Laurinaitytė, Nora Marija; Liu, Annie (Yihuizi)

Book

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LIETUVOS BANKAS
EUROSISTEMA

Combating Climate Change through Policy Instruments. A Meta-Analysis of Carbon Taxation

Occasional Paper Series

No 45 / 2023

Occasional Paper Series
No 45 / 2023
ISSN 2424-3213 (online)

Combating Climate Change through Policy Instruments. A Meta-Analysis of Carbon Taxation

Nora Marija Laurinaitytė[1]

Annie（Yihuizi）Liu[2]

[1] nlaurinaityte@lb.lt
[2] Annie Liu was a Bank of Lithuania Summer Intern in 2022.

Gedimino pr. 6, LT-01103 Vilnius

www.lb.lt

The series is managed by the Applied Macroeconomic Research Division of the Economics Department and the Center for Excellence in Finance and Economic Research.

ABSTRACT

Recently, there has been a surge of interest in policies that target climate change. This paper begins by discussing why policymakers, and central banks in particular, should be concerned about climate change, and goes on to argue why carbon pricing is an appropriate political instrument to reduce greenhouse gas (GHG) emissions. The paper details two categories of carbon pricing, namely carbon taxation and the introduction of Emission Trading Systems (ETSs), illustrating why a carbon tax is the more efficient instrument. Popular models for optimal carbon taxation and implications of carbon taxation are discussed. The paper concludes with recommendations to policymakers, which include advocacy of differentiated rather than uniform carbon taxation, phased-in carbon taxation instead of a blanket approach, introduction of the carbon border adjustment mechanism (CBAM), and Green Quantitative Easing (QE).

Keywords: carbon taxation, climate change, green QE

JEL: Q54, Q58, H23, E51, E62

1 Introduction

Climate change is an urgent global problem. Under the current climate policies, standard climate change models predict an increase of 3 degrees Celsius in global temperatures over pre-industrial levels by the end of this century[3]. If mitigation policies are not implemented, the consequences of climate change, including an increased number of floods, storms, and droughts, will pose a serious risk to life and property[4]. Due to this potential threat, all policymakers should be concerned about climate change. In the case of central banks, changing climate may affect their ability to achieve the main goal of monetary policy: price stability.

First, climate change could diminish the conventional monetary policy space, i.e., the distance between the natural rate of interest r* (the rate consistent with stable inflation and potential growth) and the effective lower bound, as climate change could affect r*. For example, higher temperatures may impair labour productivity or increase rates of morbidity and mortality[5]. In turn, these outcomes could reallocate productive resources into adaptation measures, as, in response to higher uncertainty and increased risk aversion, individuals would have a heightened propensity to save (for precautionary motives) and a lower incentive to invest, two factors that can reduce r*. These impacts, however, are uncertain and there are many channels at play.

Second, the consequences of climate change, such as floods, could generate massive losses from materializing physical risks or stranded assets[6]. For instance, Cantelmo et al. (2022) shows that Hurricane Keith, which hit Belize in October 2000, and Hurricane Iris, which hit the same country in October 2001, each caused damage valued at 30% of the country's GDP, and GDP growth in 2001 and 2002 was 8 percentage points lower than in the pre-shock year (*Graph 1*). To put these data in perspective, during the 1970s oil crisis—often regarded as the prototypical large exogenous shock in macroeconomics—the U.S. GDP growth in 1974 and 1975 was about 6 percent lower than in 1973. This illustrates that natural disasters can cause shocks whose impact is comparable to that of major macroeconomic shock.

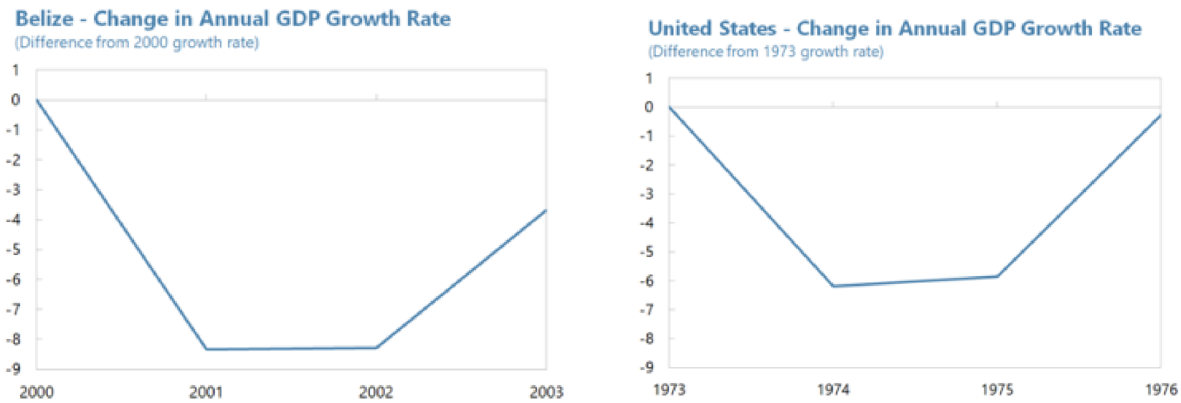
According to Bella et al. (2022), a global reduction in GHG emissions, especially carbon dioxide (CO_2), is key to fighting climate change. In the Paris Agreement, signed in 2015, the international community agreed to limit global warming to a maximum of 2 °C compared to pre-industrial levels, with the ambition to stay within 1.5 °C to avert the worst effects of climate change[7]. To

[3] IPCC, 2014
[4] Cantelmo et al., 2022
[5] Schnabel, 2021
[6] Schnabel, 2021
[7] Schleussner et al., 2016

achieve this goal, CO_2 emissions must be reduced by approximately 45% from their 2010 level by 2030, and eventually reach net-zero emission by 2050[8].

Graph 1.

Change in Annual GDP Growth Rate in the Aftermath of a Large Macroeconomic Shock



(a) Change in Annual GDP Growth Rate in Belize After Hurricane Keith (2000)

(b) Change in Annual GDP Growth Rate in the United States After the 1973 Oil Crisis

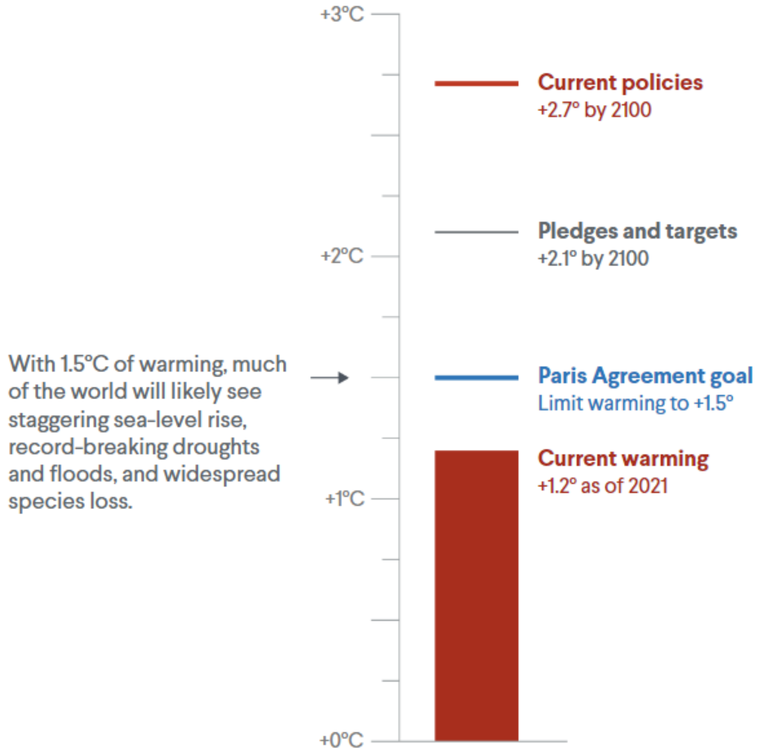
Note: The change in GDP growth in Belize during the climate disaster period 2001-2002, and the change in GDP growth in America during oil crisis period 1974-1975. These were the disaster-years that inflicted damage of at least 1 percent of the country's GDP. The raw data are taken from the World Bank, and the worldwide countries' selection is from Cantelmo et al. (2022)'s research.

According to the Climate Action Tracker (2021), many countries submitted bolder pledges ahead of the COP26 in November 2021. A signature example is that of President Joseph Biden, who, in April 2021, announced that the US will aim to cut emissions by 50% by 2030, doubling former President Barack Obama's commitment. Hence, if the more than 100 countries that have set or are setting net-zero targets were to follow through, global warming should be limited to 1.8 °C[9]. However, this scenario seems unlikely, as most of these countries are already behind their targets. Thus, it is likely that the world's average temperature will be at least 2.1 °C above the pre-industrial levels by 2100 (*Chart 1*).

[8] Guterres, 2020
[9] Meinshausen et al., 2022

Chart 1

Current policies, pledges and targets are projections.



Note: In each scenario, the temperature shown is the most likely of a range of possible outcomes. Pledges and targets include submitted and binding commitments for 2030 and beyond.

