 - \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2\right] I_t^G \tag{3.23}$$

where ϕ_G is the investment adjustment cost parameter.

3.6 Government

The government announces the intensity target for the production sector. It procures fossil fuel from the market and sells it to thermal power plants and the production sector at a real price p_t^R. It follows an AR(1) process given by

$$\log(p_t^R) = \rho_o \log(p_{t-1}^R) + \epsilon_{R,t} \tag{3.24}$$

where ρ_o is the autocorrelation coefficient and $\epsilon_{R,t} \sim \mathcal{N}(0, \sigma_o^2)$ is an idiosyncratic shock.

The government provides subsidies/financial aids using tax from thermal power plants, riskless bonds, and revenue from selling fossil fuels. The government budget is given by:

$$\tau^F p_t^R R_t^F + p_t^R R_t^F + B_t = f p_t^G R_t^G + p_t^R R_t^F + (1 + r_{t-1})B_{t-1} + \mathcal{T}_t + G_t \tag{3.25}$$

where R_t^F is the total fossil fuel consumed in the economy given by

$$R_t^F = R_{1,t} + R_{2,t} \tag{3.26}$$

and G_t is the public expenditure that follows an AR(1) process given by

$$\log(G_t) = (1 - \rho_S) log(\bar{G}) + \rho_S \log(G_{t-1}) + \epsilon_{S,t} \tag{3.27}$$

where ρ_S is the autocorrelation coefficient and $\epsilon_{S,t} \sim \mathcal{N}(0, \sigma_S^2)$ is an idiosyncratic shock.

3.7 Market Equilibrium and Emissions

The resource constraint of the economy is given by

$$Y_t = C_t + I_t^G + I_t^Y + \varrho C E_t + \frac{\phi_C}{2}\left(\frac{I_t^Y}{I_{t-1}^Y} - 1\right)^2 I_t^Y + \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2 I_t^G + G_t \tag{3.28}$$

where part of the output goes into the capital adjustment cost and purchase of certificates by the target non-achieving firms. The total investment(I_t) is given by

$$I_t = I_t^Y + I_t^G \tag{3.29}$$

The bonds market, the secondary carbon market and the fossil fuel markets clear. Hence, eq (3.25) reduces to

$$\tau^F p_t^R R_t^F = f p_t^G R_t^G + G_t + \mathcal{T}_t \tag{3.30}$$

4 Parameterization

We set the baseline parameterization of the model in two steps. The first set of parameters is drawn from the literature or estimated using time series data. A second set is calibrated using Bayesian estimation.

4.1 Data Description

The model is estimated using Indian data from 2004Q4 to 2023Q4. This period is selected based on data availability of various observed variables. The macroeconomic time series on output, consumption, investment, and government expenditure at constant prices are from the *Reserve Bank of India - Database on Indian Economy (RBI-DBIE)*. The data is converted to base year 2011-12 using a linking factor. We proxy the government short-term bond rate with weekly weighted average of yield of auctions of 91-day Government of India Treasury Bills. The data comes from the *RBI-DBIE* and covers 6 October 2016 to 25 June 2025. Following Banerjee et al. (2020), we consider the data after the inflation targeting regime[21].

The monthly data on thermal, nuclear, and renewable electricity generation are compiled from the *Executive Summary of Monthly Archive Reports, Central Electricity Authority, New Delhi*. We take the sum of nuclear and renewable electricity to estimate green electricity. The data on the production of fossil fuels are from *`https://robbieandrew.github.io/india/`* and the missing data on coal are filled using *Indiastat*. The time series on fossil fuel prices and electricity are from the wholesale price index of the *Office of the Economic Adviser* on a monthly frequency. The share of global CO2 emissions comes from *Our World in Data*.

The monthly price data are averaged. Data on energy generation and fossil fuels at a monthly frequency are aggregated to produce quarterly series. To remove seasonality,

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[21] India adopted an inflation target regime in 2016 and held its first MPC meeting on 4 October 2016 (Pandey et al., 2025).

x13 in EViews 13 is used, followed by first differencing to detrend the data. We check for stationarity using Augmented Dickey-Fuller test and Phillips-Perron test.

4.2 Calibration

Table 1 reports the calibrated parameters for the baseline model. The time unit is in quarters. As a standard practice, we calibrate the model so as to match some features of the observed data.

The annualized steady state value of the government bond rate is set to $r = 5.564\%$, giving $\beta = 0.9861$. The labor disutility parameter μ_L is set to 6.7, in order to get the steady state of labor $L = \frac{1}{3}$. Following Carattini et al. (2023), the inverse of Frisch elasticity of labor supply, $\eta = 1$.

Reserve Bank of India (2023) predicts a damage $(1 - \Lambda) \in (3\%, 10\%)$ due to climate change when there is no policy intervention. This range is the estimated annual loss in GDP of India by 2100 due to climate change in the absence of mitigation policies. In line with this range, we choose the share of labor in production, $\alpha = 0.45$ and the share of capital in production, $\gamma = 0.43$. Our choice of parameters leads to a damage of 6.5% in the baseline no-policy scenario. Furthermore, the consumption-to-output ratio $C/Y = 0.59$ and the investment-to-output ratio $I/Y = 0.27$ predicted by model are closer to the data[22]. The capital depreciation factor is set to $\delta_K = 0.025$. The investment adjustment cost $\phi_C = 2$ is taken from Banerjee et al. (2020).

In line with India's share of emissions, we set $e = 0.06$. The emission intensity constant $\varphi = 0.22$. This value is in line with India's annual average emission intensity from 2005 to 2023, $Z/Y = 0.2$. We set taxes on fossil fuels $\tau^F = 0.18$[23]. The average share of thermal power in total electricity generation (ω_2) is 80%. The share of fossil fuels

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[22] The ratio based on data are $C/Y = 0.56$ and $I/Y = 0.32$.

[23] While coal falls under the 5% bracket of GST, some petroleum products fall under 18% bracket. For simplicity, we have set this tax equal to the highest GST possible on goods.

in the total use of energy by industries, $\omega_1 = 0.4$, comes from *India Energy Statistics Report 2025*. The damage function parameters $\eta_0 = 1.395e-3$, $\eta_1 = -6.6722e-6$, $\eta_2 = 1.4647e-8$, pollution decay, $\delta_M = 0.0021$, abatement cost parameters $\phi_1 = 0.185$ and $\phi_2 = 2.8$ are calibrated from Annicchiarico and Di Dio (2015).

Moving to the environmental policy regimes, the Government of India has targeted a 45% reduction in the emission intensity by 2030 compared to the 2005 level. Reports suggest that India can achieve a reduction between 48-57%[24]. India's emission intensity in 2005 was 0.223. We set the target emission intensity $\nu = 0.09$, which corresponds to a 60% reduction in emission intensity from the 2005 level. We set the persistence parameter for the target shock $\rho_\theta = 0.95$, the standard value of persistence. In line with Annicchiarico and Di Dio (2015), we set the carbon tax equal to the equilibrium price of a carbon certificate in the CCTS regime, i.e., $pc = 1.11$.

4.3 Bayesian Estimation

To implement the Bayesian estimation for the unknown set of parameters, we use historical data for a set of observables and prior distributions of the parameters. We consider historical data series of thermal power generated (E^F), electricity price (p^E), fossil fuel in the economy (R^F), investment ($invest$), and output (Y)[25]. The data series are made stationary by taking the first differences. Following the literature, we propose priors and their distributions that would fit the Indian data. We select higher standard deviations to allow the data to determine the location of relevant parameters.

Table 2 lists the prior and posterior means, prior distributions, and posterior means with 90% confidence intervals subject to posterior standard deviations. Our estimation result suggests that all the parameters are well identified[26].

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[24] https://www.ceew.in/press-releases/india-on-track-to-exceed-2030-ndc-target-on-carbon-emissions-reduction *Accessed on 13-08-2025.*

[25] Since we have 5 shocks in the baseline model, we can only use 5 data series. To choose the combination of data, we run simulations and compare volatilities and cross-correlations. If two models have similar moments, we choose the combination with a higher log data density

[26] We employ identification method of dynare to check the validity of parameters. We find that parameters are well identified.

