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Estimating Threshold Level of Carbon Tax on CO_2 Emissions in South Africa Economy

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ABSTRACT

In recent decades, the growing importance of carbon taxes has led researchers to investigate their drivers and effects on economic growth and the environment. This study analyses the relationship between carbon emissions, carbon tax, and economic growth in South Africa, utilizing data from 1993 to 2022 and was collected from World Development Bank, International Energy Agency, and the South African Reserve Bank. Employing a threshold method, the study estimates the carbon tax necessary to reduce CO_2 emissions while stimulating growth. The analysis indicates that carbon tax serves as a regime switch, with a bootstrap value of 0.019, which is below the 0.05 threshold. The findings reveal a positive relationship between carbon tax and carbon emissions, GDP and CO_2 emission across both regimes. Consequently, it is suggested that South Africa should continue increasing its carbon tax, as it has not yet reached its maximum threshold for effectively reducing CO_2 emissions.

Keywords: Carbon Tax, Carbon Emissions, Economic Growth, and Threshold
JEL Classifications: Q54, Q58, E23, C32

1. INTRODUCTION

The interplay between environmental preservation and economic development is a critical global issue, especially concerning greenhouse gas emissions and climate change. To mitigate emissions, carbon taxes have been implemented in over 56 countries by 2024, up from 19 in 2010, with South Africa being the only African nation to do so. The tax rates vary significantly, from <\$1.6/ton in Poland and Ukraine to over \$106 in Sweden (Uddin et al., 2017; Bavbek, 2016; World Bank, 2024).

South Africa's energy sector, predominantly monopolized by Eskom, accounts for 95% of the country's electricity and contributed to 55% of CO_2 emissions in 2010, which increased due to the construction of coal-fired power stations. The 2019 integrated resource plan (IRP) aims to diversify energy sources by increasing renewable energy use and reducing coal reliance (Bernard and Kichian, 2021; Delport, 2018). The carbon tax in South Africa has risen from an initial rate of R75 in 2010 to R159 per tonne by 2023, with plans for a 10% annual increase (South African Reserve Bank, 2024).

While carbon taxes are effective in reducing emissions, they may negatively impact economic growth and social welfare by raising electricity prices without benefiting producers (Nurdianto and Resosudarmo, 2016; Alper, 2017; Emami et al., 2021; De Jager et al., 2018). Increasing costs could hinder the competitiveness of energy-intensive industries, potentially leading to job losses and reduced household spending, which in turn affects production and investment (Loganathan et al., 2014; Lin and Li, 2011; Nong and Simshauser, 2020; Winkler and Marquard, 2011). South Africa ranks 18th among 34 OECD countries for environmentally related tax revenue as a share of GDP, with energy taxes constituting 93% of this revenue (StatsSA, 2021).

Despite efforts to transition to renewable energy, South Africa's reliance on fossil fuels poses significant challenges to implementing effective carbon legislation. The Carbon Tax

Bill was introduced in 2015, targeting key sectors like energy, mining, and manufacturing, which significantly contribute to pollution (Pegels, 2016; South African National Assembly, 2015; Hughes, 2017). The article is structured to include a literature review, methodology, results presentation, and conclusions with recommendations.

2. LITERATURE REVIEW

This section of reviews both the theoretical and empirical literature. The theoretical literature highlights theories related to carbon tax and CO_2 emissions, while the empirical literature reviews work on carbon tax and CO_2 emissions around the world.

2.1. Theoretical Literature

2.1.1. Pigouvian tax theory

Arthur Pigou is recognized for proposing the concept of utilizing taxes to address the market inefficiency that occurs due to the existence of externalities, as elucidated in his book The Economics of Welfare, published in 1920 (Beeks and Ziko, 2018).

As economic activity has caused a reduction in environmental quality over the years, concerns about sustainable development have grown. The primary emphasis of sustainable development goals (SDGs) is on reducing poverty and transforming the environment. Pigouvian tax is a socially efficient resource allocation tax theory that addresses negative externalities associated with carbon emissions (Nerudova et al., 2019). It aims to make the price of goods equal to social marginal costs and add carbon taxes to total charges. Carbon taxes, a specific application of Pigouvian theory, aim to increase the cost of production for industries producing high levels of emissions.