Source: As published by Climate Action Tracker (2021)

To control and subsequently reduce carbon emissions, many countries have developed policy and regulation instruments, such as an Emission Trading System (ETS) and a carbon tax[10]. Either of these measures would lead to higher carbon prices. Through higher prices of carbon-intensive products and services, consumer preferences would be forced to shift to climate-friendly products and services[11]. Hence, introducing a price for carbon makes renewable/low-carbon energy resources more competitive.

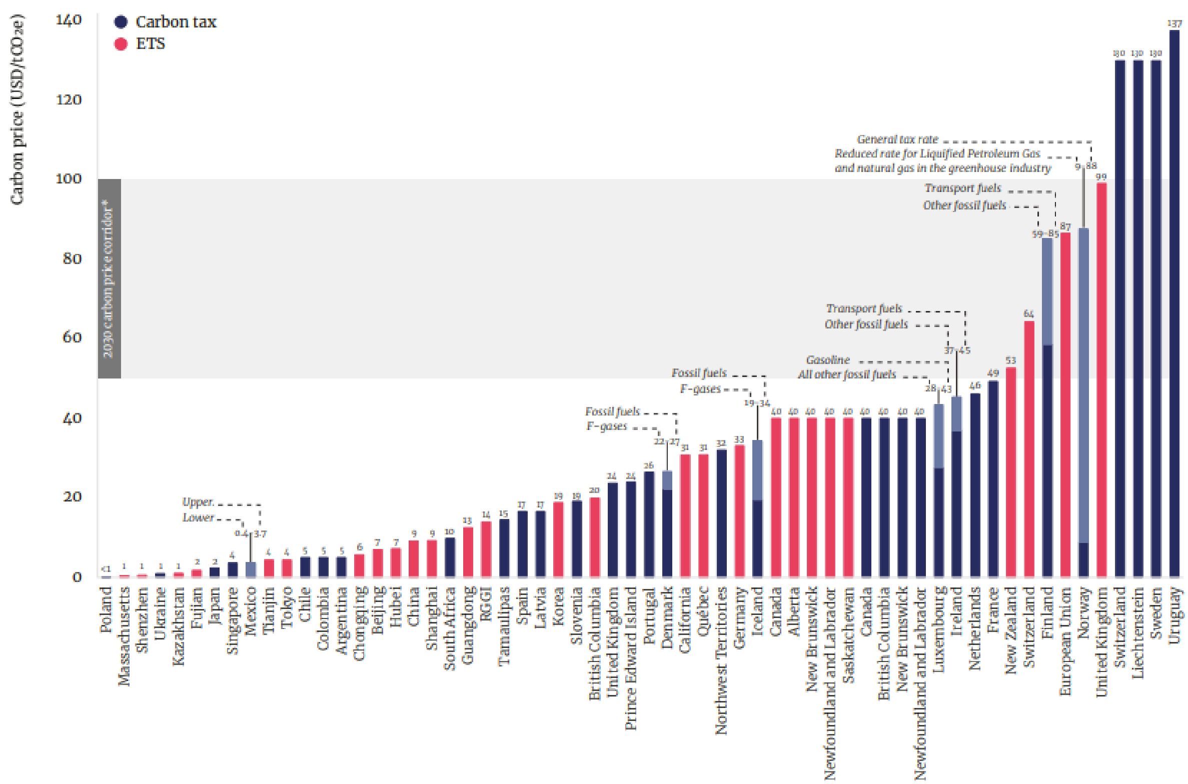
[10] Parry et al., 2022
[11] Yongjian and Fei, 2021

2 On Carbon Pricing

The World Bank[12] provides information on carbon prices as of April 2022 (*Graph 2).* The IMF[13] provides information on carbon prices and carbon pricing schemes (*Graph 3*).

Graph 2

Normal Carbon Prices as of April 1, 2022



Note 1: The 2030 carbon price corridor is based on the recommendations of the High-Level Commission on Carbon Prices report.

Note 2: Several jurisdictions apply different carbon tax rates to different sectors or fuels. In these cases, the World Bank indicated the range of tax rates applied, with the dark blue shading showing the lower rate and the combined dark blue and light blue shading representing the higher rate.

Source: The World Bank.

Countries that have a carbon pricing mechanism in place chose to implement ETS, or tax carbon emissions, or both. Some countries, like the United Kingdom and China, implemented different carbon pricing mechanisms in different national regions. Furthermore, there is huge variation in carbon prices among different countries and regions.

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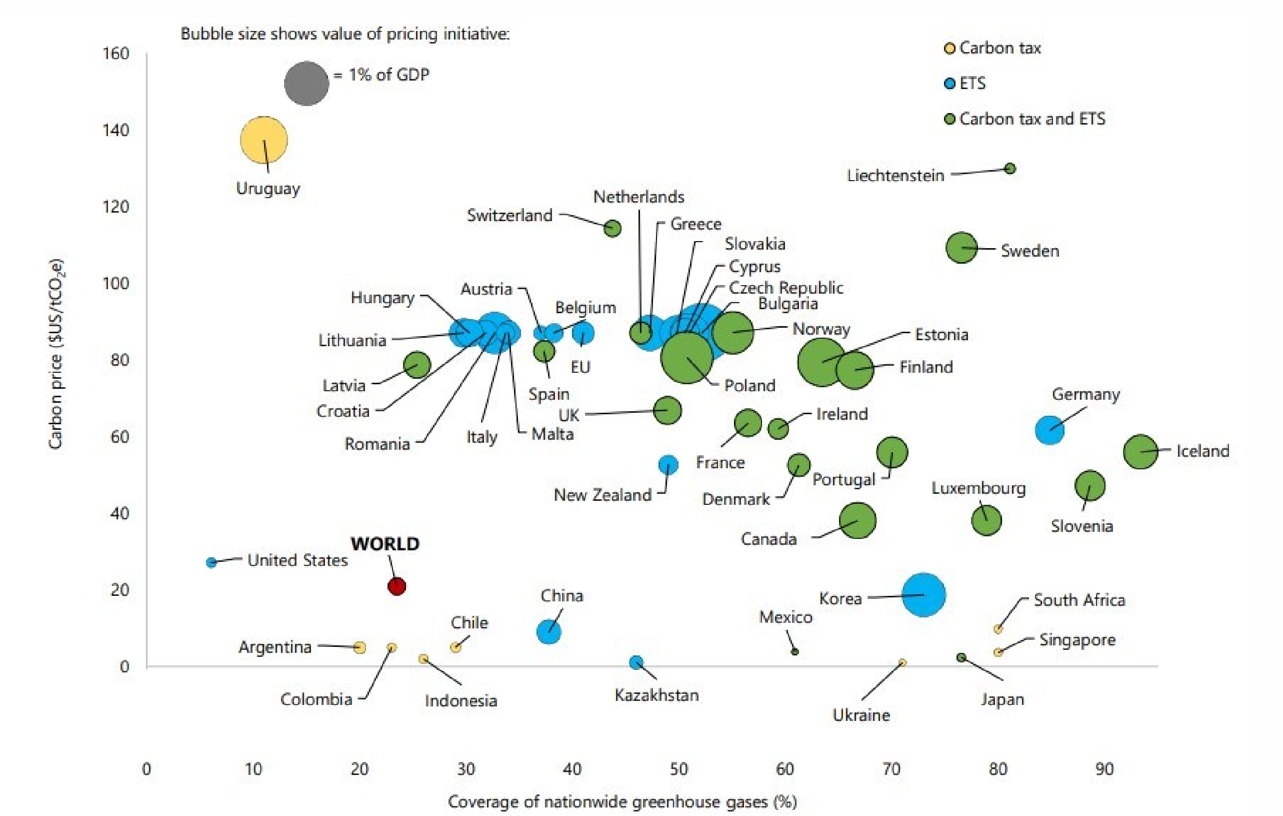
[12] The World Bank – State and Trends of Carbon Pricing 2022
[13] Parry et al., 2022

Graph 3

Subnational, National and Regional Carbon Pricing Schemes by Country, 2022



Notes: EU ETS includes Iceland, Liechtenstein, and Norway. Prices are emission-weighted averages of schemes at national, subnational and, if applicable, EU level. At present, China's system takes the form of a tradable emissions intensity standard with no fixed cap on emissions. Mexico does not include subnational schemes due to lack of coverage data.

Source: IMF.

2.1 Carbon Taxation vs. Emission Trading Systems (ETSs)

The two most popular methods of carbon pricing are carbon taxes and Emission Trading Systems (ETSs). The design choices for these instruments include administration, price levels, emissions coverage, relation to other mitigation instruments, use of revenues to address efficiency and distributional objectives, supporting measures to address competitiveness concerns, political economy aspects, and coordination at the global level.[14]

Compared to carbon taxes, ETSs help to achieve emissions targets with more certainty[15]. Murray and Rivers (2015) reviewed the existing evidence regarding the effect of the carbon tax on greenhouse emissions and concluded that the tax has reduced fuel consumption and greenhouse

[14] Parry et al., 2022
[15] Parry et al., 2022

gas emissions by between about 5% and 15% since being implemented at $10/t$CO_2$e in 2008 in British Columbia. In comparison, installations covered by the EU ETS reduced emissions by about 35% between 2005 and 2019[16].