Parameters	Description	Value
RBC parameters		
β	Discount Factor	0.9861
μ_L	Labor disutility parameter	6.7
η	Inverse of Frisch elasticity	1
α	Labor share in goods production function	0.45
γ	Capital share in goods production function	0.43
δ_K	Capital depreciation rate	0.025
ϕ_C	Investment Adjustment cost	2
Environmental parameters		
τ^F	Aggregate taxes on fossil fuel	0.18
e	Share of India's pollution	0.06
φ	Emission intensity constant	0.22
ω_1	Weight on Electricity in Energy mix	0.4
ω_2	Weight on Thermal Power in Electricity mix	0.8
ϕ_1	Abatement cost function coefficient	0.185
ϕ_2	Abatement cost function coefficient	2.8
δ_M	Pollution Stock depreciation factor	0.0021
η_0	Parameter of damage function	$1.395e^{-3}$
η_1	Parameter of damage function	$-6.6722e^{-6}$
η_2	Parameter of damage function	$1.4647e^{-8}$
f	Subsidy on purchase of green resources	0
Environmental policy specific parameters		
ν	Target in CCTS policy	0.09
ρ_θ	Persistence parameter of target shock	0.95
pc	Carbon tax	1.11

Table 1: Calibrated parameters for models

Estimated Parameters	Priors		Posteriors	
	Mean	Distribution	Mean	90% CI
ε_1	0.50	Normal	0.52	[0.415, 0.618]
ε_2	0.50	Normal	0.74	[0.622, 0.859]
δ_G	0.025	Beta	0.024	[0.016, 0.032]
ϕ_G	2.00	Gamma	1.52	[0.0796, 2.9516]
ρ_A	0.80	Beta	0.82	[0.714, 0.923]
ρ_{AF}	0.80	Beta	0.3	[0.168, 0.424]
ρ_{AG}	0.80	Beta	0.31	[0.178, 0.442]
ρ_O	0.80	Beta	0.32	[0.183, 0.455]
ρ_G	0.80	Beta	0.34	[0.156, 0.526]
ϵ_Y	0.01	Inv Gamma	0.043	[0.037, 0.049]
ϵ_{AG}	0.01	Inv Gamma	0.061	[0.052, 0.07]
ϵ_{AF}	0.01	Inv Gamma	0.019	[0.016, 0.022]
ϵ_O	0.01	Inv Gamma	0.017	[0.014, 0.02]
ϵ_G	0.01	Inv Gamma	0.406	[0.345, 0.468]

Table 2: Prior densities and posterior estimated of the baseline model

Target	**Data**	**Model**	**Correlations**	**Data**	**Model**
$\frac{\sigma_C}{\sigma_Y}$	1.08	1.26	$(C,\ Y)$	0.86	0.45
$\frac{\sigma_I}{\sigma_Y}$	2.01	1.9	$(I,\ Y)$	0.91	0.76
$\frac{\sigma_{R^F}}{\sigma_Y}$	1.1	0.9	$(R^F,\ Y)$	0.71	0.96
$\frac{\sigma_{E^F}}{\sigma_Y}$	1.11	0.96	$(E^F,\ Y)$	0.71	0.94
$\frac{\sigma_{E^F}}{\sigma_{R^F}}$	1.02	1.07	$(E^F,\ R^F)$	0.75	0.97
$\frac{\sigma_{p^E}}{\sigma_{E^F}}$	0.49	0.52	$(p^R,\ p^E)$	0.27	0.42

Table 3: Comparing moments between data and model

4.4 Model Validation

Table 3 presents the comparison between moments generated by the data and their data counterparts. Moment matching is done to examine the reliability of the baseline model. We compare consumption-to-output ratio, investment-to-output ratio, and volatilities for a set of variables and key cross-correlations. It is noticeable that moment predictions of our model are closer to those of the data.

5 Results and Discussion

We first compare three policies, a baseline or no policy, a carbon tax and a CCTS, in equilibrium, followed by an analysis of their impulse responses. Next, we introduce a subsidy on green capital purchase to analyze the impact of the subsidy on macroeconomic dynamics. To verify the validity of our results, we perform sensitivity analysis that includes different weights on green electricity in the electricity mix and the elasticity of substitution between green electricity and thermal power in the electricity mix.

5.1 Deterministic Steady States

Given the parameterization, Table 4 presents the steady states of variables for three policy scenarios. To compare CCTS and carbon tax policies, we maintain the basic framework of environmentally aware producers in both policies. Similar to Annicchiarico and Di Dio (2015) and Xiao et al. (2018), we set the carbon tax equal to the steady state value of the certificate price in CCTS.

While existing literature often yields identical steady states by treating taxes and caps as interchangeable proxies and passive mathematical mirrors, our framework establishes a structural distinction between the carbon tax and CCTS regimes. Consequently, the steady-state outcomes diverge, leading to unique long-run equilibrium values inherent to each specific regulatory instrument.

Environmental policies that price emissions raise the cost of production (Annicchiarico and Di Dio, 2015). As emissions are proportional to output, firms find it optimal to reduce output and increase their green efforts, i.e., abatement efforts and the adoption of green electricity. Hence, consumption, investment, and emissions reduce. The adoption of green electricity raises green investment while the reduction in emissions reduces damage due to environmental externalities.

Variables	**Description**	**Baseline**	**Carbon tax**	**CCTS**
Y	Output	1.657	1.467	1.606
C	Consumption	0.986	0.903	0.941
Z	Emissions	0.332	0.153	0.144
E	Fossil fuel share	0.911	0.634	0.531
E^G	Green electricity	0.015	0.08	0.082
I^G	Green Investment	0.0004	0.0019	0.002
I^K	Investment	0.456	0.351	0.437
$1 - \Lambda$	Damage on output	8.56%	1.48%	1.31%
U	Abatement Effort	-	0.507	0.459
CA/Y	Abatement cost per unit output	-	0.014	0.01
V	Profit in ICM	-	-	0.007

Table 4: Long-term steady state values

CCTS monetizes emission intensity reduction through free allocation and certificate trading. Thus, it creates an incentive mechanism that reduces the regulation costs borne by firms. As a result, output contracts 8.4% less from baseline level under the CCTS regime than under carbon tax regime, while achieving higher contractions in emissions and fossil fuel share by 2.71% and 11.3% from baseline level, respectively. Since the adoption of green electricity expands 2.5% more in the presence of incentives[27], firms need to take less abatement. Hence, abatement contracts by 9.47%. Our steady state results show that CCTS is more efficient in advancing economy on the transition path while mitigating the adverse impact of environmental policies on macroeconomic variables than a carbon tax.

Note that we report a higher reduction in output (3.1% - 11.5%) and consumption (4.6% - 8.4%) than in the literature (see Fischer and Springborn (2011), Annicchiarico and Di Dio (2015), and Xiao et al. (2018)). These values show that transitions are more costly for India than for other countries such as the United States and China.

We also provide sensitivity analysis by varying two critical structural parameters: (i) the elasticity of substitution between thermal power and green electricity, which de-

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[27] This value corresponds to comparison between CCTS and carbon tax only.

termines how easily firms can decarbonize, and (ii) the weight on green electricity in preferences, which captures households' valuation of clean energy.

Table G.1 provides the results for long run steady states under different values elasticity of substitution between thermal power and green electricity, ε_2. As it increases, thermal power becomes more easily replaceable by green electricity, causing the fossil fuel share to decline and green electricity to rise in the economy. This reduced dependence on abatement to meet emissions targets decreases the demand for certificates, reflected in lower certificate prices. Since cost of green efforts fall, producers redirect resources toward other productive inputs, increasing overall output. The findings suggest that the government should prioritize investments in green electricity research and development that improve substitutability. This will help achieve the desired outcome more effectively by lowering the CCTS compliance costs.

Table G.2 provides the results for long run steady states under different values of weights on green electricity. As expected, increasing the weight of green electricity consumption has a positive impact on macroeconomic variables such as production and investment. It also encourages the use of green electricity and discourages thermal power. This leads to a decrease in the fossil fuel share in the economy. Since there is a greater reliance on green electricity for higher weights, firms find it optimal to reduce their abatement efforts. Furthermore, green electricity is more accessible in the economy, certificate trading is also reduced, and thus V reduces.

5.2 Subsidy

So far, we have worked with a zero subsidy. This section examines the potential of subsidies to improve the effectiveness of CCTS. For alternative parameterization, we set the subsidy $f = \{0.18,\ 0.5\}$. The 18% subsidy corresponds to the existing fossil fuel tax while the 50% subsidy corresponds to certain schemes of the government on installation of renewable energy capital.

Table F.1 presents the steady state values of selected variables under different subsidies. The subsidy results in higher output, driven by the increase in green electricity production. For example, the introduction of a 50% subsidy increases output by 5.6% and raises emissions by 7.1%, while reducing the fossil fuel share by 5.7% relative to the no-subsidy benchmark. Green investment also increases as a result. The dependence on abatement decreases as the subsidy increases.

Our results are in line with Boehl and Budianto (2025), Priftis and Schoenle (2025), and Airaudo et al. (2023)). The subsidy reduces green electricity prices, inducing the adoption of green electricity in the long run. This reduces the reliance on abatement efforts. Furthermore, by Prop. 1, fossil energy sources increase, but their energy share decreases. Hence, output increases with subsidy. Thus, a subsidy on green resource prices acts as a supply effect and reduces the strictness of the target. As the target is easier to achieve, demand for certificates decreases, leading to a decline in their prices.

