硕士研究生学位论文

题目： **比较化石燃料出口地区碳税和碳奖励的相对收益**

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摘要

政府间气候变化专门委员会，气候科学家和《巴黎协定》均表明，为了将全球变暖限制在 1.5°C以内，全球经济需要进行大规模的结构调整。在碳排放与全球经济脱钩的时间有限的背景下，本文对一项新的气候政策进行研究，以追求通过经济转型实现全球快速脱碳。因为化石燃料出口地区的短期经济利益与《巴黎协定》中 1.5°C 的气候目标的高度不一致，本研究以化石燃料出口地区的清洁能源转型为切入点，使用综合评估模型和分析方法来比较两种不同的气候政策对实现全球 1.5°C 目标的可行性。第一种气候政策是在区域层面实施的强有力的全球碳税，而第二种政策是陈等人制定的新市场政策——全球碳奖励——在此称为“碳奖励”。碳价是气候和生物圈的全球公共产品，而陈等人定义的正外部性从根本上改变了碳价的标准模型。本研究通过研究实现 1.5°C 目标所需的碳税水平及其对国内生产总值的相关影响，探讨了环境经济学中的一些非常重要的问题，提出一套描述全球碳奖励的分析公式；评估全球碳奖励实现 1.5°C 目标的可能性；并且，比较高碳税与碳奖励以实现 1.5°C 目标的区别。碳税的评估基于综合评估模型的结果，而碳奖励的评估基于分析公式。

这项研究发现，相对于气候政策更温的基线情景，当提高碳税时，所有化石燃料出口地区的国内生产总值将在 2055 年减少8%。 综合评估模型结果还显示，化石燃料出口地区所需的税收如此之高，以至于碳税方法似乎无法为实现 1.5°C 目标提供可行的社会经济途径。本研究随后分析评估了全球碳奖励提供的资金方式，认为全球碳奖励可以为化石燃料出口经济体的脱碳提供足够的资金水平（在相应的奖励高峰年份占区域国内生产总值的 0.6% 至2.1%），并为实现 1.5°C 目标的社会经济/地缘政治提供了一条大大改善的途径。与高碳税情景相比，目前的可行性评估表明全球碳奖励是有希望的。

然而本研究也存在一定的局限性。综合评估模型不包括可能降低必要碳价格的负排放。用于评估全球碳奖励的分析公式无法定量评估政策的整体宏观经济影响。此外，为了更客观地评估全球碳奖励的效用和社会经济可行性，并改进其实现《巴黎协定》 1.5°C 目标的政策机制，应该对全球碳奖励进行更详细的审查和评估。

关键词：全球碳奖励、碳税、碳风险成本

COMPARING THE RELATIVE BENEFITS OF CARBON TAXES AND CARBON REWARDS IN FOSSIL FUEL EXPORTING REGIONS

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ABSTRACT

Recent reports from the IPCC have shown that large structural adjustments to the global economy are required to limit global warming to 1.5°C, as agreed to under the 2015 Paris Agreement. Given that the time available to decouple carbon emissions from the global economy is limited, this study has focused on a new climate policy that has the potential to speed the transition to a low carbon economy. It focuses on the clean-energy transition for fossil fuel exporting regions because their short-term economic interests are most at odds with the 1.5°C climate goal of the Paris Agreement. This study uses an integrated assessment model (IAM) and analytical methods to compare the feasibility of limiting global warming to 1.5°C through two policy options: (1) strong global carbon taxes that are implemented at the regional level, and (2) a novel market policy developed by Chen et al. (2017), called the global carbon reward (GCR), and referred to here as GCR or "carbon reward." The GCR is supported by a new theory that fundamentally differs from the standard model for carbon pricing by introducing a positive externality, which is defined by Chen et al. (2017) as the global public good associated with stabilising the climate and biosphere. The ideal value of the carbon reward—for creating the proposed positive externality for limiting climate change to an agreed level of certainty—is called the *risk cost of carbon* (RCC).

This study explores some highly important issues in environmental economics by (1) examining the level of carbon taxes that are needed to address the 1.5°C goal and their associated effect on gross domestic product (GDP); (2) presenting a set of analytical formulas for describing the GCR; (3) examining the macroeconomics of the GCR for addressing the 1.5°C goal; and (4) comparing the feasibility of high carbon taxes versus carbon rewards for meeting the 1.5°C goal. The assessment of carbon taxes is based on the results of the IAM, whereas the assessment of carbon rewards is based on the analytical formulas.