The Pigouvian theory and carbon tax provide an effective mechanism for internalizing the external costs of carbon emissions and promoting more efficient and sustainable economic outcomes. Policymakers should continue exploring the use of carbon taxes as part of a broader strategy to promote sustainable economic growth and reduce the risks of climate change. As carbon prices increase, firms have a financial incentive to invest in cleaner technologies, leading to long-term emissions reductions (Slater et al., 2020). The National Bureau of Economic Research found that a carbon tax could increase investment in clean technologies and lead to long-term emissions reductions (He et al., 2019). Additionally, the Pigouvian theory and carbon tax can be revenue-neutral, as it can be designed to return revenue generated by the tax to households through rebates or fund investments in clean technologies (Tuladhar et al., 2015).

In conclusion, the Pigouvian theory and carbon tax have several strengths, including internalizing the costs associated with carbon emissions, reducing emissions, encouraging innovation in clean technologies, and the potential for revenue neutrality. While there are some concerns about the regressive nature of the tax, studies have shown that the Pigouvian theory and carbon tax can be an effective tool in reducing greenhouse gas emissions and promoting a transition to a low-carbon economy.

2.2. Empirical Literature

The research on carbon taxation reveals diverse effects on inflation, emissions, and economic growth across various contexts. Konradt and Weder (2021) found that carbon taxes are generally not inflationary and can even have deflationary effects in Europe and Canada. Similarly, McKibbin et al. (2021) noted that carbon taxes primarily alter relative prices without significantly affecting core inflation. Kaenzig (2021) also reported that carbon price fluctuations in the European ETS positively impacted energy and consumer costs, suggesting temporary inflationary effects.

Using the synthetic control method, Xiang and Lawley (2019) observed a 7% reduction in per capita residential natural gas consumption due to the British Columbia carbon tax, indicating a substantial impact on energy consumption. Williams et al. (2015) highlighted that while carbon taxes tend to be regressive, their effects largely depend on the use of tax revenues.

Moessner (2022) analysed the impact of carbon pricing on inflation across 35 OECD countries, revealing that a $10 increase in ETS prices raises energy CPI inflation by 0.8% points but has negligible effects on core CPI inflation. In contrast, Wong and Zhang (2022) reported a 22.1-68.0% increase in wholesale electricity prices due to carbon taxes in Australia. Research also suggests that carbon taxes can have adverse effects on employment and economic growth in energy-intensive sectors. Meng et al. (2021) found that carbon taxes negatively impacted the Chinese tourism industry, while Marin and Vona (2017) reported a negative relationship between carbon taxes and employment in energy-intensive sectors. Similarly, Pereda et al. (2019) concluded that carbon taxes negatively affected GDP, wages, and jobs in Brazil.

Despite concerns, some studies indicate potential positive effects on GDP. Metcalf (2020) found no negative GDP impact from the British Columbia carbon tax and a small positive effect in European countries. Goulder et al. (2019) suggested that a carbon tax in the U.S. could reduce GDP expenses without significantly affecting overall GDP. Yoshino et al. (2021) used a structural vector autoregression technique to show that rising energy prices due to carbon taxes negatively affect Japan's GDP while increasing interest rates and consumer price indices. In contrast, Elbaum (2021) found that a gradual carbon tax increase in OECD countries led to significant CO_2 emissions reductions over time.

The studies underscore the need for policymakers to consider both the environmental and economic implications of carbon taxes. A well-designed carbon pricing mechanism can help mitigate climate change while balancing economic realities, particularly through targeted revenue use. The findings emphasize the importance of context-specific analyses to inform effective and sustainable environmental policies, as seen in studies across Brazil, China, and Sweden, which explore the intricate relationships between economic growth, energy consumption, and carbon emissions. Ultimately, continuous empirical research is essential for developing effective strategies for reducing carbon emissions while fostering economic growth (Konradt and Weder, 2021; McKibbin et al., 2021; Kaenzig, 2021; Xiang and Lawley, 2019; Williams et al., 2015; Moessner, 2022; Wong and Zhang, 2022;

Meng et al., 2021; Marin and Vona, 2017; Pereda et al., 2019; Goulder et al., 2019; Metcalf, 2020; Yoshino et al., 2021; Elbaum, 2021; Boyce et al., 2018).