5.3 Impulse Response Functions

In this subsection, we analyze the macroeconomic dynamics of three policy scenarios in the short run in the presence of four temporary shocks: (i) technology shock in the production sector, (ii) technology shock in the green electricity sector, (iii) fossil fuel price shock, and (iv) target shock. The first two technology shocks act as supply shocks since a positive shock increases the production. The other two are demand shocks as a positive fossil fuel price shock reduces the demand of fossil fuel in the economy and a negative target shock, i.e., reducing emission target increases the demand for green electricity. The target shock appears only for the CCTS policy. We also show how a green capital purchase subsidy affects the dynamics. All results are reported as percentage deviations from the initial steady state over a 20-quarter period.

5.3.1 Technology shock in the production sector

Fig. 2 presents impulse response functions for a positive technology shock in the production sector under the three different environmental policy regimes. Our main finding is that the CCTS generates more green electricity, green investment and abatement efforts, and less fossil fuel use than the carbon tax regime.

The general pattern of responses is consistent across all three regimes. A positive technology shock increases output, capital, investment, and consumption. Since the beneficial effects of shocks are temporary, households accumulate capital during the initial adjustment phase, generating the characteristic hump-shaped response. The turning point in capital occurs when the depreciation rate become higher than the increment in investment. Our results corroborate the findings of Annicchiarico and Di Dio (2015), Xiao et al. (2018), and Economides and Xepapadeas (2025).

The increase in output stimulates the demand for energy. It leads to an increase in emissions and green electricity prices. Hence, green investment becomes lucrative and it increases. Green electricity and green investment follow a hump-shaped path. The turning point occurs when the initial scarcity diminishes. As demand pressure lowers, the prices of green electricity decrease. The delay in the fall of green investment is due to the presence of adjustment frictions in capital formation. Such a structure generates slower but persistent investment activity, with a peak occurring later than prices.

The critical difference across regimes emerges in the mechanism through which firms finance abatement activities. Under the CCTS regime, rising emissions increases the demand for certificates, leading to an increase in certificate prices. Hence, selling certificates increases the revenue of target-achieving producers. This is the incentive mechanism of the CCTS. Firms may use this "increased" revenue to finance their abatement efforts. By contrast, such an incentive channel is missing under the carbon tax regime and it operates purely through penalties on emissions. Producers must simultaneously pay emission taxes and bear abatement costs, reducing available funds for both input use and abatement efforts under the carbon tax regime compared to the CCTS regime.

In addition, producers find it optimal to increase the demand for fossil fuels in the carbon tax regime for two reasons. First, because of the lower weight on green electricity in the electricity mix, producers cannot fully phase out thermal power, making it a necessary input. Second, profits from increased production as a result of increased input use may be used to pay for carbon taxes, effectively smoothing the financial burden of environmental compliance and, therefore, the profit of firms.

Furthermore, Fig. F.1 in the Appendix presents results for a positive technology shock in the presence of different levels of subsidy under the CCTS regime. For comparison purposes, we take three different cases: no subsidy ($f = 0$), low subsidy ($f = 0.18$), and high subsidy ($f = 0.5$). A subsidy reduces the cost of green resources leading to an increase in the green electricity production. Since green electricity is an input in the production function, it amplifies the effects of the production technology shock.

5.3.2 Technology shock in the green electricity production sector

Fig. 3 presents impulse responses to a positive technology shock in the green electricity production sector, revealing clear policy-dependent asymmetric responses of the variables under the different regimes. More specifically, technological advancement increases green electricity production. This allows firms to comply with the mandated target by increasing green electricity adoption. Thus, it reduces the abatement efforts taken by firms by weakening the incentive mechanism under the CCTS and tax burdens in the carbon tax regime.

Due to a positive technology shock in the green electricity sector, the supply of green electricity increases and its price reduces. With the adoption of cheaper green electricity, the dependence on abatement decreases under both the carbon tax and CCTS regimes.

However, under the CCTS regime, it is much easier for firms to comply with the target given higher green electricity usage. Hence, the demand for certificates decreases, leading to a decrease in their price and therefore the green profit. As the incentive mechanism weakens under the CCTS regime, the marginal benefit of abatement falls, and firms optimally reduce abatement efforts more sharply under CCTS than under the carbon tax. Moreover, due to increased utilization of all inputs, firms are able to increase output more than in the carbon tax regime while remaining compliant. Therefore, consistent with Proposition 1, thermal power and fossil fuel initially increase, leading to a short term increase in emissions. By contrast, emissions remain costly under the carbon tax regime, encouraging the use of green electricity. However, since there is no incentive to increase the use of thermal energy and fossil fuels, it leads to a decrease in emissions.

5.3.3 Fossil fuel price shock

Fig. 4 presents results for a negative fossil fuel price shock. This section presents a novel finding: CCTS acts as an automatic macroeconomic stabilizer against fossil fuel price shocks, a property not previously identified for emission trading systems and particularly valuable for energy-importing economies like India.

The results stem from the interaction between a market-driven substitution effect and a policy-driven incentive effect. Following a negative fossil fuel price shock, there is a tendency to substitute toward fossil fuels. However, the CCTS certificate market responds instantaneously by raising the certificate prices, since any attempt to increase fossil fuel usage raises emissions, immediately increasing certificate demand. This financial countershock is sufficient to contain the rise in fossil fuel consumption, thermal power generation, and total emissions to quantitatively negligible levels (of 10^{-5} order). Thus, the CCTS policy acts as an immediate deterrent, preventing significant environmental damage.

The high certificate prices make green electricity valuable. The price of green electricity increases sharply, moving closely with the certificate price, as its value becomes tied to the high-priced certificates it helps generate. Although there is an increase in green investment, actual green electricity production increases only slightly due to investment adjustment costs. The abatement effort increases modestly because the emissions surge never occurred as the certificate mechanism prevented environmental damage before it could occur.

Finally, the CCTS decouples economic activity from environmental harm and dampens the macroeconomic impact of the shock. Although cheaper energy provides a modest boost on the supply side, the resulting gains in output and consumption are negligible. The policy thus acts as a stabilizer, containing volatility in both environmental and real variables by absorbing the shock primarily through financial adjustments (changes in certificate price) rather than quantity adjustments (actual energy use changes).

In contrast, under a carbon tax regime, the stabilization mechanism does not exist. The price burden due to tax is mitigated by increasing revenue through higher production using the cheaper fossil fuels. Therefore, the usage of thermal power also increases, and producers have no incentive to increase green electricity. Hence, emissions increase. This demonstrates one of the limitations of the carbon tax regime, it sets a fixed price on emissions but cannot dynamically adjust to external shocks.

Our finding that CCTS acts as a stabilizer and nearly insulates the macroeconomy from fossil fuel price shocks contrasts sharply with empirical estimates for economies without emission trading. For instance, Chafwehé et al. (2025) report a 0.6% decline in output in the presence of a 20% rise in prices. Coenen et al. (2024) report a higher decrease of 1.1% when prices rise by 20%. Känzig (2021) reports that a 10% increase in real oil price leads to a 1% decrease in US industrial production, while Peersman and Van Robays (2012) reports a decrease of 0.3% in the Euro Area. Our results under carbon tax and no-policy regimes are in line with the aforementioned literature[28].

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[28] Note that, we focus on negative fossil fuel price shock, unlike the literature that emphasizes positive shocks.