However, allowance of price volatility in ETSs can be problematic[17]. Carbon taxes, by contrast, guarantee price certainty, and have the potential for coverage of broader emissions sources. Overall, carbon taxation is considered to have a significant advantage over ETSs, as it also is deemed easier to administer than an ETS (*Table 1*).

Table 1

Comparison of Carbon Taxes and ETSs

Design issue	Instrument	
	Carbon tax	ETS
Administration	Administration is more straightforward (for example, as extension of fuel taxes)	May not be practical for capacity constrained countries
Uncertainty: price	Price certainty can promote clean technology innovation and adoption	Price volatility can be problematic; price floors, and cap adjustments can limit price volatility
Uncertainty: emissions	Emissions uncertain but tax rate can be periodically adjusted	Certainty over emissions levels
Revenue: efficiency	Revenue usually accrues to finance ministry for general purposes (for example, cutting other taxes, general investment)	Free permit allocation may help with acceptability but lowers revenue; tendency for auctioned revenues to be earmarked
Revenue: distribution	Revenues can be recycled to make overall policy distribution neutral or progressive	Free allowance allocation or earmarking may limit opportunity for desirable distributional outcomes
Political economy	Can be politically challenging to implement new taxes; use of revenues and communications critical	Can be more politically acceptable than taxes, especially under free allocation
Competitiveness	Border carbon adjustment more robust than other measures (for example, threshold exemptions, output-based rebates)	Free allowances effective at modest abatement level; border adjustments (especially export rebate) subject to greater legal uncertainty
Price level and emissions alignment	Need to be estimated and adjusted periodically to align with emissions goals	Alignment of prices with targets is automatic if emissions caps consistent with mitigation goals
Compatibility with other instruments	Compatible with overlapping instruments (emissions decrease more with more policies)	Overlapping instruments reduce emissions price without affecting emissions though caps can be set or adjusted accordingly
Pricing broader GHGs	Amenable to tax or proxy taxes building off business tax regimes; feebate variants are sometimes appropriate (for example, forestry,	Less amenable to ETS; incorporating other sectors through offsets may increase emissions and is not cost effective
Global coordination regimes	Most natural instrument for international carbon price floor	Can comply with international price floor; mutually advantageous trades from linking ETSs but does not meet global emissions requirements

Note: Green indicates an advantage of the instrument; orange indicates neither an advantage nor disadvantage; red indicates a disadvantage of the instrument.

Source: As published by Parry et al., 2022, IMF.

16 https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

17 Parry et al., 2022

While there are some practical advantages to carbon taxes, ETSs may be preferable for other reasons—there is no 'one carbon pricing instrument that fits all'. ETSs can be designed (for example, through price floors and allowance auctions) to mimic some of the advantages of carbon taxes. Furthermore, even if carbon taxation is chosen to implement carbon pricing policy, tax calibration (scope and levels) and chosen implementation design (phase-in vs. blanket approach, uniform vs. differentiated taxation, etc.) will have a significant impact on carbon taxation's effectiveness in reducing emissions as well as its distributional impact.

2.2 Modelling Carbon Taxation and its Implications for Inflation

Table 2 sets forth the main estimation models employed by researchers to calculate optimal carbon taxation and analyse carbon tax implications to the economy. The model findings in specific case studies are summarised in the *Appendix.*

Table 2.

Summary of Estimation Models of Carbon Taxation

Model Name	Main Interpretations	Journal Reference
Heckscher-Ohlin (HO) Model	The concept of the model, developed in 1990s, is that the country that is relatively abundant in emission permits exports relatively emission-intensive goods. Hence, developing countries are expected to export "dirty" products. This model is the inspiration for the Leontief paradox theory, later developed into Leontief's IO model. Leontief proved the HO theory inaccurate with US case studies.	India: Dietzenbacher and Mukhopadhyay (2007)
Leontief Pricing Model/ Input-output (IO) Model	The IO model aggregates the intermediate transactions in the production of all goods and services and the distribution of all final goods produced in an economy. These data are used to estimate how a price on carbon emission (through either a direct tax or a cap-and-trade policy) would filter through to every good and service produced and sold in the economy. Researchers utilise such a model in comparing multi-national/cross-border carbon taxation effects or discovering interrelations of carbon taxation and other sectors. However, the original IO model does not consider conditions of the market's adjustment and assumes that the sectors automatically decide the rise in prices based on their costs. Thus, scholars tend to add new factors into the matrix equation to match their research needs.	United States: Choi et al. (2010) Spain: Labandeira and Labeaga (1999) Gemechu et al. (2014) China: Liu et al. (2009) Guo et al. (2012) Meng et al. (2014) Chen et al. (2015) Brenner et al. (2007) Sun and Ueta (2011) Wang et al. (2011) Jiang and Shao (2014) Latin American countries (Brazil, Mexico, and Chile): Cristian and Nicolas (2018) Brazil: da Silva Freitas et al. (2016) Mexico: Renner (2018) The European Union: Rocchi et al. (2014) Cross-border effect: Zhang et al. (2017a) Zhang et al. (2017b) Zhang and Zhu (2017)

Computable General Equilibrium (CGE) model	One of the fundamental and main analytical tools for climate change policy analysis, particularly to establish the carbon-pricing relationship with GHG emission reduction and economic fluctuation.	South Africa: Van Heerden et al. (2006) China: Liu et al. (2018) Li et al. (2018) Lin and Jia (2018) British Columbia: Bernard et al. (2018) Australia: Meng et al. (2015) Multi-country scale: Wissema and Dellink (2007) Zhang et al. (2016) Metcalf and Stock (2020)
Environmental Dynamic Stochastic General Equilibrium (E-DSGE) Model	The E-DSGE model is the extended version of the DSGE model. The original DSGE model characterises a general equilibrium between households and firms. Both make dynamic and rational decisions in a stochastic environment with various types of shocks. Researchers usually pair the E-DSGE model with the CGE model to reinforce the significance level.	Model introduction: Fischer and Springborn (2011) Heutel (2012) United States: Annicchiarico and Di Dio (2015) Heutel (2012) Dissou and Karnizova (2016) China: Chan (2019) Chan (2020) Cao et al. (2021)
Dynamic Integrated Climate-economy (DICE) Model	The DICE model framework is utilised to optimise the carbon tax rate to discover the macro-economic effects with the environmental changes under carbon taxation. The discounted sum of per capita consumption of utilities is set as the optimization objective and a dynamic integrated climate-economy model was adopted for carbon tax optimization.	Model introduction: Nordhaus (1992)
Quadratic Almost Ideal Demand System (QUAIDS) Model	QUAIDS are demand system-based models. QUAIDS models tend to be more flexible and allow for complementarities and substitution relationships between goods, which can improve the identification of distributional effects.	Sweden: Brannlund and Nordstrom (2004) Brazil: Moz-Christofoletti and Pereda (2021) South Africa: Banks et al. (1997) Mexico: Rosas-Flores et al. (2017) and Renner et al. (2018)
The Global Change Assessment Model (GCAM)	The GCAM is a global integrated assessment model combining representations of the economy, energy system, agriculture, land use, and climate change. The model is a dynamic recursive, partial equilibrium model that adjusts prices until supply and demand balance for all energy and agricultural markets.	Model introduction: Clarke et al.,2007 United Kingdom: Barrage (2020)
TIMES Integrated Assessment Model of the Energy Research Centre of the Netherlands (TIAM-ECN) Model	TIAM-ECN is a linear optimization model, based on energy system cost minimization with perfect foresight until 2100. The model simulates the development of the global energy economy over time from resource extraction to final energy use.	Model introduction: Rosler et al.,2014

Normally, carbon taxation would generate the replacement of fuel-intensive products, cause changes in the structures of production and the consumption of energy, and promote investment to improve energy efficiency[18]. However, carbon tax inevitably has some negative impacts. In the short term, carbon tax could raise energy prices, increase costs, and undermine the competitiveness of industries with extensive energy use.

Energy prices are a primary component of headline inflation[19], and any large incremental growth in the price of energy is expected to be reflected by a similar increment in economies' general price indices. Consequently, drastic price surges in the power markets risk destabilizing general price dynamics and resurrect fears of inflation. For instance, a $15 carbon tax implemented in the US is associated with a rise in inflation of 0.8% during the first year of the policy.[20]

Choi et al. (2018) provide evidence of an asymmetry in the responses of inflation to fuel price shocks as positive oil price shocks lead to a larger effect on inflation than negative price shocks. Furthermore, Gelos and Ustyugova (2017) also find that commodity price shocks such as fuel prices have stronger effects on domestic inflation in developing countries than in advanced economies. However, several later studies contradict such claims. Firstly, McKibbin et al. (2021) find that the carbon tax is negatively correlated with the core euro-area inflation. They conclude that carbon taxes affected mainly relative prices rather than the overall price level. Their results have been verified by Konradt and Weder di Mauro (2020). They discover that the increase in energy price is more than offset by a fall in the prices of services and other non-tradable assets. The method they employed was the synthetic control method[21] and local projections[22] to identify the effect on the consumer price index (CPI). The results are illustrated in *Graph 4.*

From *Graph 4* it can be concluded that energy prices rise in the period after carbon taxes are implemented (compared to a synthetic control group). At the same time, prices fall for other components of the CPI basket, mostly non-tradable goods. In addition, in Europe, this holds true for early as well as late carbon tax adopters, although the deflationary effect is smaller for the latter group.