3. METHODOLOGY

3.1. Empirical Model

The threshold model, developed by Tong (1978) and Lim (1981), is commonly used in discrete time series analysis featuring piecewise linearity, contributing to various data analytic techniques. Its regression coefficients reflect structural breaks or endogenously determined threshold variables, allowing for sample division into regimes without needing dummy variables for unknown structural breaks (Mehrara et al., 2015). This research also aims to enhance Hansen's (2000) threshold estimation method, enabling the identification of growth regimes while allowing model parameters to vary across these regimes, similar to Caner and Hansen's (2004) approach.

The threshold model emphasizes the importance of identifying thresholds and assessing the impact of carbon taxation across different regimes, highlighting that carbon tax effects vary due to differences in production functions and institutional quality (Hansen, 2022).

A single threshold regression model is defined as:

$$y_{it} = \mu_i + \theta' x_{it}' + \beta_1 x_{it} I(q_{it} \leq \gamma) + \beta_2 x_{it} I(q_{it} > \gamma) + \varepsilon_{it} \quad (1)$$

In equation 1, I and t denote area and time effect, respectively; $I((q_{it} \leq \gamma),(q_{it} > \gamma))$ represents an indicator function, equal to 1 or 0. 1 represents a single-threshold effect and 0 represents a linear effect exists. Variable q_{it} acts as the threshold variable and is referred to as chosen one of South Africa's tax and CO_2 emissions, economic transitions as structural breaks in this study. γ denotes the threshold value that splits the equation into two regimes, with two separate threshold coefficients, β_1 and β_2. Besides, x_{it} indicates the core explanatory variable, while y_{it} means the explained variable, which refers to the GDP and carbon emissions in South Africa, respectively. Lastly, the set of control variable x_{it}' indicates other aspects of social and economic transitions in South Africa, other than the index, as threshold variable with coefficient θ', while μ_i denotes the individual effect, and ε_{it} represents the disturbance term.

Firstly, the estimated threshold value (γ) can be derived by minimizing the residual sum of squared errors $S_n(\gamma)=\varepsilon_{it}'\varepsilon_{it}$. Once the threshold value is calculated, the corresponding parameter estimates of threshold (β) will be obtained by the ordinary least squares (Chen, 2012). Furthermore, in order to verify whether there exists a threshold effect, that is, whether the threshold coefficients are identical in each regime, the null hypothesis (H_0: $\beta_1=\beta_2$) is set against the alternative hypothesis (H_1: $\beta_1+\beta_2$). Accordingly, if the null hypothesis (of linearity) is rejected, a single threshold effect nonlinear regression (with two threshold regimes) will be performed.

To predict the model in Eq. (1), individual threshold will be eliminated through threshold effect transformation by deducting its own average value, which can be simplified into Eq. (2) as follows:

$$y_{it} = \mu i + \theta' x_{it}' + \beta' x_{it} (q_{it}, \gamma) + \varepsilon_i \quad (2)$$

The threshold model can be simulated by following two major processes, namely, the evaluation for the threshold values (γ) with corresponding threshold coefficients (β_1), as well as the test for the existence or significance of the threshold effect with a relevant confidence level.

The estimation analysis begins with a unit root test of all main variables included in the estimation. All variables show P-values close to zero, which indicates that the null hypothesis of data containing unit roots is rejected. These results suggest that none of the main variables suffers from the nonstationary problem.

$$CO_{2t} = \beta_1 lGDP_t + \beta_2 lEC_t + \beta_3 lINF_t + e_t \text{ If carbon tax}_t \leq \gamma \quad (3)$$

$$CO_{2t} = \beta_1 lGDP_t + \beta_2 lEC_t + \beta_3 lINF_t + e_t \text{ If carbon taxt} > \gamma \quad (4)$$

Where $_t$ the subscript t denotes the period, and e_t is the error term. Carbon tax is the threshold variable, and γ is the threshold value. Explanation variables: GDP, carbon tax, energy consumption and inflation model.