This study found that fossil fuel exporting regions face GDP reductions of up to 8% in 2055 when carbon taxes are raised to limit global warming to 1.5°C relative to a baseline scenario of moderate climate polices and higher levels of warming. All fossil fuel exporting regions other than the Middle East also saw reduced economic output from their fossil fuel industries. The IAM results also reveal that to achieve the 1.5°C goal, the required carbon taxes in fossil fuel exporting regions were up to $US 19,162/ton. Because the high carbon tax approach does not appear to offer a feasible socioeconomic pathway, additional mitigation policies must be considered if the Paris Agreement goal is to be reached.

This study is the first to consider the impact of the GCR and is therefore still preliminary. It finds that the GCR (a) can provide sufficient levels of finance to decarbonise fossil fuel exporting economies (between 0.6% and 2.1% of regional GDP in respective peak reward years); globally, the rule for cleaner energy provided debt-free financing of $US 240.19 billion in 2025 which grew until it peaked at $US 3,132.72 billion in 2050. And (b) offers an improved socioeconomic pathway to the 1.5°C goal when compared to the high carbon tax option.

The current feasibility assessment suggests that the GCR is promising, but this study has certain limitations. The IAM did not include negative emissions such as carbon sequestration, which may lower the necessary carbon price. The analytical formulas used to assess the GCR cannot quantitatively assess the policy’s overall macroeconomic effects. Ultimately, the GCR should be reviewed in more detail to help evaluate its socioeconomic feasibility and review its policy mechanisms for achieving the 1.5°C goal.

KEY WORDS: Global Carbon Reward, Carbon Tax, Risk Cost of Carbon, Social Cost of Carbon, Paris Agreement, Fossil Fuels

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List of Abbreviations

Acronym	Term
CC	carbon currency
CDR	carbon direct removal
CO_2e	greenhouse gas emissions with equivalent warming potential to carbon dioxide
GCR	global carbon reward
GDP	gross domestic product
GHG	greenhouse gas
HMH	holistic market hypothesis
IAM	integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
NET	negative emissions technology
RCC	risk cost of carbon
SCC	social cost of carbon
SSP	shared socioeconomic pathway
TCC	total externalized cost of carbon
toe	energy produced equivalent to the energy produced by one ton of oil
$US	United States dollar

Chapter 1: Introduction

The April 2022 report from the Intergovernmental Panel on Climate Change (IPCC) shows that the remaining carbon budget to limit global warming to 1.5°C above pre-industrial levels (>50%) is 510 gigatons of carbon dioxide ($GtCO_2$)[1] (IPCC Working Group 3, 2022b, p.20). With current international climate policy, this goal is out of reach. Current mitigation trends will lead to more than 3°C of global warming (IPCC Working Group 3, 2022b, p.19). Key contributors to this climate risk are fossil fuels and the emissions 'locked in' to fossil fuel infrastructure (International Energy Agency, 2021b, p.39; IPCC Working Group 3, 2022b, p.20). Based on historical operating patterns, the 'locked-in' emissions from 2018 to the end of the lifetime of existing fossil fuel infrastructure are 660 $GtCO_2$[2]; these 'locked-in' energy emissions alone are 30% greater than the entire carbon budget for a 50% probability of limiting global warming to 1.5°C (International Energy Agency, 2021b, p.39). This means, to limit global warming to 1.5°C, fossil fuel resources worldwide must be retired *before* the end of their lifetime; large scale-carbon capture and storage may also be required (Rogelj et al., 2018, p.327).

Recent research demonstrates that there are long-term financial incentives for fossil fuel exporters with high marginal costs of production to shift to low carbon alternatives (Mercure et al., 2018, 2021). However, in spite of small steps in this direction there has not yet been a significant shift from high- to low-carbon energy assets among major fossil fuel producers (M. Li et al., 2022); the sunk costs and high private and government revenues of existing fossil fuel infrastructure incentivize them to continue use of the infrastructure until it is written off (Fattouh et al., 2018). If the Paris Agreement goals are to be met, significantly more funding must be allocated towards decarbonising global energy infrastructure (McCollum et al., 2018, p.589). The speed and extent of the energy transition in fossil fuel exporting regions will ultimately shape the entire global energy transition (Fattouh et al., 2018). A key challenge for global policymakers is to maximise the speed of this transition while minimising the costs to fossil fuel exporters by aligning their short-term financial needs with the long-term need to safeguard the planet.