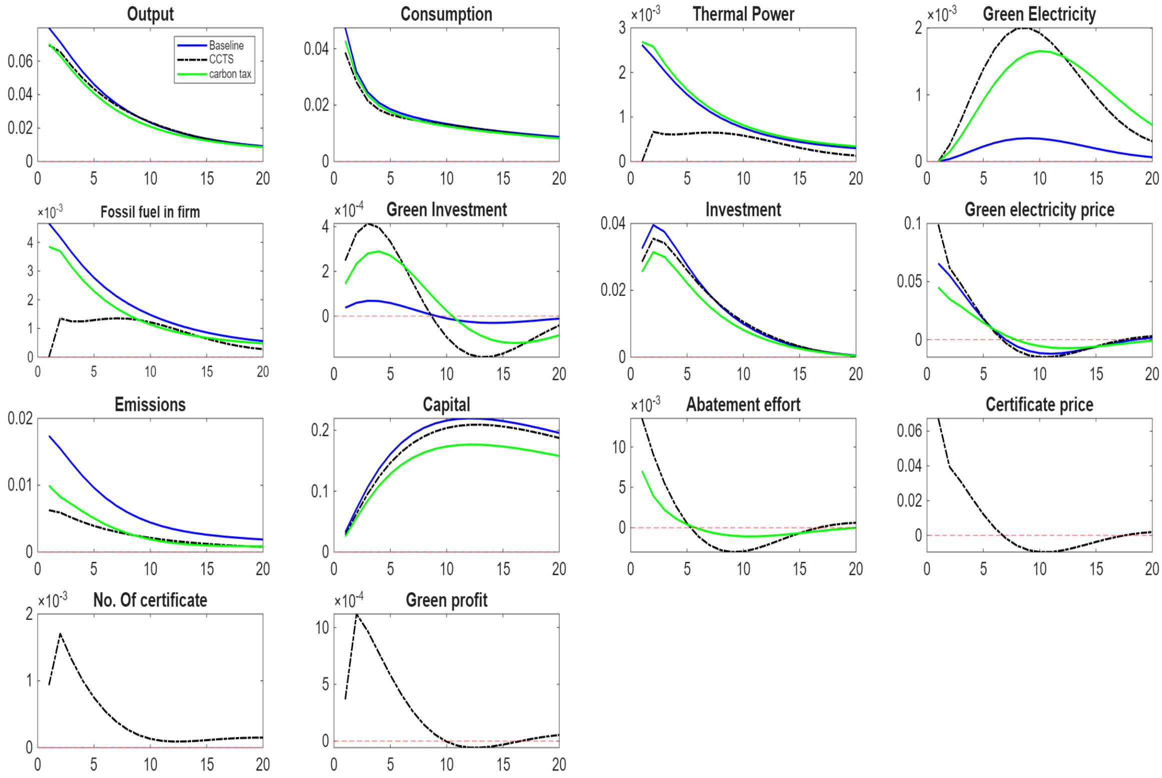

Figure 2: Positive technology shock in production sector

5.3.4 Target shock

Fig. 5 presents results for a 1% tightening of the emission intensity target under the CCTS regime. This analysis addresses a critical policy design question: How much does accelerating the green transition through stricter targets cost in terms of short-run economic performance?

A stricter target implies that the emissions must decline to maintain compliance at the existing output levels. Firms respond through three channels as captured by the IRFs: (i) green electricity substitution, (ii) undertaking higher abatement efforts, and (iii) decreasing the demand for fossil fuels. The tighter target raises the certificate demand and