This is in line with Hansen's baseline estimate (2000). This permits a variation in the parameter estimates based on the threshold value (γ). Bose et al. (2008) employed a comparable methodology and found no statistical issue resulting from an analogous equation. In a single threshold regression, equations 4.26 and 4.27 can be expressed as follows:

$$y_{it} = \beta_1 X_t I(\text{carbon tax}_{it} \leq \gamma) + \beta_2 X_{it} I(\text{carbon tax}_{it} > \gamma) + e_t \quad (5)$$

Where y_t is CO_2 emission, carbon tax, γ, et and X_t is GDP, carbon tax and inflation, and I is an indicator function of the threshold variable.

The first test is to check for evidence of the carbon tax threshold. We run Equation 5 to test for the presence of the first threshold, which shows that the first threshold is obtained at the carbon tax level.

The bootstrap P-values confirm that the null hypothesis of "no threshold" is rejected at the 5% level. A graphical method to plot the likelihood ratio against the threshold value (γ) is shown below. The importance of bootstrap P-values in sample splitting time series analysis lies in their ability to provide more reliable and robust statistical inference, especially when faced with challenges like small sample sizes, non-normality, and the need for model validation. The likelihood ratio (the red line) is constructed at 9, and the threshold value exists when the threshold estimate value (the blue line) crosses the red line. This process allows for the calculation of standard errors, confidence intervals, and hypothesis testing (Hanson, 2000).

3.2. Data

The present study used annual data series for the period 1990-2022. The data for empirical analysis has been collected from various data source, like international energy agency, World Bank and

Table 1: ADF, PP and KPSS results

ADF				
Variables	**LTAX**	**LCO_2**	**GDP**	**LINF**
At level (0)				
None	0.001	0.985	0.899	0.265
Intercept	0.016	0.6011	0.837	0.014
Trend and intercept	0.043	0.9012	0.847	0.047
Conclusions	Stationary I (0)	Non-stationary	Non-stationary	Stationary I (0)
At 1st difference I (1)				
None	0.000	0.000	0.000	0.000
Intercept	0.000	0.000	0.003	0.000
Trend and intercept	0.000	0.000	0.015	0.002
Conclusions	Stationary I (1)	Stationary I (1)	Stationary I (1)	Stationary I (1)
PP				
Variables	**LTAX**	**LCO_2**	**GDP**	**LINF**
At level (0)				
None	0.399	0.993	0.874	0.282
Intercept	0.016	0.565	0.799	0.106
Trend and intercept	0.041	0.934	0.675	0.387
Conclusions	Stationary I (1)	Non-stationary	Non-stationary	Non-stationary
At 1st difference I (1)				
None	0.000	0.000	0.000	0.000
Intercept	0.000	0.000	0.003	0.000
Trend and intercept	0.000	0.000	0.017	0.000
Conclusions	Stationary I (1)	Stationary I (1)	Stationary I (1)	Stationary I (1)
KPSS				
Variables	**LTAX**	**LCO_2**	**GDP**	**LINF**
At level (0)				
Intercept	0.188	0.601	0.533	0.407
Trend and intercept	0.110	0.180	0.122	0.166
Conclusions		Stationary I (0)	Stationary I (0)	Stationary I (0)
At 1st difference I (1)				
Intercept	0.341	0.275	0.176	0.500
Trend and intercept	0.500	0.137	0.176	0.500
Conclusions	Stationary I (1)	Non-stationary	Non-stationary	Stationary I (1)

Source: Collected by the author (Data from SARB and World Bank, 1990-2022)

South African Reserve Bank. All the variables are transformed to logarithmic form it helps the variables to be in the same unit of measurement and therefore minimise heteroscedasticity.

The study utilized unit root tests to determine the stationarity in each series before examining the model's long- and short-run dynamics. Multiple tests for stationarity have been proposed in previous research; however, in the current analysis, the most generally used unit root tests, namely Phillips-Perron (PP), Augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS). We checked the level of stationarity of all the variables at the "level" (I[0]) and the "first difference" (I[1]).

4. EMPIRICAL RESULTS

This study uses the Dickey-Fuller GLS(ADF), Phillips-Perron unit root tests (PP), and KPSS, as was covered in the previous section.

The following are the results of the null hypothesis rejections: () at the 1% significance level; () at the 5% significance level; () at the 10% significance level (Table 1).