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[1] A carbon budget estimates if global warming will be kept below a certain level (in this case 1.5°C above pre-industrial temperatures) with a modelled chance of success (ex. >50%). The IPCC's assessed 1.5°C carbon budget (>50%) has a possible range of 330-710 $GtCO_2$.

[2] Possible range of current locked in emissions is 460–890 $GtCO_2$.

Nordhaus (2019) argues the fundamental problem for climate mitigation policy is that the climate is a global public good and greenhouse gas (GHG) emissions are a public bad, or negative externality; this creates a market failure in that the costs of climate action or inaction are not captured in market prices (p.1992). The global climate system is an even more complicated market failure due to what Carney (2015) calls the *tragedy of the horizon,*[3] in which there are few direct incentives for current generations to address the negative externalities caused by climate change (p.4).

The standard market-based policy solution for addressing these market failures and properly aligning incentives has been the implementation of a negative carbon price equal to the *social cost of carbon (SCC)* — the negative externality imposed on society by carbon pollution. Many national and regional governments have addressed this externality directly through direct carbon taxes or indirectly through quota-based cap and trade systems. In the past, carbon taxes have been labelled "optimal" for controlling GHG emissions and internalising the negative externalities of greenhouse gas (GHG) emissions by economists (Nordhaus, 1992); however, even in fossil fuel exporting countries such as Canada that have adopted carbon taxes, there continues to be expansion in the use of fossil fuels that is inconsistent with Paris Agreement goals (Climate Action Tracker, 2021).

Ultimately, SCC-based regulation continues to fall short of our climate needs because it can only address the observable linear negative externality associated with the marginal cost of pollution and its alignment with the marginal benefit of energy, transportation or whatever other good the emissions are embedded in. This could be efficient in a linear system. However, the climate system is not linear; the risk of tipping points and feedback loops in the climate system is not predictable and could greatly accelerate the relationship between anthropogenic emissions and global warming (Lenton et al., 2019, p.594) if we exceed the Paris Agreement goals.

Lenton et al.'s (2019) study of tipping points contends that the uncertainty around the current carbon pathway creates an existential threat to humanity; therefore it is irrational not to take significant mitigation activities to reduce the emissions embedded in the current socio-economic structure of the global economy (p.595). The urgency of the situation calls for the

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[3] First defined by Carney (2015), the tragedy of the horizon describes the lack of resources allocated to reducing the risk of events likely to occur in the future. There appears to be little incentive for current generations to take actions that benefit future generations.

investigation of new polices using the principal of ‘meta design.’ In contrast to design which promises results that can be fully represented in advance of action, meta-design, in the context of the climate crisis, says we should consider less traditional solutions, identify ‘unthinkable-possibles’ and then ‘re-language’ them to create ‘future-possibles’ (Wood, 2022, p.17). Wood (2022) argues that this creates a culture of ‘opportunity-finding’ which this study looks to advance through the inclusion of a novel economic policy called the global carbon reward (GCR). The principal of meta-design argues we must be willing to break “with the modern and its categories” to be “able to think and act with sufficient capacity to at least ameliorate and then to gradually transform crisis” (Dilnot, 2022, p.xvii).

Despite studies that demonstrate higher carbon prices alone cannot completely decarbonise the energy system to meet the Paris Agreement goals (Daggash & Mac Dowell, 2019), there has yet to be a comprehensive and satisfactory examination of alternate market-based carbon mitigation policies that could align humanity’s inherent interest in stabilising the earth’s biophysical systems with economic development and the short-term incentives of fossil fuel exporting regions. This study aims to address this gap by investigating macroeconomic impacts of a regionally imposed carbon tax (the traditional ‘modern’ solution) as well as a novel policy called a carbon reward (a solution that moves beyond the traditional fiscal policy framework of climate policy) to transition fossil fuel exporters’ energy infrastructure and ensure that economic systems operate within planetary boundaries (see section 2.1.2 for a definition).