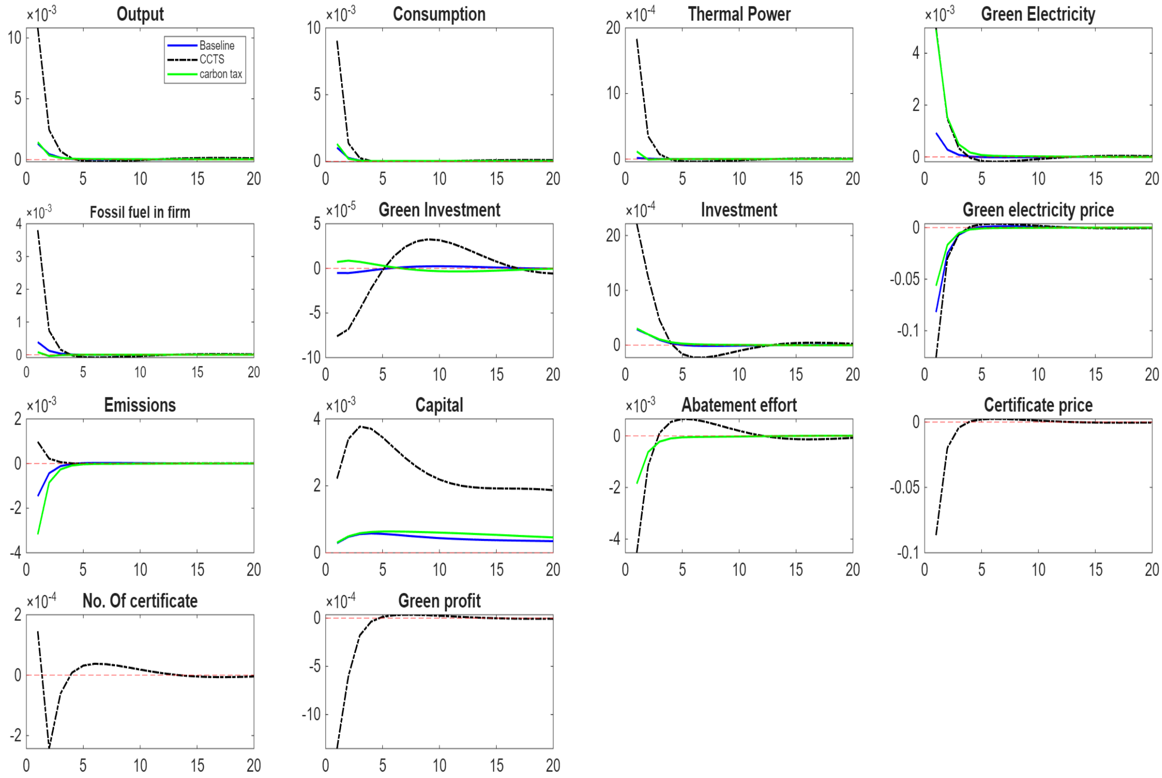

Figure 3: Positive technology shock in green electricity sector

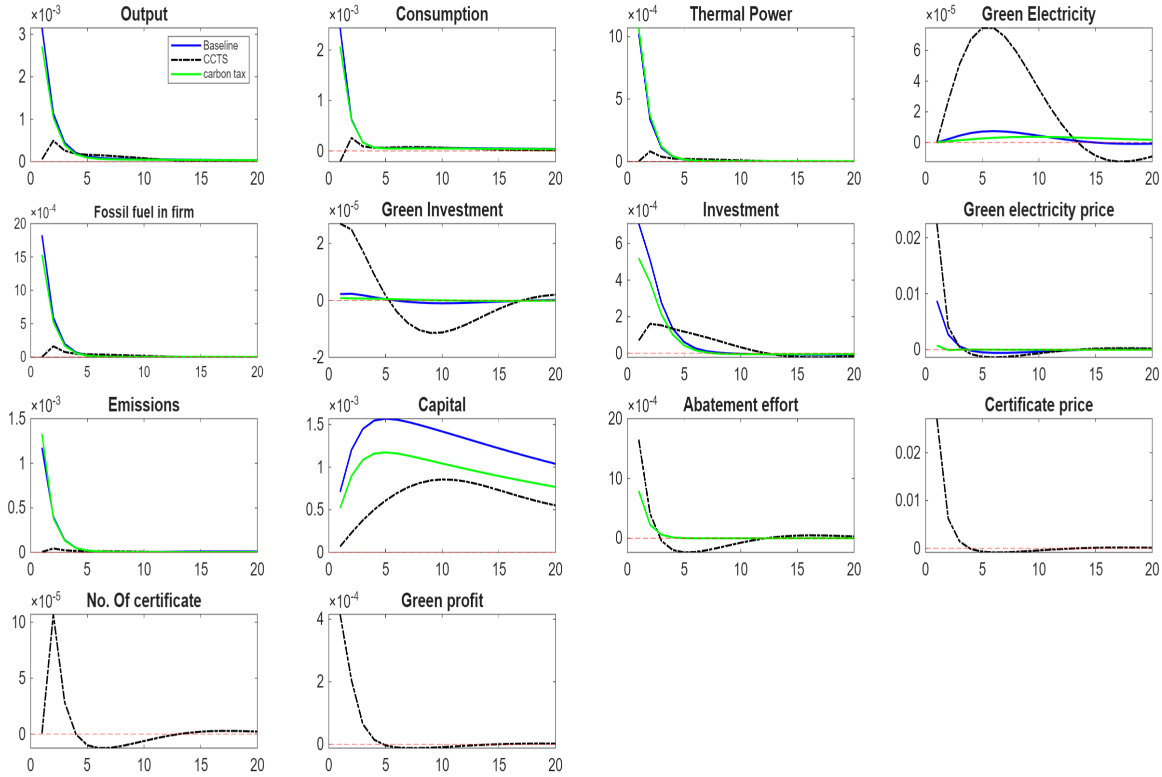

Figure 4: Negative fossil fuel price shock

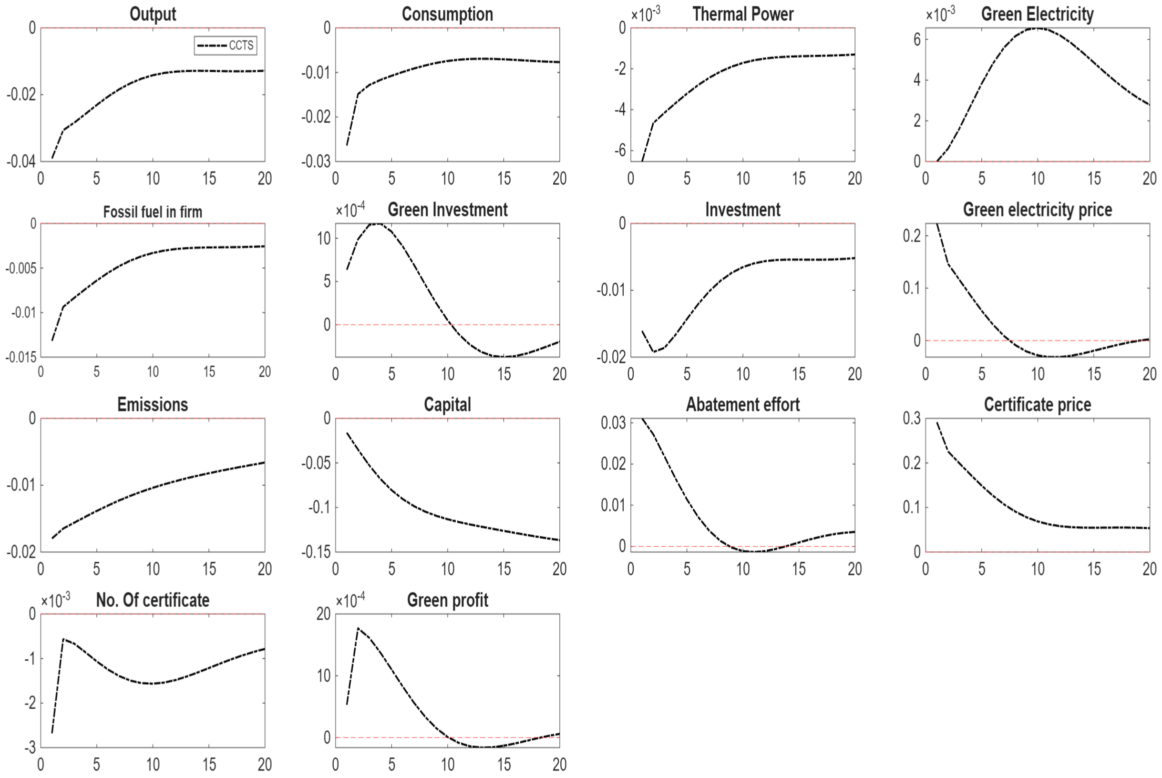

Figure 5: One unit of negative target shock

green electricity. Hence, the prices of green electricity and certificates increase. While it becomes lucrative to trade as green profit increases, it is difficult to earn a certificate with the stricter targets. Hence, aggregate certificate issuance falls.

A stricter intensity target increases the production costs of firms (i) as firms are now substituting for more expensive green electricity and (ii) diverting resources from production to abatement efforts. Due to the increase in the marginal cost of production, firms reduce output and therefore consumption and investment. According to the model's prediction, a 1% tightening of the emission intensity target can lead to a 4% decline in output and emission reduction by 2%.

Furthermore, Fig. F.2 in the Appendix presents results for a negative target shock in the presence of different levels of subsidy. For comparison purposes, we take three different cases: no subsidy ($f = 0$), low subsidy ($f = 0.18$), and high subsidy ($f = 0.5$). A stricter environmental target increases green electricity demand and a subsidy increases its supply. The resulting surge in green electricity demand offsets the decline in aggregate production as seen earlier.

6 Conclusion

We examine the macroeconomic dynamics of adopting an emission trading scheme based on intensity targets with a free allocation of certificates and a secondary carbon market. We employ an E-DSGE model that features a production sector that chooses between thermal power, green electricity, and fossil fuel as energy input for production and a government that announces an intensity target and provides subsidies for green capital purchases. To the best of our knowledge, we are one of the first to include a secondary carbon market where firms trade certificates in an E-DSGE framework.

Our finding highlights the positive impact of environmental policy on transition and emission reductions. In contrast to the literature, we find that a rate-based CCTS policy outperforms a price-based carbon tax policy in terms of sustainable energy transitions and economic growth. We find that phasing out fossil fuels remains a challenge in the short term, and their use may even increase, but a transition can still be achieved through the adoption of more green energy. Furthermore, this policy effectively insulates the economy from shocks driven by the volatility of fossil fuel prices. The transition process can be expedited if the government implements a stricter intensity target. These insights contribute to the broader discourse on the role of market-based environmental policies and national carbon markets in emerging economies, especially countries that are working toward a national carbon market.

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A Baseline model

The baseline model does not have any climate policy. Hence, producers do not have any incentive to take abatement efforts or any steps to reduce emissions.

Household Problem

We follow Sims (2024) to model and solve the household problem. The Lagrangian for the household maximization problem is:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\begin{aligned} &\left(\ln C_t - \mu_L \frac{L_t^{1+\eta}}{1+\eta} \right) + \lambda_{1,t} \left(w_t L_t + r_{k,t} K_t + (1+r_{t-1}) B_{t-1} + \Pi_t + \mathcal{T}_t - C_t - B_t - I_t \right) \\ &\qquad + \lambda_{2,t} \left(\left[1 - \frac{\phi_c}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] I_t + (1-\delta_k) K_t - K_{t+1} \right) \end{aligned} \right]$$

where $\lambda_{1,t}$ and $\lambda_{2,t}$ are the lagrange multipliers.

The FOCs for the household are:

$$\mu_L L_t^{\eta} = \frac{1}{C_t} w_t \tag{A.1}$$

$$\beta(1+r_t) = \frac{C_{t+1}}{C_t} \tag{A.2}$$

$$r_{k,t+1} = \frac{q_t}{\beta} \left(\frac{C_{t+1}}{C_t} \right) - (1-\delta_k) q_{t+1} \tag{A.3}$$

$$q_t \left(1 - \frac{\phi_c}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 - \phi_c \left(\frac{I_t}{I_{t-1}} - 1 \right) \frac{I_t}{I_{t-1}} \right) + \beta \frac{C_t}{C_{t+1}} q_{t+1} \phi_c \left(\frac{I_{t+1}}{I_t} - 1 \right) \left(\frac{I_{t+1}}{I_t} \right)^2 = 1 \tag{A.4}$$

where $\lambda_{1,t} = \frac{1}{C_t}$ and $q_t = \frac{\lambda_{2,t}}{\lambda_{1,t}}$.

Producers

The firms' problem is

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Omega_{0,t} \left[\begin{aligned} &Y_t - \left(w_t L_t + p_{F,t} E_t^F + p_{G,t} E_t^G + (1+\tau^F) p_t^R R_{1,t} + r_{k,t} K_t \right) \\ &\qquad + MC_t \left(A_t^Y (\Lambda_t L_t)^{\alpha} K_t^{\gamma} J_t^{1-\alpha-\gamma} - Y_t \right) \end{aligned} \right]$$

The FOCs are:

$$\alpha \frac{Y_t}{L_t} MC_t = w_t \tag{A.5}$$

$$\gamma \frac{Y_t}{K_t} MC_t = r_{k,t} \tag{A.6}$$

$$p^E_{F,t} = (1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}} \omega_2^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E^F_t}\right)^{\frac{1}{\varepsilon_2}} MC_t \tag{A.7}$$

$$p^E_{G,t} = (1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}} (1-\omega_2)^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E^G_t}\right)^{\frac{1}{\varepsilon_2}} MC_t \tag{A.8}$$

$$p^R_t(1+\tau^F) = (1-\alpha-\gamma)(1-\omega_1)^{\frac{1}{\varepsilon_1}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{R_{1,t}}\right)^{\frac{1}{\varepsilon_1}} MC_t \tag{A.9}$$

Thermal Power Plant

Thermal power plant solves the following static problem:

$$p^E_{F,t} E^F_t - (1+\tau^F) p^R_t R_{2,t} + \lambda_{3,t} \left(A^F_t R_{2,t} - E^F_t\right)$$

where $\lambda_{3,t}$ is the marginal cost of the thermal power plant.

The FOCs are:

$$(1+\tau^F)\lambda_{3,t} \frac{E^F_t}{R_{2,t}} = p^R_t \tag{A.10}$$

$$\lambda_{3,t} = p^E_{F,t} \tag{A.11}$$

Green Electricity Sector

The Green Electricity Sector solves the following static problem:

$$p^E_{G,t} E^G_t - p^G_t R^G_t + \lambda_{4,t} \left(A^G_t R^G_t - E^G_t\right)$$

where $\lambda_{4,t}$ is the marginal cost for the green electricity sector.