Besides this (relatively) positive relationship of the carbon tax to deflation, Kanzig (2021) finds that surprises in carbon prices in the European ETS had a positive effect on energy and consumer prices. Using model simulations, McKibbin et al. (2021) find that carbon taxes have only a transitory effect on inflation.

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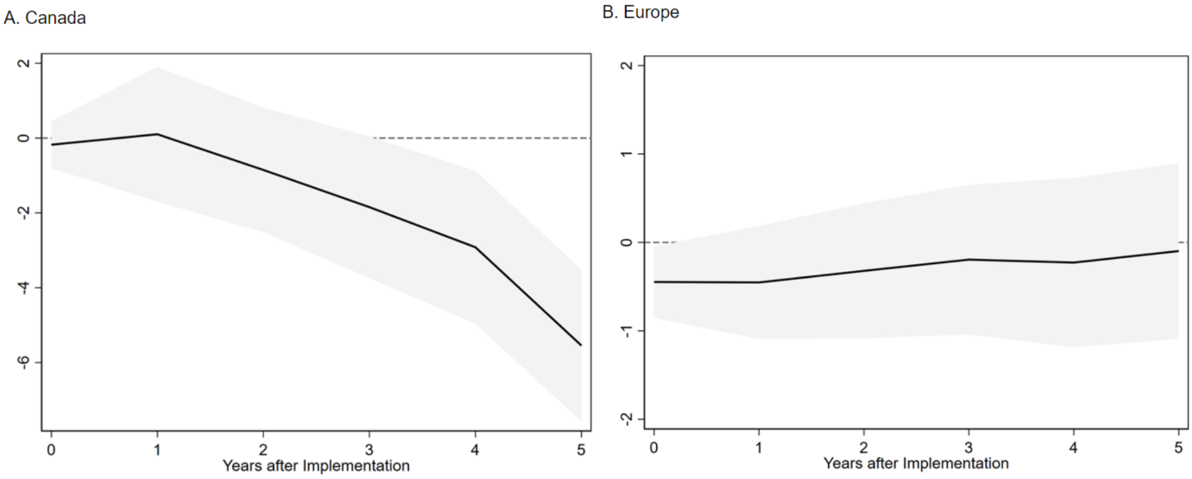
[18] Baeca and Mardones, 2018
[19] Celasun et al., 2022
[20] McKibbin et al., 2014
[21] Abadie et al., 2010
[22] Jorda, 2005

Graph 4

Cumulative Impulse Responses of CPI to An Increase in Carbon Tax



Note: This figure shows the cumulative impulse responses of CPI to a $40 carbon tax with 30% emission coverage, estimated for Canada (panel A) and Europe (panel B), respectively. Shaded grey bounds show 95% confidence bands.

Source: Konradt and Weder di Mauro, 2021

2.3 Distributional Impact of Carbon Taxation

Most of the academic research finds that due to an increase in electricity and public transportation prices, carbon tax policy results in being regressive[23]. On the contrary, an increase in fuel prices is progressive. Consequently, simultaneous price increases for energy goods lead to a higher welfare loss for the poorest and middle-income households compared to the richest households. *Table 3* provides an overview of academic studies on the distributional impact of carbon taxation.

Uribe et al. (2022) find the impact of carbon taxation to be highest for households on the brink of energy poverty and small businesses, both of which are dramatically affected by electricity prices. These household and businesses are forced to drastically reduce their already minimal energy consumption when faced with an energy price shock. This might be a symptom of the system's inability to always comply with energy demand from all agents and could be an early warning sign of energy crises and foreseeable energy shortages in the future[24].

To be more specific, this result can be verified in both developed and developing countries. In studies of developed countries, Bento et al. (2009) analyse the distributional effects of a gasoline tax increase on U.S consumers. Their results show that when revenues are not recycled, a gasoline tax is regressive. However, using the additional gas tax revenue to fund labour tax cuts makes the

[23] Okonkwo, 2021
[24] Horowitz, 2010

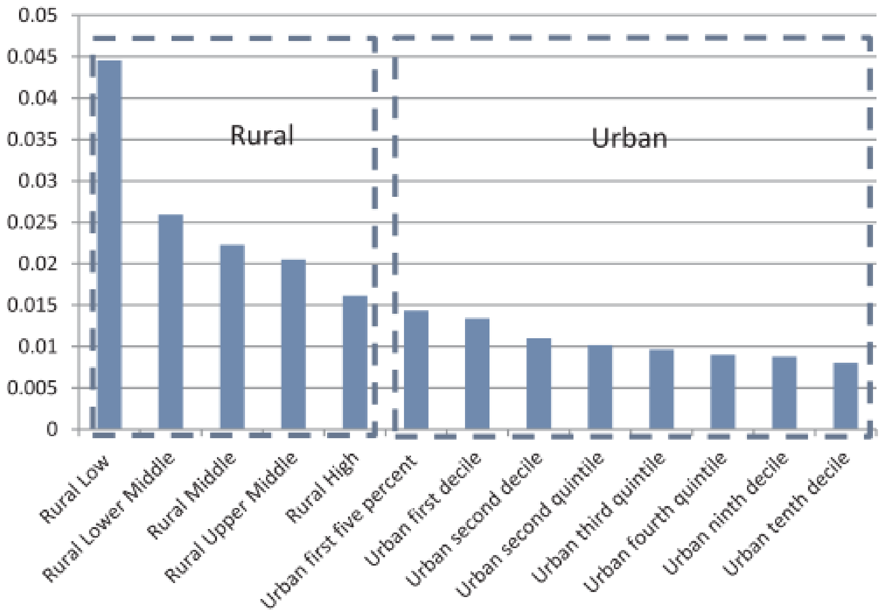
policy substantially less regressive, while using the revenue to fund lump-sum transfers makes it progressive.

Similar results have been found in developing countries. Using an input-output model, Zhang et al. (2019) explain that as the tax rate increases, both the expenditure growth rate after tax and the proportion of carbon tax to income increase in a linear form. That means that if the tax rate doubles, the negative distributional effects are also doubled.

Dorband et al. (2019) find that in contrast to the situation in low- and middle-income countries, carbon pricing tends to be regressive in countries with higher income per capita, mainly reflecting energy consumption patterns.

Graph 5

Distributional effects of carbon tax on different household groups



Note: Shown is the proportion of carbon tax to income for the case when the tax rate equals 100 yuan/ton.
Source: Zhang et al. (2019).

Graph 5 clarifies the effects of a carbon tax on different household groups. The distributional effect on the poorest households is 1.8 times that on the richest ones. Although the degree of regressivity is slight, it cannot be ignored and requires consideration of some compensation policy to offset the negative effects. In addition, the effects of the carbon tax on rural residents are significantly regressive, compared with those on urban residents.

Since the goal of a carbon tax is not to increase tax revenue but to mitigate carbon emissions, the policy should be designed so as to compensate the most vulnerable households for these adverse effects of carbon taxation. Tax revenue reallocation should be a more favourable mechanism than simply exempting these households or returning their tax contributions, due to the potential for redistribution to reduce overall inequality.

Table 3

Academic Studies on Distributional Impact of Carbon Tax

Household Segmentation	Countries/Regions Studied	Common conclusions for each category of studies
Among the income groups	Denmark, the US, the Netherlands; Ireland; the UK; France; China; Cyprus; Sweden; Taiwan; Shanghai; Singapore; Spain New Zealand. Italy. Italy; Spain; SRB (Susquehanna River Basin) in the US; China; British Columbia; Australia; Vietnam; Canada; Indonesia, Malaysia, the Philippines and Thailand	The carbon tax is regressive or exacerbates inequities The carbon tax is neutral for Italy, or neither strictly regressive nor progressive in New Zealand. The carbon tax shows progressivity. A non-monotonic (U-shaped) relationship occurs between carbon taxes and inequality/income level.
Between urban and rural households	Ireland; China; the UK; France; Indonesia, the Philippines and Thailand; Denmark; four provinces in Canada Cyprus; Malaysia	Rural (and suburban) households have higher tax burdens or welfare losses than urban households. Urban households are more affected than rural household
Among households from different regions	International: European carbon taxes; Global carbon taxes Regions within a country: The US (into 9 regions); Sweden (into 3 types of regions: big, middle and sparsely populated areas); China (into 30 provinces); four provinces in Canada	Higher tax burdens fall on poorer countries. Carbon tax incidence across regions might be modest in the US or significant in China and Canada; and in Sweden, households living in sparsely populated areas were the most affected.
Among households grouped by other demographic characteristics	Household size: Denmark; Ireland; Cyprus; Spain Socio-economic status: The UK	Larger families were less affected than smaller families. Disadvantaged families were more affected due to having fewer options to buy low carbon alternatives.
Among generations	Bovenberg and Heijdra (1998) Zhang and Baranzini (2004) Chiroleu-Assouline and Fodha (2006) Rausch (2013)	Carbon mitigation might induce an uneven distribution of cost/benefit across current and future generations; and between the younger and older generations coexisting at a given date.