A carbon reward, such as that proposed by Chen et al. (2017), aims to addresses the complex externalities and temporal aspects of the climate market failure. The proposed policy, known as the global carbon reward (GCR), would fundamentally change the standard model for carbon pricing by integrating a positive externality, called the *risk cost of carbon* (RCC) into global markets (p.233). The RCC is the positive externality associated with the value of a stable climate system; the market price is a reward for mitigated carbon based on the greenhouse gas reductions necessary to limit global warming to a specific temperature range with a prescribed level of certainty. The GCR internalises the RCC through a system of payments for global mitigation activities funded by asset purchases from a consortium of central banks rather than domestic fiscal policy. Chen et al.’s proposal would represent a paradigm shift in economics by combining three complementary economic objectives: (1) improving the allocative efficiency of markets through a carbon tax, (2) providing financing to transition from high to low carbon energy courses, and (3) ensuring that a relatively safe and stable climate will be achieved with the carbon reward. Since there is a large gap in the available clean energy funding for achieving the Paris targets (McCollum et al., 2018, p.590), the carbon reward policy is worth investigating.

This study explores some vital issues in environmental economics by (1) examining the level of carbon taxes needed to address the 1.5°C goal in fossil fuel exporting regions and their associated effect on gross domestic product (GDP); (2) presenting a set of analytical formulas for describing the GCR; (3) examining the macroeconomics of the GCR for addressing the 1.5°C goal; and (4) comparing the feasibility of high carbon taxes versus carbon rewards for meeting the 1.5°C goal. The five net fossil fuel exporting regions identified in this study (based on 2014 data) are: the Middle East, the Former Soviet Union, Africa, Canada, and Australia & New Zealand (see table 4.1).

The goal of this study is to quantitatively and qualitatively (where quantitative comparison was not possible) compare the effects of two policy pathways to limit global warming to 1.5°C in fossil fuel exporting regions:

(1) A "high carbon tax" policy scenario denoted "CT-NDC" was modelled using an integrated assessment model (IAM).

(2) A "carbon reward" policy scenario, denoted "CR" was developed using the output of the (IAM) and out-of-model calculations.

The study uses the Integrated Model of Energy, Environment and Economy for Sustainable Developed/Computable General Equilibrium (IMED|CGE) developed at Peking University (Dai, 2018) to construct two scenarios. (1) A baseline scenario (hereafter NDC) where carbon emissions are set by the Nationally Determined Contributions (NDCs) of the Paris Agreement that were announced before the 26th Conference of the Parties (COP26). (2) A high carbon tax scenario, CT-NDC, investigates the impacts of limiting global warming to 1.5°C on gross domestic product (GDP), primary energy supply and regional carbon emissions of fossil fuel exporting nations through regionally applied carbon taxes. The GCR is a novel market-based mitigation policy which could not be integrated into the IMED|CGE model in the available time. As a result, multiple research methods have been adopted (out-of-model calculations and a qualitative discussion of the CT-NDC and CR pathways) to investigate the macroeconomic potential of the GCR policy for financing cleaner energy production in fossil fuel exporting regions, for accelerating the transition to net-zero and for meeting the Paris Agreement targets.

The GCR policy has other functions, including the financing of reduced emissions and carbon removal, however, these two functions were not examined in this study. Therefore, the study is likely to underestimate the potential of the GCR policy to mitigate GHG emissions.

This study answers three questions based on the scientific consensus that global warming must be limited to 1.5°C by 2100:

(Q1) What reduction in GDP will fossil fuel exporting regions experience if warming is limited to 1.5°C by a high carbon tax scenario (CT-NDC) as compared to a moderate climate policy scenario (NDC) based on the nationally determined contributions to the Paris Agreement?

(Q2) What debt-free financing would be provided to fossil fuel exporting regions through the carbon reward (CR) scenario for cleaner energy production if the same emissions and energy intensity reductions were observed as in the high carbon tax (CT-NDC) scenario?

(Q3) Based on the current decarbonisation literature and the quantitative answers to questions (1) and (2), what policy combination is more likely to enable the global economy to meet the climate target?

This study found that all fossil fuel exporting regions faced GDP reductions (of up to 8%) in 2055 when high carbon taxes are imposed to limit global warming to 1.5°C relative to the NDC scenario. All fossil fuel exporting regions other than the Middle East also saw reduced economic output from their fossil fuel industries. The IAM results for the 1.5°C scenario also revealed that the required taxes in fossil fuel exporting regions are so high that the carbon tax approach does not appear to offer a feasible socioeconomic pathway to the 1.5°C goal. This supports Daggash and Mac Dowell (2019) who found that it was not cost effective to reach the Paris Agreement goals without a combination of market-based mitigation policies.