The FOCs are

$$\lambda_{4,t}\frac{E_t^G}{R_t^G} = p_t^G \tag{A.12}$$

$$\lambda_{4,t} = p_{G,t}^E \tag{A.13}$$

Green Capital Producer

Define $p_t^G = \frac{P_t^G}{P_t}$ where P_t is the nominal price of the consumption goods in the economy. The capital producer maximizes

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Omega_{0,t}\left[p_t^G(R_t^G - (1-\delta_G)R_{t-1}^G) - I_t^G\right]$$

The FOC is given by

$$p_t^G\left[1 - \frac{\phi_C}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2 - \phi_C\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)\left(\frac{I_t^G}{I_{t-1}^G}\right)\right] + \beta\phi_C\mathbb{E}_t\left\{p_{t+1}^G\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{I_{t+1}^G}{I_t^G}\right)^2\left(\frac{I_{t+1}^G}{I_t^G} - 1\right)\right\} = 1 \tag{A.14}$$

B Baseline Competitive Equilibrium

$$\mu_L L_t^\eta = \frac{1}{C_t}w_t \tag{B.1}$$

$$\beta(1+r_t) = \frac{C_{t+1}}{C_t} \tag{B.2}$$

$$r_{k,t+1} = \frac{q_t}{\beta}\left(\frac{C_{t+1}}{C_t}\right) - (1-\delta_k)q_{t+1} \tag{B.3}$$

$$\begin{aligned} q_t\left(1-\frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2-\phi_c\left(\frac{I_t}{I_{t-1}}-1\right)\frac{I_t}{I_{t-1}}\right) & \\ +\beta\frac{C_t}{C_{t+1}}q_{t+1}\phi_c\left(\frac{I_{t+1}}{I_t}-1\right)\left(\frac{I_{t+1}}{I_t}\right)^2 &= 1 \end{aligned} \tag{B.4}$$

$$K_{t+1}=(1-\delta_k)K_t+\left[1-\frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right]I_t \tag{B.5}$$

$$\Lambda_t=1-(\eta_0+\eta_1 M_t+\eta_2 M_t^2) \tag{B.6}$$

$$M_t=(1-\delta_M)M_{t-1}+\frac{Z_t}{e} \tag{B.7}$$

$$Z_t=\varphi E_t Y_t \tag{B.8}$$

$$E_t=\frac{E_t^F+R_{1,t}}{E_t^F+R_{1,t}+E_t^G} \tag{B.9}$$

$$Y_t=A_t^Y(\Lambda_t L_t)^{\alpha}K_t^{\gamma}J_t^{1-\alpha-\gamma} \tag{B.10}$$

$$J_t=\left[(\omega_1)^{\frac{1}{\varepsilon_1}}El_t^{\frac{\varepsilon_1-1}{\varepsilon_1}}+(1-\omega_1)^{\frac{1}{\varepsilon_1}}R_{1,t}^{\frac{\varepsilon_1-1}{\varepsilon_1}}\right]^{\frac{\varepsilon_1}{\varepsilon_1-1}} \tag{B.11}$$

$$El_t=\left[\omega_2^{\frac{1}{\varepsilon_2}}(E_t^F)^{\frac{\varepsilon_2-1}{\varepsilon_2}}+(1-\omega_2)^{\frac{1}{\varepsilon_2}}(E_t^G)^{\frac{\varepsilon_2-1}{\varepsilon_2}}\right]^{\frac{\varepsilon_2}{\varepsilon_2-1}} \tag{B.12}$$

$$\alpha\frac{Y_t}{L_t}MC_t=w_t \tag{B.13}$$

$$\gamma\frac{Y_t}{K_t}MC_t=r_{k,t} \tag{B.14}$$

$$p_{F,t}^E=(1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}}\omega_2^{\frac{1}{\varepsilon_2}}\left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}}\left(\frac{El_t}{E_t^F}\right)^{\frac{1}{\varepsilon_2}}MC_t \tag{B.15}$$

$$p_{G,t}^E=(1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}}(1-\omega_2)^{\frac{1}{\varepsilon_2}}\left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}}\left(\frac{El_t}{E_t^G}\right)^{\frac{1}{\varepsilon_2}}MC_t \tag{B.16}$$

$$p_t^R(1+\tau^F)=(1-\alpha-\gamma)(1-\omega_1)^{\frac{1}{\varepsilon_1}}\left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{R_{1,t}}\right)^{\frac{1}{\varepsilon_1}}MC_t \tag{B.17}$$

$$MC_t=1 \tag{B.18}$$

$$E_t^F=A_t^F R_{2,t} \tag{B.19}$$

$$p_t^R(1+\tau^F)=p_{F,t}^E A_t^F \tag{B.20}$$

$$E_t^G=A_t^G R_t^G \tag{B.21}$$

$$p_t^G=p_{G,t}^E\frac{E_t^G}{R_t^G} \tag{B.22}$$

$$R_t^G = (1-\delta_G)R_{t-1}^G + \left[1 - \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2\right] I_t^G \tag{B.23}$$

$$\begin{aligned} p_t^G &\left(1 - \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2 - \phi_G\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)\frac{I_t^G}{I_{t-1}^G}\right) \\ &+ \beta\frac{C_t}{C_{t+1}} p_{t+1}^G \phi_G \left(\frac{I_{t+1}^G}{I_t^G} - 1\right)\left(\frac{I_{t+1}^G}{I_t^G}\right)^2 = 1 \end{aligned} \tag{B.24}$$

$$\tau^F p_t^R R_t^F = G_t + \mathcal{T}_t \tag{B.25}$$

$$Y_t = C_t + I_t^G + I_t + \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G} - 1\right)^2 I_t^G + G_t + \frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 I_t \tag{B.26}$$

$$R_t^F = R_{1,t} + R_{2,t} \tag{B.27}$$

$$\log A_t^Y = \rho_Y \log A_{t-1}^Y + \epsilon_{Y,t} \tag{B.28}$$

$$\log A_t^G = \rho_G \log A_{t-1}^G + \epsilon_{G,t} \tag{B.29}$$

$$\log A_t^F = \rho_{AF} \log A_{t-1}^F + \epsilon_{F,t} \tag{B.30}$$

$$\log p_t^R = \rho_o \log p_{t-1}^R + \epsilon_{R,t} \tag{B.31}$$

$$\log G_t = (1-\rho_G)\log \bar{G} \rho_G \log G_{t-1} + \epsilon_{S,t} \tag{B.32}$$

$$E_t^F = \omega_2 \left(\frac{p_{F,t}^E}{p_t^E}\right)^{-\varepsilon_2} El_t \tag{B.33}$$

$$invest_t = I_t + I_t^G \tag{B.34}$$

$$cy_t = \frac{C_t}{Y_t} \tag{B.35}$$

$$iy_t = \frac{invest_t}{Y_t} \tag{B.36}$$

C Carbon Credit Trading Scheme

The households, capital producers, the government and the thermal power plant are the same as Appendix A.

Producer

A representative firm can either be a target achiever or a non-achiever. Let ϱ represent the probability of achieving the target. This is similar to a Calvo pricing structure in which a firm changes the price with a probability. The Lagrangian for profit function is

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Omega_{0,t} \begin{bmatrix} Y_t - (w_t L_t + p_{F,t} E_t^F + p_{G,t} E_t^G + p_t^R R_{1,t} + r_{k,t} K_t) \\ -\varrho \phi_1 U_t^{\phi_2} + p_t^c Y_t (\nu \theta_t - \varphi E_t (1 - \varrho U_{t-1})) \\ +MC_t \left(A_t^Y (\Lambda_t L_t)^\alpha K_t^\gamma J_t^{1-\alpha-\gamma} - Y_t \right) \end{bmatrix}$$

where MC_t is the marginal cost of the firm and $\Omega_{t,t+1}$ is the stochastic discount factor. The FOCs are:

$$\alpha \frac{Y_t}{L_t} MC_t = w_t \tag{C.1}$$

$$\gamma \frac{Y_t}{K_t} MC_t = r_{k,t} \tag{C.2}$$

$$\begin{aligned} p_{F,t}^E = (1-\alpha-\gamma) \omega_1^{\frac{1}{\varepsilon_1}} \omega_2^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E_t^F}\right)^{\frac{1}{\varepsilon_2}} MC_t \\ - p_t^c Y_t (1 - \varrho U_{t-1}) \left(\frac{E_t^G}{(E_t^F + R_{1,t} + E_t^G)^2} \right) \end{aligned} \tag{C.3}$$

$$\begin{aligned} p_{G,t}^E = (1-\alpha-\gamma) \omega_1^{\frac{1}{\varepsilon_1}} (1-\omega_2)^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E_t^G}\right)^{\frac{1}{\varepsilon_2}} MC_t \\ + p_t^c Y_t (1 - \varrho U_{t-1}) \left(\frac{E_t^F + R_{1,t}}{(E_t^F + R_{1,t} + E_t^G)^2} \right) \end{aligned} \tag{C.4}$$

$$\begin{aligned} p_t^R (1 + \tau^F) = (1-\alpha-\gamma)(1-\omega_1)^{\frac{1}{\varepsilon_1}} \left(\frac{Y_t}{J_t}\right) \left(\frac{J_t}{R_{1,t}}\right)^{\frac{1}{\varepsilon_1}} MC_t \\ - p_t^c Y_t (1 - \varrho U_{t-1}) \left(\frac{E_t^G}{(E_t^F + R_{1,t} + E_t^G)^2} \right) \end{aligned} \tag{C.5}$$

$$MC_t = 1 - \varrho\phi_1 U_t^{\phi_2} + p_t^c(\nu\theta_t - \varphi E_t(1 - \varrho U_{t-1})) \tag{C.6}$$

$$\phi_1\phi_2 U_t^{\phi_2 - 1} = \varphi\beta\left(\frac{C_t}{C_{t+1}}\right)\left(\frac{Y_{t+1}}{Y_t}\right)p_{t+1}^c E_{t+1} \tag{C.7}$$