Okonkwo (2021) uses a CGE model to find the potential for a double or triple dividend if revenues from energy-related environmental taxes are recycled to households by reducing existing taxes. Okonkwo (2021) finds a triple dividend – reduced poverty, decreased emissions and increased economic growth – when any of the simulated environmental taxes is recycled through a reduction in food prices.

When the amount of carbon tax directly paid by households is spent on the groups with low income levels, the progressivity of a carbon tax will be largely removed. In addition, if the total carbon tax directly and indirectly borne by households is reallocated to the groups with low income levels, the inequality will be improved. *Table 4* lists some options for carbon tax revenue recycling mechanisms.

Table 4

Carbon tax revenue recycling

Approach	Pros – Opportunities	Cons – Challenges
Reduce other taxes	Improve efficiency of tax system Promote economic activity	Preferential treatment of certain groups Reducing other taxes can reduce efficacy of carbon tax
Direct household transfers	Fairness and social impact Public support	Missed opportunities to improve productivity of whole economy Administratively complex Possible rebound affects
Transitional support for industry	Economic growth Reduce social and industry opposition Boosts environmental benefits	Can reduce efficacy of carbon price Can unfairly benefit some firms or sections that have competitive advantage
Public debt and deficit reduction	Long-term economic benefits Intergenerational affordability: reduces cost of climate change that must be paid back by future generations	Limited public acceptability, as it is less tangible than other options No direct environmental benefit
General spending	Increases government resource availability Economic support	Lack of clear returns
Climate investment funding	Funding prioritisation of climate change investments Corrective potential by targeting those adversely impacted by climate change Thematic coherence and public support	Negative perceptions of increased public spending Inadequate levels of expenditure if revenues shrink

Note: The Carbon Pricing Leadership Coalition (2016) report lists these different carbon tax revenue recycling options with pros and cons, including potential challenges for household transactions.

Source: Carbon Pricing Leadership Coalition.

Furthermore, the concept of fuel subsidies should be revised when discussing an introduction of carbon taxation. Many studies provide evidence that the fuel subsidies in developing countries are poorly targeted, and that fuel price increases are in general either neutral or progressive, although the impact on the poor is not negligible[25].

Considering subsidies, and taking "adjusting subsidies" as an example, fossil-fuel subsidy reform could be investigated as a possible future renewable energy investment focus. Many countries heavily subsidise energy consumption. However, subsidy reform without clear justification could lead to unexpected social reactions.

Terton et al. (2015) argues that even under low international energy prices, some countries could significantly benefit from the elimination of fossil-fuel consumption subsidies and achieve their Paris Agreement targets solely by implementing corresponding energy subsidy reform policies.

3 Policy Recommendations

3.1 Differentiated Carbon Tax Might Be Preferable

A differentiated carbon tax has been found to work better than a uniform carbon tax. Conventional economic theory suggests that the price of carbon should be uniform[26], as this allows abatement costs to be equalised across sectors, ensuring cost-effectiveness. The UK currently has a number of different carbon prices across the economy, due to overlapping policies and implicit and explicit price signals. Although unintended, this may not necessarily be a bad thing if the price levels are designed with the appropriate complementary policies. For example, differentiated prices may be better utilised during transition periods to stimulate rapid implementation while allowing sectors that can decarbonise relatively cheaply to do so unburdened[27]. Moreover, differentiated sectoral pricing recognises that each sector has different emissions abatement opportunities, and that investment needs to reach net zero.

In sectors where it is cheap to decarbonise, the carbon price can be lower or rise more slowly. For energy-intensive sectors, such as steel and cement, reaching net zero will be more costly and requires rapid technological innovation. Here the carbon price should be higher, therefore, although greater reductions in emissions within difficult-to-decarbonise sectors may be achieved by also investing in low-carbon technologies[28], as a carbon price by itself is unlikely to stimulate the innovation required. For those sectors, sacrificing economic efficiency may be worthwhile to ensure political acceptability.

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[25] Solie and Mu, 2015, Kpodar and Djiofack, 2010
[26] Stiglitz, 2019
[27] Burke et al., 2019
[28] Vogt-Schilb et al., 2018

It is essential to consider the optimal usage of the carbon tax categories. This is because a traditional carbon tax would always cause inequalities[29]. Some new forms of carbon tax regulation, such as *progressive carbon tax*[30] *and differentiated carbon tax*[31], have been proposed by academics and recommended for governments. In these forms of regulation, the *differentiated carbon tax* can also be applied across product types with varying carbon emissions, as well as across regions, sectors, and enterprises. For example, in Norway, the carbon tax rates of different fuels depend on the carbon content. In 2005, the carbon tax rate of mineral oil was €41 per ton of carbon dioxide, and those of light oil and heavy oil were €24 and €21 per ton of carbon dioxide, respectively.

Yuanyuan et al. (2020) found that the impacts of a carbon tax on CO_2 emissions are similar to those on the GDP: significant reduction when the tax is imposed on the sectors of fossil-fuel electricity and coal, and limited reduction when the tax is imposed on other sectors. Thus, differentiated tax rates for each sector have a high potential to better balance the requirements of economic development and carbon emissions reduction.

Furthermore, in the analysis of Yongjian and Fei (2021), a differentiated carbon tax across new and remanufactured products is considered. Even though remanufacturing reduces energy consumption and carbon emissions, it still causes environmental damage in the process of recycling, remanufacturing, and disposal. Therefore, the carbon tax should also be applicable to the remanufactured products[32]. To this end, some manufacturers, such as Caterpillar and Levis, have invested in technology and equipment to reduce carbon emissions under the carbon tax regulation[33]. Yongjian and Fei (2021) concluded that for governments which utilise differentiated carbon tax regulation, a low tax rate is best for remanufacturing activity.

In addition, to maximise social welfare, the government should levy a higher carbon tax rate for enterprises/industries with great environmental damage and a lower rate for enterprises/industries with little environmental damage. Therefore, the formulation of a differentiated carbon tax regulation requires that the government not only trade off enterprise profit, consumer surplus and environmental damage but also discriminate among different industries, emissions reduction technologies and product characteristics of enterprises. This is a challenging and politically sensitive task.

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29 Zhang et al., 2021
30 Yan and Eskeland, 2018
31 Fremstad and Paul, 2019
32 Wang and Li, 2018
33 Lash and Wellington, 2007; Drake and Spinler, 2013

3.2 Phased-in Carbon Tax Appears Superior to the Blanket Approach

The likelihood of implementing an economy-wide carbon price in one single, large legislative reform is low. Sectors for which carbon prices already exist can be grouped together in a first phase of tax policy reform. However, a carbon price may need to be phased in over time for those sectors where the institutional architecture to implement a tax does not exist, where the salience of pricing is low or where monitoring, reporting and verification (MRV) is likely to be complex.

A phased approach also allows consumers to become familiar with the tax and understand its effectiveness[34]. Many countries struggle with design and implementation of MRV systems for agriculture and agroforestry due to technical and institutional challenges[35] and therefore a phased approach may be especially helpful for those in the land use sector.

3.3 Carbon Border Adjustments as a Solution to Carbon Leakage

There is a longstanding concern among policymakers that ambitious climate policies may lead to a loss of competitiveness in some industries[36]. Stringent environmental policies may increase the production cost and decrease the competitiveness of energy-intensive industries. Leakages of carbon can occur as production may shift offshore to countries without a carbon tax.

One possible solution to counter this leakage is the implementation of a CBAM on the imports of energy-intensive goods from countries without appropriate environmental policies[37]. CBAMs reduce free-riding and put pressure on 'climate laggards' to reduce their own emissions, by confronting them with higher exporting costs[38].

CBAM functions as an import tax on both final goods and imported intermediate inputs and increases consumption prices, reducing the welfare of consumers in the home country. There is mixed evidence for the impact of CBAMs on consumption prices or welfare. Some studies have found no welfare effects[39], while others have found that CBAMs increase welfare costs to households through higher import costs[40]. These welfare losses are potentially greatest for the very poor and very rich as these groups consume larger shares of imported goods that experience a price increase through the CBAM[41].

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34 Carattini et al., 2018
35 Rosenstock et al., 2019
36 Dissou and Eyland, 2011
37 Dissou and Eyland, 2011
38 Mehling et al., 2019
39 Kortum and Weisbach, 2016
40 Dissou and Eyland, 2011
41 Sager, 2019

Empirical evidence suggests that current carbon policies have had little impact on competitiveness[42], reducing the importance of adjustment measures. Moreover, there are potential barriers to CBAMs. Since they act as hidden trade barriers, CBAMs are not necessarily compatible with World Trade Organization rules[43] unless foreign and domestic goods are similar so that no product discrimination arises[44]. There are also high administrative costs. Choosing which goods and countries to cover is costly and complex, as it is difficult to measure foreign producers' emissions and to put a price on them[45].