Using a conservative estimate of potential debt-free financing from the GCR, this study found that the policy can provide sufficient levels of finance to decarbonise fossil fuel exporting economies (between 0.6% and 2.1% of regional GDP in respective peak reward years). Globally, the rule for cleaner energy modelled using IMED|CGE data provided debt-free financing of $US 240.19 billion in 2025. GCR financing grew until it peaked at $US 3,132.72 billion in 2050. Over this period, the GCR financing is in line with McCollum et al.'s (2018) estimates for the investment gap between a baseline energy scenario and a scenario that decarbonised the global energy system and limited warming to 1.5°C (p.590);[4] however, the financing provided by the GCR using the IMED|CGE data was not as front loaded as the research suggests is necessary for limiting global warming to 1.5°C. Section 4.4 demonstrates that the GCR rule for cleaner energy may also be calibrated as needed to shift investment from fossil fuels to lower-carbon energy sources in line with the goals of the Paris Agreement.

Compared to the high carbon tax option, the GCR may also offer an improved socioeconomic pathway to the 1.5°C goal by incentivising the early retirement of fossil fuel infrastructure with 'locked-in' emissions and by making rapid renewable deployment scenarios feasible. While most fossil fuel exporting regions are not currently introducing, and are unlikely to implement, sufficient carbon taxes, a global reward for carbon mitigation and specifically the transition of high carbon to lower carbon energy sources could align their short-term incentives with the Paris climate goals. Further development and testing of the GCR is recommended to strengthen the understanding of how the policy could be integrated into the global financial system, its effects on global warming and its impact on the economy – of particular interest is its utility in preventing dangerous or even catastrophic global warming.

This study also finds that the GCR policy is highly sensitive to assumptions about the required level of carbon direct removal (CDR), the future price development of carbon removal and the estimation of the carbon intensity of energy baseline values, all of which should be carefully considered in its future policy design. It must be noted that estimates of the reward for cleaner energy that would be available for limiting global warming to 1.5°C are likely low because the 1.5°C carbon budget used in the model is higher the IPCC's most recent estimates and the model relies on reductions in primary energy supply to achieve a high level of emissions reductions rather than the rapid deployment of renewable energy. Owing to data constraints, this study cannot quantitatively determine how this reward would affect GDP and other socioeconomic indicators in fossil fuel exporting regions.

Section 2.1 reviews the key definitions used in this thesis, section 2.2 reviews the short- and long-term macroeconomic incentives in fossil fuel exporting regions, and section 2.3 reviews

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[4] McCollum et al. (2018) found that $US 480 billion of additional clean energy investment (an investment gap) was needed to achieve global energy goals between 2016 and 2030 when compared to total energy investment in their baseline scenario; total energy investment required as estimated in the authors' 1.5°C scenario is approximately US$ 3.38 trillion annually between 2016 and 2050.

the two policy pathways considered in this study and the theories that support them. Due to the novelty of the GCR in environmental policy, this study dedicates significant space to explaining the GCR policy and the methodology used to compare the different mitigation policies. Chapter 3 discusses the methodology developed for comparing the feasibility of the carbon tax and carbon rewards to limit warming to 1.5°C. Chapter 4 discusses the quantitative results of the IMED|CGE and developed models. Chapter 5 integrates these quantitative results with a qualitative discussion of the capacity of each policy to incentivize fossil fuel exporting regions to bring the global economic system in line with the planetary boundary framework.

Chapter 2: Fossil Fuel Exporters' Economic Incentives in the Energy Transition

This section introduces the key definitions used in this thesis, discusses the key climate risk created by the fossil fuel economy, and outlines carbon taxes and carbon rewards as potential ways to mitigate the climate risk created by the fossil fuel economy. Section 2.2 reviews the literature on the behaviour of and incentives for fossil fuel exporting regions during the transition to an economy consistent with planetary boundaries. Section 2.2.1 reviews the standard economic incentives for fossil fuel exporters to decarbonise, looking at the "free-rider problem" in particular. Section 2.2.2 highlights new research that argues if global decarbonisation starts to accelerate, fossil fuel exporting regions will be better off in the long term if they rapidly decarbonise their domestic economies. Section 2.2.3 highlights the inherent contradictions between the short- and long-term incentives of fossil fuel exporting regions and the need to align their short- and long-term interests with global climate goals. Section 2.3 defines the market incentives – carbon taxes and rewards – that could be used to reduce climate risk and incentivise a more rapid transition to a low carbon economy.