Green Electricity Sector

We include a subsidy f on purchase in the model.

$$p_{G,t}^E E_t^G - (1-f)p_t^G R_t^G + \lambda_{4,t}\left(A_t^G R_t^G - E_t^G\right)$$

where $\lambda_{4,t}$ is the marginal cost for the green electricity sector.

The FOCs are

$$\lambda_{4,t}\frac{E_t^G}{R_t^G} = p_t^G(1-f) \tag{C.8}$$

$$\lambda_{4,t} = p_{G,t}^E \tag{C.9}$$

Government

The government budget is

$$\tau^F p_t^R R_t^F = f p_t^G R_t^G + G_t + \mathcal{T}_t \tag{C.10}$$

D CCTS Competitive Equilibrium

$$\mu_L L_t^\eta = \frac{1}{C_t}w_t \tag{D.1}$$

$$\beta(1+r_t) = \frac{C_{t+1}}{C_t} \tag{D.2}$$

$$r_{k,t+1} = \frac{q_t}{\beta}\left(\frac{C_{t+1}}{C_t}\right) - (1-\delta_k)q_{t+1} \tag{D.3}$$

$$\begin{aligned} q_t \left(1 - \frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2 - \phi_c \left(\frac{I_t}{I_{t-1}} - 1\right)\frac{I_t}{I_{t-1}}\right) \\ + \beta \frac{C_t}{C_{t+1}} q_{t+1}\phi_c \left(\frac{I_{t+1}}{I_t} - 1\right)\left(\frac{I_{t+1}}{I_t}\right)^2 = 1 \end{aligned} \tag{D.4}$$

$$K_{t+1} = (1-\delta_k)K_t + \left[1 - \frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}} - 1\right)^2\right] I_t \tag{D.5}$$

$$\Lambda_t = 1 - (\eta_0 + \eta_1 M_t + \eta_2 M_t^2) \tag{D.6}$$

$$M_t = (1-\delta_M)M_{t-1} + \frac{Z_t}{e} \tag{D.7}$$

$$Z_t = \varphi E_t Y_t \tag{D.8}$$

$$E_t = \frac{E_t^F + R_{1,t}}{E_t^F + R_{1,t} + E_t^G} \tag{D.9}$$

$$Y_t = A_t^Y (\Lambda_t L_t)^{\alpha} K_t^{\gamma} J_t^{1-\alpha-\gamma} \tag{D.10}$$

$$J_t = \left[(\omega_1)^{\frac{1}{\varepsilon_1}} El_t^{\frac{\varepsilon_1 - 1}{\varepsilon_1}} + (1-\omega_1)^{\frac{1}{\varepsilon_1}} R_{1,t}^{\frac{\varepsilon_1 - 1}{\varepsilon_1}}\right]^{\frac{\varepsilon_1}{\varepsilon_1 - 1}} \tag{D.11}$$

$$El_t = \left[\omega_2^{\frac{1}{\varepsilon_2}} (E_t^F)^{\frac{\varepsilon_2 - 1}{\varepsilon_2}} + (1-\omega_2)^{\frac{1}{\varepsilon_2}} (E_t^G)^{\frac{\varepsilon_2 - 1}{\varepsilon_2}}\right]^{\frac{\varepsilon_2}{\varepsilon_2 - 1}} \tag{D.12}$$

$$\alpha \frac{Y_t}{L_t} MC_t = w_t \tag{D.13}$$

$$\gamma \frac{Y_t}{K_t} MC_t = r_{k,t} \tag{D.14}$$

$$\begin{aligned} p_{F,t}^E = (1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}} \omega_2^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E_t^F}\right)^{\frac{1}{\varepsilon_2}} MC_t \\ - p_t^c Y_t (1 - \varrho U_{t-1}) \left(\frac{E_t^G}{(E_t^F + R_{1,t} + E_t^G)^2}\right) \end{aligned} \tag{D.15}$$

$$\begin{aligned} p_{G,t}^E = (1-\alpha-\gamma)\omega_1^{\frac{1}{\varepsilon_1}} (1-\omega_2)^{\frac{1}{\varepsilon_2}} \left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{El_t}\right)^{\frac{1}{\varepsilon_1}} \left(\frac{El_t}{E_t^G}\right)^{\frac{1}{\varepsilon_2}} MC_t \\ + p_t^c Y_t (1 - \varrho U_{t-1}) \left(\frac{E_t^F + R_{1,t}}{(E_t^F + R_{1,t} + E_t^G)^2}\right) \end{aligned} \tag{D.16}$$

$$\begin{aligned} p_t^R(1+\tau^F) = (1-\alpha-\gamma)(1-\omega_1)^{\frac{1}{\varepsilon_1}} \left(\frac{Y_t}{J_t}\right)\left(\frac{J_t}{R_{1,t}}\right)^{\frac{1}{\varepsilon_1}} MC_t \\ - p_t^c Y_t(1-\varrho U_{t-1})\left(\frac{E_t^G}{(E_t^F+R_{1,t}+E_t^G)^2}\right) \end{aligned} \tag{D.17}$$

$$MC_t = 1-\varrho\phi_1 U_t^{\phi_2} \tag{D.18}$$

$$\phi_1\phi_2 U_t^{\phi_2-1} = \beta\varphi p_t^C\left(\frac{C_t}{C_{t+1}}\right)\left(\frac{Y_{t+1}}{Y_t}\right)E_{t+1}C_{t+1} \tag{D.19}$$

$$E_t(1-\varrho U_{t-1}) = \theta_t\frac{\nu}{\phi} \tag{D.20}$$

$$E_t^F = A_t^F R_{2,t} \tag{D.21}$$

$$p_t^R(1+\tau^F) = p_{F,t}^E A_t^F \tag{D.22}$$

$$E_t^G = A_t^G R_t^G \tag{D.23}$$

$$p_t^G = p_{G,t}^E\frac{E_t^G}{R_t^G} \tag{D.24}$$

$$R_t^G = (1-\delta_G)R_{t-1}^G + \left[1-\frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G}-1\right)^2\right]I_t^G \tag{D.25}$$

$$\begin{aligned} p_t^G\left(1-\frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G}-1\right)^2-\phi_G\left(\frac{I_t^G}{I_{t-1}^G}-1\right)\frac{I_t^G}{I_{t-1}^G}\right) \\ +\beta\frac{C_t}{C_{t+1}}p_{t+1}^G\phi_G\left(\frac{I_{t+1}^G}{I_t^G}-1\right)\left(\frac{I_{t+1}^G}{I_t^G}\right)^2 = 1 \end{aligned} \tag{D.26}$$

$$\tau^F p_t^R R_t^F = f p_t^G R_t^G + G_t + \mathcal{T}_t \tag{D.27}$$

$$Y_t = C_t + I_t^G + I_t + \frac{\phi_G}{2}\left(\frac{I_t^G}{I_{t-1}^G}-1\right)^2 I_t^G + G_t + \frac{\phi_c}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2 I_t \tag{D.28}$$

$$R_t^F = R_{1,t}+R_{2,t} \tag{D.29}$$

$$\log A_t^Y = \rho_Y \log A_{t-1}^Y + \epsilon_{Y,t} \tag{D.30}$$

$$\log A_t^G = \rho_G \log A_{t-1}^G + \epsilon_{G,t} \tag{D.31}$$

$$\log A_t^F = \rho_{AF} \log A_{t-1}^F + \epsilon_{F,t} \tag{D.32}$$

$$\log p_t^R = \rho_o \log p_{t-1}^R + \epsilon_{R,t} \tag{D.33}$$

$$\log G_t = (1-\rho_G)\log \bar{G} + \rho_G \log G_{t-1} + \epsilon_{S,t} \tag{D.34}$$

$$E_t^F = \omega_2 \left(\frac{p_{F,t}^E}{p_t^E}\right)^{-\varepsilon_2} El_t \tag{D.35}$$

$$invest_t = I_t + I_t^G \tag{D.36}$$

$$cy_t = \frac{C_t}{Y_t} \tag{D.37}$$

$$iy_t = \frac{invest_t}{Y_t} \tag{D.38}$$

$$n_t = \varrho(\theta_t \nu - (1-U_{t-1})\varphi E_t)Y_t \tag{D.39}$$

$$\mathcal{C}_{A,t} = \varrho\phi_1 U_t^{\phi_2} Y_t \tag{D.40}$$

$$V_t = p_t^C n_t - \mathcal{C}_{A,t} \tag{D.41}$$

E Carbon Tax

The household, electricity production sector and green capital sector remain same as in Section A. The dynamic problem of firms does not have the trading structure and there is a fixed tax on emissions (p^c). The firms' problem is