Table 1 presents the results of unit root tests, indicating that some variables in the study exhibit different levels of stationarity. The Augmented Dickey-Fuller (ADF) test reveals that the natural logs of GDP, and CO_2 emissions (LCO_2) are non-stationary at level (I(0)) but become stationary at first difference (I(1)). Conversely, inflation (LINF) and tax (LTAX) are stationary at level (I(0)) with a trend. The Phillips-Perron (PP) unit root test also identifies a mix of stationarity; it shows that LCO_2, become stationary at I(1) after differencing, while LTAX remains stationary at level (I(0)). The study employs ADF, KPSS, and PP tests, with the KPSS results indicating that GDP, and LCO_2, are stationary at I(0), while LTAX and LINF are stationary at I(1).

The relationship between each carbon tax and CO_2 emissions per capita for South Africa was examined using two steps. In the first step, whether carbon tax influences CO_2 emissions per capita was examined. In the second step, considering that there exists a long-term relationship between the variables, it was questioned whether the effect of each carbon tax on CO_2 emissions per capita changes according to threshold level.

4.1. Sample Spitting Threshold Result

From the Figure 1, there is a threshold in the model, as the line cuts across the 95% confidence interval. This result is also agreed by Aydin and Esen (2018), who established a threshold link between carbon tax and CO_2 emissions. This implies that carbon tax affects CO_2 emissions in South Africa.

After testing the presence of the threshold value, the next step is to construct the first threshold value and regress the parameter estimates. Figure 2 may help to clarify the construction of a carbon tax threshold value.

The blue line represents the threshold's likelihood ratio (γ), and the red line represents the 95% critical value of 7.35 (Hansen, 2000). The value of the carbon tax threshold is 1.65%, i.e., at the point where the red and blue lines cross. Based on the carbon tax threshold value, the estimation results are constructed for both the first and second regimes. The first regime displays the estimated parameters levels below 1.65%, and the second regime shows the estimated parameters with carbon tax levels above 1.65% this threshold result was also founded by Aydin and Esen (2018). All the estimation results are presented in Table 2.

The confidence interval region can be an indication of a threshold; the confidence interval is between 1.504 and 2.518, which is not too close to those from which we can decide the existence of the second threshold.

The first regime consists of carbon tax level below the threshold, and the second subsample consists of carbon tax level above the threshold of 1.65%. The first subsample contains 33 observations. This can be seen on the Table 2.

Figure 1: Presence of threshold

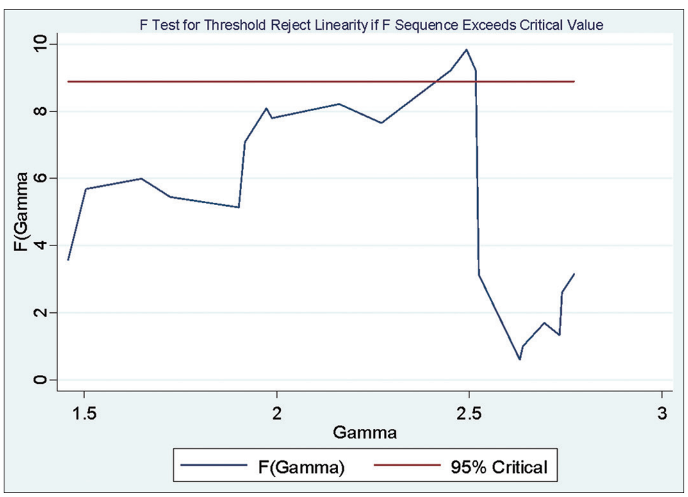
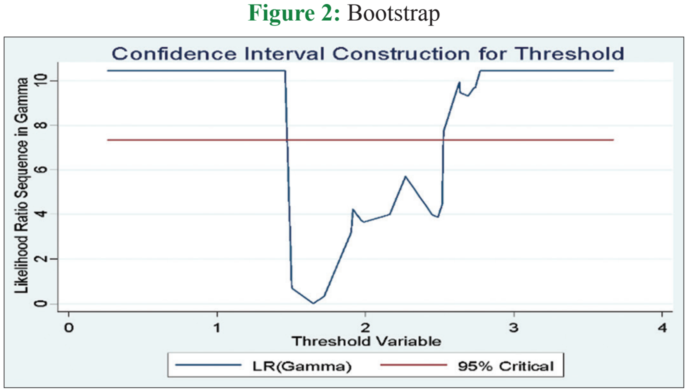