2.1 Definitions

2.1.1 Fossil Fuel Exporting Regions

This study defines fossil fuel exporting nations as those with net fossil fuel exports which comprise more than 2.5% of GDP in the Global Trade Analysis Project (GTAP) base year (2014) data of (*GTAP Data Bases: GTAP 10 Data Base*, n.d.). The 2014 base year data is used in the IMED|CGE model and identifies five net fossil fuel exporting regions: the Middle East, the Former Soviet Union, Africa, Canada, and Australia & New Zealand (see table 4.1).

This study modifies the definitions of low-cost and high-cost crude and petrol oil producers established by Mercure et al. (2021, p.5). In that study the authors note that the Organization of the Petroleum Exporting Countries (OPEC) are considered low-cost producers; OPEC production costs often fall below US$20 per barrel. This is relative to high-cost producers like the United States, Canada, South America and (to a lesser extent) Russia, whose production costs usually sit between US$20 and US$80 per barrel (Mercure et al., 2021, p.5). In this study, the Middle East and Africa are considered low-cost producers due to the domination of OPEC members in the fossil fuel production of those regions. Canada, Australia & New Zealand, and the Former Soviet Union are considered high-cost producers.

2.1.2 Global Climate Risk

There is growing evidence that human activities have pushed the earth's climate system beyond the relative stability of the Holocene epoch (the geological period of the last 10,000 years, entirely encompassing the development of human civilisation) in which fluctuations in global average temperature have been no greater than 1°C (Steffen et al., 2018). The planetary boundary framework developed by Rockström et al. (2009a, 2009b) demonstrates that there are biophysical limits that, once passed, can trigger irreversible tipping points, permanently altering the equilibrium of the planet's biophysical systems. This framework proposes nine quantitative boundaries for different earth systems that, when passed, take humanity outside a safe operating space and risk catastrophic consequences. The threshold for the climate system sits somewhere between 350 and 550 parts per million (ppm) of CO_2 in the atmosphere. In the zone between 350 and 550 ppm of CO_2, we would likely observe the disappearance of the polar ice sheets which would trigger warming feedback loops and the return of a much warmer and largely ice-free planet (Rockström et al., 2009a). Other potential triggers for feedback loops include "carbon bombs" such as the collapse of the Amazon rainforest and the widespread melting of permafrost (Rockstrom & Gaffney, 2021). Because of the uncertainty around the concentration of greenhouse gasses that would trigger runaway global warming, Rockström et al. (2009a) placed the planetary boundary at 350 ppm of CO_2. We now know human activities have pushed carbon levels in the atmosphere to over 410 ppm of CO_2 (Lindsey, 2021).

Since we have already transgressed that boundary, the next best goal is to limit global warming from preindustrial levels to 1.5°C by 2100, which is the scientific consensus created by the IPCC: *Global Warming of 1.5°C: Special Report* (IPCC, 2018). Limiting global warming to 1.5°C does not remove the risk of triggering irreversible feedback loops in the earth's climate system, nor does it mean that humanity won't suffer the consequences of the effects of a warming planet. However, the IPCC argues that it is a level of warming below which we can have a high degree of confidence that we are limiting the risk of irreversible changes as well as significantly reducing human suffering as compared with 2°C or more of warming (IPCC, 2018).

Lenton et al. (2019) provide a clear precautionary argument for the development of aggressive policies to limit warming to 1.5°C:

> Given its [global average temperature increases beyond 1.5°C] huge impact and irreversible nature, any serious risk assessment must consider the evidence, however limited our understanding might still be. To err on the side of danger is not a responsible option. If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization.

Following this logic, there is a need to consider rejecting the traditional search for "optimal" or "least-cost" warming pathways assessed by a cost-benefit analysis to determine "efficient" carbon prices. Such thinking has been fundamental in our understanding of climate mitigation, but it has also led to slow action based on high 'optimal' levels of warming such as the 3.5°C of warming first published by Nordhaus's DICE model in 1992 (Nordhaus, 1992). As Kate Raworth (2017) notes, "optimal" levels of warming, as well as least-cost transition pathways that involve higher levels of warming, must be questioned as optimal for whom? While these levels may maximise the GDP of the fossil fuel economy, it may lead to catastrophic consequences from tipping points and will lead to increased suffering for populations with the least resources for adaptation as demonstrated by the latest IPCC Working Group 2 report (2022). Therefore, this study does not look at what "optimal" warming pathways may be or provide a cost-benefit analysis of what level of warming would limit total costs. Adopting the logic of Lenton et al. (2019) and that of meta-design it investigates the feasibility of economic policies to transform the global economy so that it operates within the biophysical constraints of the planetary boundaries.