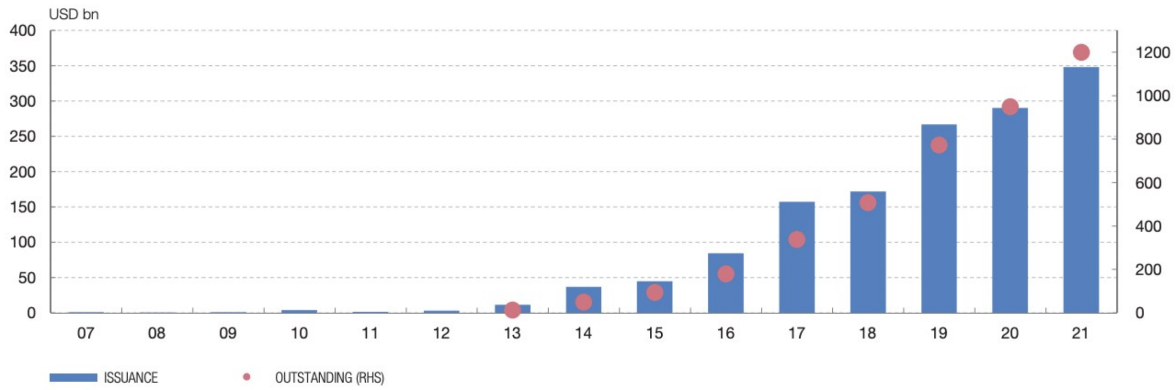
3.4 On Green QE

Green QE refers to a policy that tilts the central bank's balance sheet towards green bonds and bonds with better climate performance[46]. To mitigate the impact of climate change, Green QE could provide support to a sustainable economy through lowering the cost of borrowing[47].

In 2020, the Bank of England was the first central bank to announce a green criterion for asset purchases under its quantitative easing program. The ECB recently also decided to tilt Eurosystem's holdings of corporate bonds towards issuers with better climate performance.[48]

Graph 6

Global Green Bond Issuance and Corresponding Volumes (2007-2021)



Source: Climate Bond Initiative.

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42 Dechezleprêtre and Sato, 2017
43 Trachtman, 2016
44 Majocchi, 2018
45 Kortum and Weisbach, 2016
46 Ferrari and Landi, 2020
47 Bank of England, 2022)
48 https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220704~4f48a72462.en.html and https://www.ecb.europa.eu/press/pr/date/2022/html/ecb.pr220919~fae53c59bd.en.htm l

The lack of a green bond market is often mentioned as one of the major issues central banks face when considering whether to green their balance sheets. Even though a growing supply of green bonds globally has been observed since 2017[49] (*Graph 6*), the general feeling is that demand still significantly outstrips supply.

Although the Green QE benefits the green bond market and encourages a green transition of the economy, market volatility should also be taken into consideration. On the one hand, Yi et al. (2021) shows that the green bond market has a high level of uncertainty resulting from investors' concerns about credit risk. Dutta et al. (2020) investigate the response of green investment to shocks in the oil market. Their findings suggest that green assets are more vulnerable to volatility in the oil market than to oil price levels.

On the other hand, Naeem et al. (2021) find that the green bond market is more efficient than the conventional bond market during external market turmoil, and that investment in the green bond market serves as a good diversifier for investors in conventional bonds. Arif et al. (2021) support this conclusion and find that under extreme external shocks, a green bond is a safe-haven asset for investors in the conventional bond market but also for those in the stock, currency, and commodities markets.

Though central banks' research on the movement of market prices is expanding rapidly, studies that capture the dynamics of the volatility of the green bond market are rather rare compared to studies that examine the volatile nature of the conventional fixed-income market. In this regard, future research should focus not only on the price co-movements of the green bond market and traditional markets, but also on the volatility co-movements.

4 Conclusion

There is no denying the importance of climate change. An increase in global temperature levels from GHG emissions will trigger various catastrophes which will eventually affect countries' GDP, especially in developing nations. The introduction of carbon taxation appears to be a superior policy tool to tackle GHG emissions. Such a tax, however, unless accompanied by other policy measures, is likely to have significant undesirable distributional effects. Furthermore, it is vital to calibrate carbon taxation carefully.

It has been argued that carbon tax may push up energy prices, including the price of electricity. As the price of electricity is a component of headline inflation, a carbon tax might risk triggering national inflation. However, this issue remains controversial since several recent publications find no impact by the carbon tax on the overall price level. Notably, research has mainly concentrated

[49] Climate Bond Initiative, 2019.

on the surge in electricity prices, neglecting the relationship between the electricity price and the price of natural gas, and the possible implications of a change in the energy mix for the transmission of a carbon tax to headline inflation levels.

In terms of distributional impact, the literature indicates that carbon pricing tends to be regressive in countries with higher income per capita, mainly reflecting energy consumption patterns. The risk of inequality in households and small business on the brink of energy poverty is inevitable and impossible to ignore. Policymakers should thus carefully consider how to use carbon tax revenues. Recent studies have shown revenue reallocation from carbon taxation that is targeted towards the most vulnerable households to have the potential to reap a triple dividend – reduce poverty, decrease emissions, and increase economic growth.

In terms of carbon tax calibration, studies have shown that a differentiated carbon tax is more efficient (also in terms of distributional impact) than a uniform carbon tax or progressive taxation. Taking into account that a carbon tax may need to be adopted over time for different sectors, a phased approach has been found more efficient than monitoring, reporting and verification (MRV).

CBAM should be considered as a solution to carbon leakage, as production may shift offshore to countries without a carbon tax upon introduction of such taxation. Though intuitively necessary, CBAM may end up being a highly costly administrative process without tangible impact on climate, unless other relevant policy measures are implemented first.

Finally, Green QE should continue where it is already in place and be considered where it is not yet available. To this end, maintaining green bond market stability is crucial, which means that central banks should stay alert for potential market volatility, including companies‘ greenwashing intentions, further evolution of the COVID-19 pandemic, and the aftermath of Russia‘s war against Ukraine.

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Appendix – Model Explanations

	Model Name
I.	**Heckscher-Ohlin (HO) Model**
II.	**Leontief Pricing Model/ Input-output (IO) Model**
III.	**Computable General Equilibrium (CGE) model**
IV.	**Environmental Dynamic Stochastic General Equilibrium (E-DSGE) Model**
V.	**Quadratic Almost Ideal Demand System (QUAIDS) Model**
VI.	**The Global Change Assessment Model (GCAM)**
VII.	**IMF-ENV Model** (Used in IMF scenario planning but does not occur in other literature)

I. Heckscher-Ohlin (HO) Theorem

The HO theorem, also referred to as the Pollution Haven Hypothesis (PHH), posits that because pollution regulations are stronger or restrictions on emissions are tighter in developed countries than in developing countries, the latter will export 'dirty' products and import 'clean' products[50]. Consequently, according to the PHH, developing countries have a comparative advantage in relatively emission-intensive goods. Dietzenbacher and Mukhopadhyay (2006) analysed the relationship between pollution level and exporting revenue in India. According to the PHH, a developing country loses from extra trade while its trading partner gains. However, the results of this study do not support the hypothesis.

Fifty years ago, Leontief (1953) tested the HO theorem with labour and capital as factors and found similar surprising results. That is, the USA, commonly believed to be the most capital-abundant country at that time, was found to export labour-intensive goods and to import capital-intensive goods. This result, which became known as the *Leontief Paradox*, stimulated research that would later become the *Leontief pricing model/ IO model.*

II. Leontief Pricing Model/ Input-Output (IO) Model

Modern input–output analysis is based on the pioneering work of the Russian-American economist Wassily Leontief, who in the 1930s described the relationships between prices and quantities with respect to supply and demand in a market economy.

[50] Dietzenbacher and Mukhopadhyay, 2006

An IO Model provides a framework that can be used to estimate detailed commodity price effects in response to a carbon policy[51]. The major mechanism of an IO model is an *intermediate transaction matrix*, which describes the mix of production inputs required for every commodity output in an economy. Such a model is capable of capturing not only the direct effects based on the carbon intensity of inputs used in production, but also the sum of all the indirect effects based on the carbon intensity of all the secondary, tertiary, and higher-order inputs to production (i.e., the inputs to the inputs to the inputs, etc.)[52].

The IO Model assumes the following:

1) Labor and capital markets are perfectly competitive.
2) Production functions are fixed, which precludes any factor substitution in response to higher (or lower) input prices. Because of this assumption, the results from these models can only be interpreted as the **short-run**, first-order effects of a carbon pricing policy.

However, Leontief's original model does not consider conditions of market adjustment and assumes that the sectors automatically decide the rise in prices based on their costs. Therefore, studies extend the proxies in the traditional IO model to match their research purposes. For instance, Tarancon and Del Rio (2012) employ different input-output techniques applied to energy-related carbon emissions to identify the transactions between sectors that have the greatest impact on emissions. Choi et al. (2016) extend the traditional IO model by proposing a sequential IO model to analyse the economic and environmental effects of gas taxes and fuel subsidies.

II.1 United States

In Choi et al. (2010)'s research, they proposed a methodology based on an intersectoral approach to analyse a CO_2 tax in the United States. This approach uses several equations sequentially, based on the input-output model combining economic data with the physical flows of fossil fuels, the consumption of natural resources and the emissions for each economic sector.

II.2 Spain

Labandeira and Labeaga (1999) explore the effects of a tax levied on Spanish energy-related CO_2 emissions, employing an input–output demand model. They find a limited short-run reaction to the carbon tax, hampering its environmental success. However, the carbon tax burden is significant with a proportional distribution across households.