Figure 2: Bootstrap



The threshold model allows the estimated coefficients and significance levels in the first and second regimes to be 10%. In the first regime, the carbon tax effect is positive relative to CO_2 emissions and significant. This would not align with the intended purpose of carbon taxes, which is to provide economic incentives for reducing carbon emissions. This means the carbon tax rate is too small to effect any changes. A 1% increase in carbon tax will increase CO_2 emissions by 2.07% when carbon tax is lower than 1.65. Freire-González and Puig-Ventosa (2019) found that a carbon tax of €10/ton or lower cannot reduce CO_2 emissions within 5-7 years but can be achieved for a tax of €20/ton. British Columbia's carbon tax has reduced CO_2 emissions by 5-15%, has minimal effects on the economy, and has generally been supported by the public after 3 years of implementation (Murray and Rivers, 2015).

GDP and CO_2 emission have a positive relationship; at the current low level of carbon tax of below 1.65, a 1% increase in GDP will lead to a 6.27% increase in South African CO_2 emissions. That implies that growth in South Africa results in more emissions. The Environmental Kuznets Curve hypothesis is not valid in developing countries, as GDP per capita is positively and significantly related to CO_2 emissions, challenging its validity as a theoretical basis for economic growth policies (Sirag et al., 2018; Shikwambana et al., 2021). The economic impact in this context pertains to South Africa needs to diversify its energy consumption for emission to be reduced and to maintain growth in South Africa.

After careful examination of carbon tax below 1.65, we will examine how both GDP and CO_2 emissions behave if the carbon tax is increased about that.

When the carbon tax is over 1.65%, GDP and carbon emissions have a positive and significant relationship, that is, a 1% increase in GDP will increase CO_2 emissions by 6.27%. This agrees with the fact that South Africa's growth is most energy-intensive for generation of electricity (Javed et al., 2023).

When carbon tax is over 1.65, carbon tax and carbon emissions have a positive and significant relationship. That is, a 1% increase in carbon tax will decrease CO_2 emissions by 2.07%. This agrees with the fact that South Africa's growth has the largest energy consumption for generation of electricity. In pursuit of the explicit goal of examining a potential correlation threshold between the CO_2 emissions as the dependent variable and GDP, carbon tax, energy consumption and Inflation as independent variables, and carbon tax is the regime switch. It could be seen that there is a threshold, since the bootstrap is 0.019 which is <0.05.

The threshold model allows the estimated coefficients and significance levels to vary in the first and second regimes. The

Table 2: Regime1 q<=1.64865863

Variables	T-statistic	Conclusion
GDP	6.27	Stationary
Tax	2.07	Stationary
Inflation	−0.50	Non-Stationary

The dependent variable is Carbon emissions. The P value significance levels (P<0.1; P<0.05; P<0.01) are indicated by the asterisks

Table 3: Regime2 q>1.64865863

Variables	T-statistic	Conclusion
GDP	24.58	Stationary
Tax	2.15	Stationary
Inflation	−0.61	Non-stationary

The dependent variable is Carbon emissions. The asterisks represent the P-value significance levels (P<0.1; P<0.05; P<0.01)

bootstrap is 0.019, with heteroskedasticity >2 which makes it statistically significant. In Table 3, we observe that, in the regime with a low-carbon tax level, both the lower and upper regimes gave similar results. This implies that the carbon tax will need to be increased, and various other measures will need to be used to reduce CO_2 emissions.

5. CONCLUSION AND RECOMMENDATIONS

The relationship between carbon tax and carbon emissions in both regimes show a positive relationship, also with GDP and CO_2 emission being positive. It could be concluded that carbon tax and other tools need to be used to reduce emissions in South Africa.

The policy implications raised by this study are that carbon tax is positively and significantly related to CO_2 emissions. This will imply that policy recommended a reduction in CO_2 emissions to reduce carbon tax increase. However, on the policy implication raised on the established relationship between carbon tax and CO_2 emissions, if South Africa implemented the tax well, the mitigation policy package would promote low-carbon investments, raise government revenues, and support economic growth. According to the researcher, the government could recover its losses and stimulate growth without raising CO_2 emissions if it redirected its carbon tax programmes towards industries with higher emissions and invested in other areas. This would lead to lower emission taxes and economic expansion.

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