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \Omega_{0,t} \begin{bmatrix} Y_t - (w_t L_t + p_{F,t} E_t^F + p_{G,t} E_t^G + p_t^R R_{1,t} + r_{k,t} K_t) \\ -\varrho\phi_1 U_t^{\phi_2} - p^c Z_t \\ +MC_t \left(A_t^Y (\Lambda_t L_t)^\alpha K_t^\gamma J_t^{1-\alpha-\gamma} - Y_t\right) \end{bmatrix} \tag{E.1}$$

The tax on emissions is paid to the government. The government budget equation is then

$$\tau^F p_t^R R_t^F + p^c Z_t = f p_t^G R_t^G + \mathcal{T}_t \tag{E.2}$$

F Subsidy

Variables	$f = 0$	$f = 0.18$	$f = 0.5$
Output	1.61	1.63	1.7
Consumption	0.94	0.96	1
Emissions	0.14	0.147	0.15
Fossil fuel share	0.53	0.52	0.5
Green electricity	0.08	0.09	0.12
Green Investment	0.002	0.0022	0.003
Abatement Effort	0.46	0.42	0.34
Certificate price	1.11	0.98	0.71

Table F.1: Long-term steady state of variables under different subsidy values

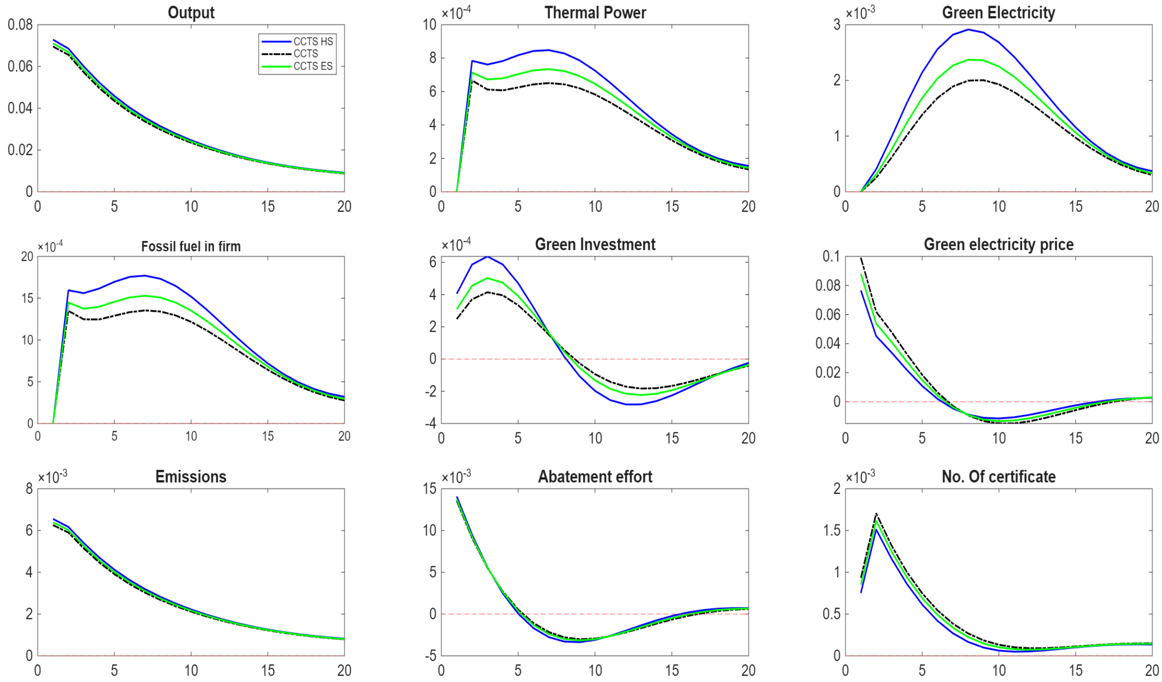

Figure F.1: Positive technology shock in production sector

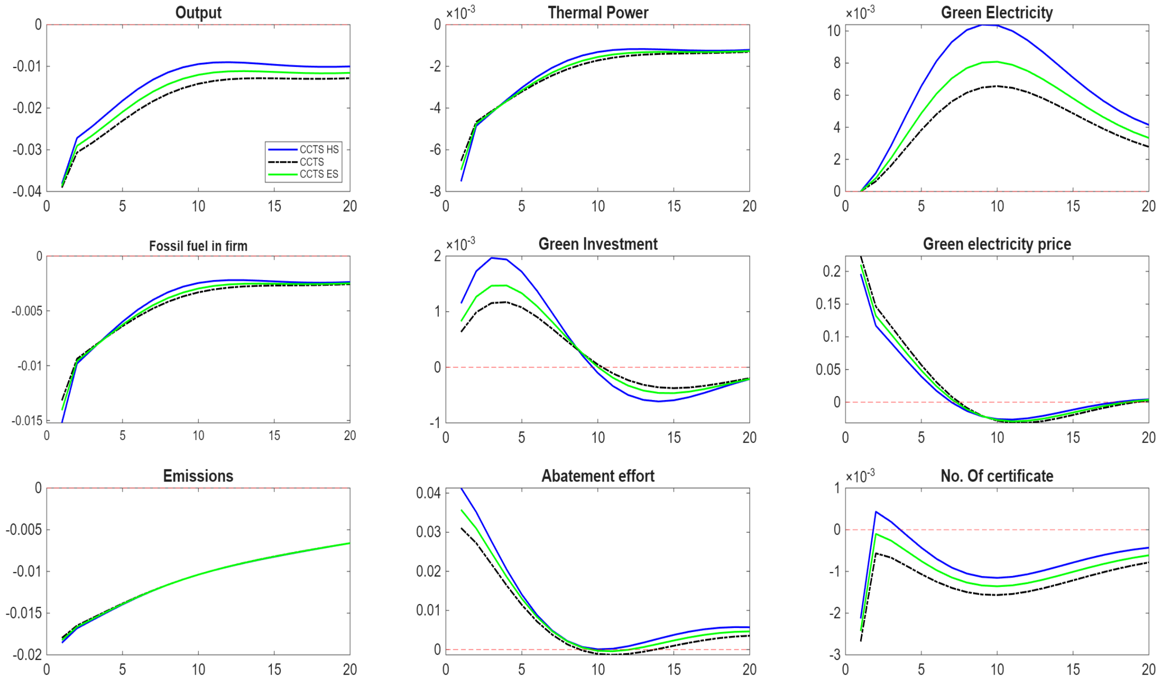

Figure F.2: One unit of negative target shock

G Sensitivity Analysis

Elasticity of substitution between thermal power and green electricity

Variables	$\varepsilon_2 = 0.74$	$\varepsilon_2 = 0.52$	$\varepsilon_2 = 1.5$
Output	1.61	1.6	1.65
Consumption	0.94	0.93	0.97
Emissions	0.14	0.143	0.15
Fossil fuel share	0.53	0.54	0.51
Green electricity	0.08	0.08	0.09
Green Investment	0.002	0.002	0.002
Abatement Effort	0.46	0.48	0.4
Certificate price	1.11	1.18	0.86

Table G.1: Long-term steady state of variables under different ε_2

Weight on green electricity

Variables	$\omega_2 = 0.4$	$\omega_2 = 0.5$	$\omega_2 = 0.6$
Output	1.61	1.7	1.75
Consumption	0.94	1	1.03
Emissions	0.14	0.15	0.16
Fossil fuel share	0.53	0.51	0.5
Green electricity	0.08	0.09	0.1
Green Investment	0.002	0.0022	0.0024
Abatement Effort	0.46	0.4	0.33
Certificate price	1.11	0.9	0.67

Table G.2: Long-term steady state of variables under different ω_2