Gemechu et al. (2014) investigate the direct and indirect effects of CO_2 taxation on Spanish products, using environmental input-output (EIO) and price models. They find that, in general, the environmental and economic goals cannot both be met at the same time through environmental

[51] Perese, 2010
[52] Perese, 2010

taxation, unless there is a way in which the public revenues could be used to compensate those who are negatively affected by the tax.

II.3 China

In journals that carry out ex-ante evaluations, the input-output approach allows the identification of interdependencies between different sectors of the economy. This intersectoral method is important because the electricity sector is key to the economic development of countries, due both to its strategic importance and to its impact on the economy.

Liu et al. (2009) evaluated how energy policies impact producer prices, consumer prices and the income of rural and urban households. They concluded that improvements in energy efficiency and increase in energy prices allow several economic and energy goals to be achieved.

Guo et al. (2012) used a multi-regional input–output model to analyse China's carbon emissions embodied in international and interprovincial trade from the provincial perspective.

Meng et al. (2014) identified the sectors and economic regions in China with larger electricity-saving potential based on an input-out analysis.

Chen et al. (2015) used a multiregional input-output model at the provincial level in China to evaluate a Pigouvian tax[53] to correct the externality of CO_2 emissions from coal usage.

Moreover, the IO model is employed in the *distributional household impact*, especially when it comes to estimating the poverty disparity in rural and urban areas:

Brenner et al. (2007) find that the introduction of carbon charges on the use of fossil fuels in China would have a progressive impact on income distribution.

Sun and Ueta (2011) examine the scenario presented in a report on the necessity and feasibility of imposing carbon taxes in China and measure the potential distributional impacts of carbon tax. They find that a carbon tax would be regressive in urban areas, but progressive in rural areas.

Wang et al. (2011) provide a detailed analysis of short-term impacts of carbon tax on sectoral competitiveness, based on the Chinese 2007 input–output table. They find that a high tax level (100yuan/tCO2) may necessitate compensatory measures for certain highly affected industries, and that a low tax rate (10yuan/tCO2) would generate few competitiveness problems for all industries.

Liang et al. (2013) find that a carbon tax could have a weakly progressive effect within the rural areas and would widen the income and welfare gap between urban and rural households, and within urban groups.

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[53] A Pigouvian tax is a fee paid by the polluter per unit of pollution and is set to be exactly equal to the aggregate marginal damage caused by the pollution (Kolstad, 2000).

Jiang and Shao (2014) take Shanghai as a case study and estimate the distributional effects of a carbon tax on households across various income groups by using an input–output model and the Suits index, an index based on the principle of the concentration curve and widely adopted to examine the progressivity or regressivity of taxes. Their results indicate that the comprehensive distributional effect of the carbon tax is regressive.

II.4 Brazil

da Silva Freitas et al. (2016) investigate the impact of a policy of taxing GHG emissions on the Brazilian economy as a whole and on different household groups based on income levels in 2009, also using an input-output model. Their main results show that, for Brazil, the taxation system was slightly regressive and had a small negative impact on output but generated significant emission reductions.

II.5 Mexico

Renner (2018) explores the Mexican welfare effects of different carbon tax rates on the income distribution by simulating an input-output model coupled with household survey data. The results indicate that higher simulated tax rates show a slight progressivity, but welfare losses remain moderate, and by widening the tax base to include natural gas and the other greenhouse gases, welfare losses regressivity and poverty rise more.

II.6 *Multi-national Studies in Latin American Countries (Brazil, Mexico, and Chile)*

Cristian and Nicolas (2018) facilitate the Leontief pricing model and develop their new input-output model in an environmental extension. They define a Leontief pricing model merely used to measure economy operates (technical relations of production and primary costs), but their environmental extension of the input-output model is utilised to measure total CO_2 emissions generated by the production of an economic sector, consisting of direct emissions from that sector and indirect emissions produced by other sectors that are required as inputs by the first sector. The objective is to simulate a carbon tax's effects in three Latin American countries. Their results show that the decrease in emissions would be approximately 4% for Brazil, and 36–47% for Mexico and Chile, as well as a reduction of economic sectors under the highest tax scenario.

II.6.1 The European Union

Rocchi et al. (2014) applied a multiregional input-output model to evaluate the effect of an energy tax on prices in different sectors of the 27 countries subject to the European Energy Tax Directive (ETD). Their simulation results indicate that the new energy tax regime would not have had a strong and wide impact on prices: the tax increase would have caused a price variation greater than 0.50% only for a few sectors in a few countries; expressing the price changes through a consumer price index, the effect of the reform would have been even weaker.

II.6.2 *Cross-border Effect*

Zhang et al. (2017a) discussed the environmental effects of global production fragmentation using a multi-regional input-output analysis. Their results show that international trade corresponds to negative balances of avoided emissions over 1995–2009. In the absence of international trade, global carbon emissions would increase by 822.61 million tons in 2009, even though international trade became less environmentally friendly after the shock of the economic crisis in 2008. The trade in final products became increasingly less environmentally effective for 1997–2009 because downstream production gradually shifted to developing countries with higher carbon intensities, such as China. From a bilateral perspective, the largest net carbon flow is from China to the USA through the trade in final products, which corresponds to a positive balance of avoided emissions.

Zhang et al. (2017b) focused on border-crossing frequencies of carbon footprints and showed its impact on the effectiveness of climate regulations. Building on *2017a*, they found that the implementation of carbon tariffs faces the problem of multiple taxation. They illustrate that the multiple taxation problem of carbon tariffs would become increasingly serous with an increase in the number of countries adopting border carbon adjustments because carbon emissions embodied in intermediate traded products may be targeted by border carbon adjustments of different countries. Thus, this significant study highlights the policy implication of the concept of border-crossing frequencies of carbon footprints.

Zhang and Zhu (2017) traced carbon transfer along cross-border supply chains of the United States and the European Union. They find that the border carbon rebates reduce production costs, and the consumers of the exported products benefit from the lower price level. Their calculation shows the largest share of the rebate revenue received by the consumers of China. China has close economic links with the United States and the European Union. Frequent trade flows determine that the rebate revenue received by consumers in China is more sensitive to the border-crossing frequency associated with carbon footprints.

III. Computable General Equilibrium (CGE) Model

III.1 South Africa

Van Heerden et al. (2006) first constructed the South African CGE model to find the potential for a double or triple dividend if revenues from energy-related environmental taxes are recycled to households by reducing existing taxes. They find a triple dividend – reduced poverty, decreased emissions and increased economic growth – when any of the simulated environmental taxes is recycled through a reduction in food prices.

III.2 *China*

Liu et al. (2018) established a CGE model for Saskatchewan, Canada to quantify the inter-relationships of the carbon tax, GHG emission reduction, and economic growth. The results showed that the GDP decline was mainly caused by consumption reduction and import increases.

Based on an improved two-region CGE model, Li et al. (2018) found that the highest carbon tax of 221 USD/ton-CO2 in Liaoning province will lead to a carbon reduction of 44.92% at a cost of 5.54% of GDP loss in 2030.

Based on the simulation results of a CGE mode of China, Lin and Jia (2018) suggested that the government should impose a higher carbon tax on energy sectors. That is because such a tax could maximise emissions reductions and have small effects on GDP.

III.3 *British Columbia & Australia*

To estimate the effects of carbon tax on GDP in British Columbia, Bernard et al. (2018) set the tax rate from \$10/t-CO_2 to \$30/t-CO_2 in the period of 2008–2017 with the modelling strategy, and they found that the effects on GDP were not significant.

In Australia, Meng et al. (2015) reported that in 2004–2005, a carbon tax rate of \$23/t-CO2 could lead to a 12% reduction in carbon emissions and cause a slight economic contraction.

III.4 *Multinational scale*

At the national scale, more research has been performed. For example, Wissema and Dellink (2007) found that a carbon tax of 10–15 euro/t-CO_2 would cause CO_2 emissions to drop by 25.8% compared with the 1998 figure in Ireland, while the social welfare would fall.

Zhang et al. (2016) developed a new multi-country CGE model to evaluate the impact of a carbon tax and combined policy mixes, and demonstrated that policy mixes could benefit both economic efficiency and emission performance better than a carbon tax.

By using a new dataset on carbon tax rates (including 25 countries around the world), Metcalf and Stock (2020) estimated the macro-economic tax's impacts on GDP and employment growth rates for various specifications and samples with CGE model, and suggested that there were no negative impacts.

IV. Environmental Dynamic Stochastic General Equilibrium (E-DSGE) Model

The E-DSGE model concept is first proposed by Fischer and Springborn (2011) and Heutel (2012). The model serves as an extension of the DSGE model that is a standard tool in the macroeconomic literature. The terminology 'E-DSGE' was first introduced by Khan et al. (2019). Most studies utilise the E-DSGE model for the following reasons:

1) The E-DSGE model predicting the intertemporal decisions of firms and households is dynamic and forward-looking. Hence, the time-varying optimal carbon tax rates can only be solved by the W-DSGE model.
2) Shocks from different sources are incorporated in the E-DSGE model, and therefore the optimal carbon tax rate can be solved conditional on the realizations of different shocks. Therefore, the E-DSGE model might be more favorable because the CGE model cannot show the economic shocks.
3) The E-DSGE model performs better in dealing with the dynamics and uncertainties of the economy to analyse the role of a carbon tax in the presence of multiple sources of macroeconomic uncertainty (such as tourism under the pandemic[54]).

IV.1 United States

Firstly, Annicchiarico and Di Dio (2015) and Heutel (2012) show that the optimal carbon tax rate should be procyclical: it should increase during economic booms and decrease during busts. Hence, it is expected that the optimal climate policy which is jointly decided by the countries should depend on the economic environment of each country, especially for the countries whose business cycles are less synchronised. In this regard, this paper determines the optimal carbon tax rates in an international environmental agreement for countries that have different economic conditions.

However, the flaw in these two studies is that they only focus on shock transmission across the countries and do not solve for the optimal climate policy in their model. Both studies solve the problem solely in a one-sector setting and do not solve for the optimal carbon tax rate in response to international shocks or the shocks from another country.

Consequently, Chan (2020) extends Annicchiarico and Di Dio (2015) by presenting a two-sector environmental dynamics stochastic general equilibrium (EDSGE) model.

1) **On the household side**, each country is populated by a continuum of identical households, each of which derives its utility from consumption and leisure and makes dynamic consumption and saving decisions.
2) **On the production side**, the final output is made of capital, labor, and energy. Capital and labor are supplied by the household, while energy is imported, with the energy price that is exogenously determined. The final good, whose market is perfectly competitive, is composed of a continuum of intermediate goods. The intermediate goods market is monopolistic-competitive. For the environmental setting, Chan (2020) assumes that CO_2 is emitted during the production process. The CO_2 emissions stock, which is accumulated by the CO_2 emissions in both countries, would reduce firms' productivity. The government (in

[54] Cao et al.,2021

each country) can levy a carbon tax rate to mitigate the CO_2 emissions. If a carbon tax is levied in a country, the intermediate good firms can abate their CO_2 emissions by exerting an abatement effort which would incur an abatement cost.

Dissou and Karnizova (2016) propose a two-sector E-DSGE model and note the importance of the shocks arising from the energy sector in the US. They found no significant difference between the cap and the tax regimes when shocks come from non-energy sectors. In contrast, the cap has lower volatility but higher welfare costs than the tax for the shocks to energy production.

IV.2 China

Chan (2020) considered the impacts of international environmental agreements and used the EDSGE model to determine the optimal carbon tax rates for countries that were with and without an agreement, focusing on the Ramsey problems that allow social planners to choose all the endogenous variables in order to maximise the social welfare of the economy.

Cao et al. (2021) extended Dissou and Kamizoya (2016)'s methodology and applied a multi-sector E-DSGE Model to show that the output and carbon emissions vary significantly across tourism sectors in response to productivity and carbon tax shocks. They found that an increase in the carbon tax rate leads to a rise in the marginal cost of tourism sectors, which suppresses the production of tourism sectors and in turn reduces output.

V. Quadratic Almost Ideal Demand System (QUAIDS) Model

V.1 Sweden

Brannlund and Nordstrom (2004) use a QUAIDS model to observe that the poorest and richest households experience a welfare loss of 0.52% and 0.33% of their disposable income, respectively. The regressive nature of CO_2 taxes in both studies can be explained by two factors:

1) CO_2 intensities vary strongly between consumption goods, with food and transport being highly CO_2-intensive, and services and financial transfers being at the other end of the scale.
2) Low-income cohorts mainly consume carbon-intensive necessities, while high-income cohorts spend a large part of their income on "luxury" items that have a higher service component.

V.2 Brazil

Moz-Christofoletti and Pereda (2021) analyse the effectiveness of implementing an economy-wide carbon tax as an option among carbon pricing mechanisms, given that tax system reform is a top priority for the current Brazilian government. Their results indicate that a carbon tax tends to be regressive by causing welfare losses of 0.06% and 0.10% in relation to total expenditures for richest and poorest households, respectively. Low-income households are less price-responsive for the majority of carbon intensive categories, thus, they suffer a larger relative welfare loss due to the carbon tax. They are also more likely to suffer from a larger relative indirect effect of food and beverages and housing-related consumption, which accounts for a greater budget share of these households. Significant changes in total GHG emissions would require a higher tax rate, which would reinforce the repressiveness of the policy.

V.3 South Africa

Banks et al. (1997) first introduced the idea when evaluating the distributional and welfare impacts of carbon taxation in South Africa. Using South African household survey data with about 73,000 observations and five expenditure categories – electricity, motor fuels, public transport, food, and other goods – income and price elasticities are derived. The elasticities were then used to simulate the effects of energy price changes on South African households.

V.4 Mexico

Rosas-Flores et al. (2017) and Renner et al. (2018) use the QUAIDS model to study the effect of environment taxes on Mexican households. They find that a tax on electricity, gas and transport is regressive while a tax on gasoline and motor fuel is progressive.

More specifically, the analysis of the emission implications of different tax scenarios indicates that short-run emission reductions at the household level can be substantial - though the effects depend on how the revenue is recycled. This effectiveness, combined with moderate and manageable adverse distributional impacts, renders the carbon tax a preferred mitigation instrument. Considering the large effect of food price increases on poverty and the limited additional emission-saving potential, the inclusion of CH_4 and N_2O in a carbon tax regime is not advisable.

VI. The Global Change Assessment Model (GCAM)

The model operates in five-year time steps from 1990 to 2100 and comprises 32 regions of the world. Primary energy reserves are based on Rogner (1997) and energy resources are assumed to be fairly abundant which, along with assumed technological progress, results in lower growth in extraction cost due to resource depletion. Substitution across energy types in production is driven by relative cost differences, and a logit formulation is employed to avoid a winner-take-all result.

VI.1 United Kingdom

Barrage (2020) characterised the optimal climate policy in suboptimal fiscal settings where income taxes were constrained to remain at their observed levels and established a theoretical relationship between the optimal taxation levels of carbon and of capital income.

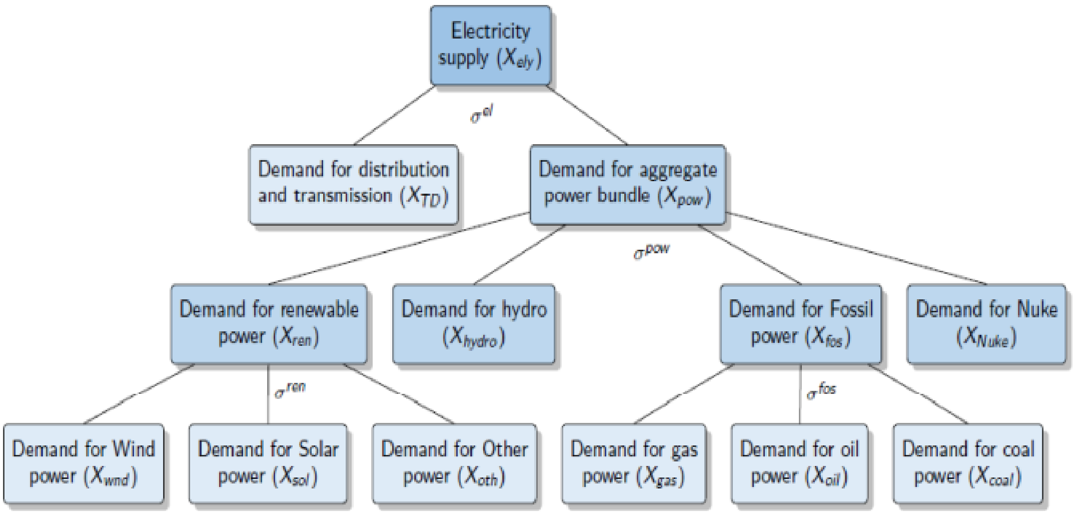
VII. IMF-ENV Model[55]

The IMF-ENV model is utilised to analyse the economic effects of climate policy options in a CGE perspective. This model allows simulation of impacts of climate mitigation policies on emissions, macroeconomic variables, sectoral outcomes, and trade. The model is based on a neo-classical framework, dealing only with real values and with almost perfect markets for commodities and production factors.

For instance, the standard representation of electricity supply in each region rr in the IMF-ENV model assumes that a representative electricity provider chooses an optimal mix of electricity generation across electricity generation technologies a = {solar, hydro, nuclear, wind, other renewables, oil power, gas power, coal power}:

$$Max\ X_{ely}\,.P_{ely} - X_{TD}\,.P_{TD} - \sum_a X(a).p(a)$$
$$X_{ely} < F\big(X_{TD}\,;\ X_{pow}(X(a_1), \dots, X(a_n))\,\big)$$

where the supply of electricity X_{ely} is a combination of X_{TD}, the demand for electricity transmission and distribution services, and the demand for power X_{pow}. Electricity generation X_{pow} is a combination of electricity generation from various primary energy sources. X(a).p(a) is the production cost by type of electricity generation technology, in USD per kilowatt hour. The production function F (.) is a nested CES function of electricity generated by the various primary energy sources *a.*



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