2.1.3 The Environmental Threat Posed by the Fossil Fuel Economy

The IPCC notes that, based on historical operating patterns, the emissions estimate from 2018 to the end of the operating lifetime of existing fossil fuel infrastructure is 660 $GtCO_2$ (with a possible range of 460–890 $GtCO_2$); when planned infrastructure is included (more of which has been added since the estimates were made) lifetime emissions from fossil fuel infrastructure would amount to 850 $GtCO_2$ (with a possible range of 600–1100 $GtCO_2$) (IPCC Working Group

3, 2022b, p.20). The IEA concurs, noting that if current energy infrastructure continues to operate until the end of its historic lifetime, there will be 30% more energy-related emissions than the remaining carbon budget to limit warming to 1.5°C (50% probability) (International Energy Agency, 2021b, p.39).

Ultimately the success of economic diversification efforts on the part of fossil fuel exporting regions will not only determine the speed and success of their domestic decarbonisation efforts: "the transformations in these major oil-exporting countries will, in turn, shape the global energy transition" (Fattouh et al., 2018, p.3). The early retirement of fossil fuel infrastructure will be required if warming is to be limited to 1.5°C.

2.2 The State of Economic Incentives for Fossil Fuel Exporting Regions

Section 2.2 discusses the macroeconomic incentives of fossil fuel exporting regions to decarbonise. It identifies a short-term incentive to free ride (section 2.2.1) and a longer-term incentive for most fossil fuel exporting regions to decarbonise even without taking into account the climate risk (section 2.2.3). Nevertheless, the literature shows that fossil fuel exporting regions remain a major threat to the world's decarbonisation goals and that more needs to be done to solve the contradiction between their short- and long-term macro-economic incentives.

2.2.1 Short-term Incentives for Fossil Fuel Exporters

The debate around the lack of global climate action, particularly that of countries and regions that are reliant on fossil fuel exports, has long been centered around free riding. Free riding is when an economic actor (individual, corporation, state, etc.) receive the benefit of a public good without paying the cost of creating that public good (Nordhaus, 2015, p.1339). Climate change economies reliant on fossil fuels are considered to have an incentive to continue to maximise profit from their resources while benefiting from emission reductions elsewhere.

Renewable and non-fossil energy is able to replace fossil energy in the domestic energy mix, but cannot, in its current configuration, replace the revenues fossils fuel production and exports add to the government budget; investment in renewables, while cost-efficient for the price of energy, does not generate the same economic rents (high investment returns) that the oil and gas industries do (Fattouh et al., 2018). Therefore, fossil fuel exporting regions have a strong financial incentive to be lax on mitigation (Fattouh et al., 2018).

Fossil fuel producing regions are still the most likely to aggressively oppose both domestic and international decarbonisation efforts. Fouquet notes that incumbent industries are historically responsible for delaying energy transitions and resist carbon reductions because they want to maximise the value of their assets (Fouquet, 2016). Regions with incumbent oil industries (especially those with a high marginal cost of production) face large industrial declines in 1.5°C scenarios (Mercure et al., 2018, 2021; Pye et al., 2016), and are the most likely to oppose a domestic and global low carbon economic transition.

Fattouh et al. (2018) argue that the sunk costs in existing fossil fuel infrastructure "creates inertia and provides an economic incentive to utilize them until they are written off" (p.10). Standard economic theory suggests that fossil fuel producing regions will attempt to extract every dollar they can from these assets, using them until the marginal benefit of production reaches zero.

For these reasons, analysis of international climate agreements often use game theory to conclude that the prisoner's dilemma or a tragedy of the commons will result in too little abatement (Nordhaus, 2015, p.1342). There is an incentive for nations to resist climate targets and even to try to benefit from the competitiveness gains over those that do. Since each country has the same incentive to not comply in the prisoner's dilemma game, this results in a Nash equilibrium[5] where every country doesn't comply with the climate targets; this happens even though total welfare would be higher if every country complied with the targets (Nordhaus, 2015, p.1342). This suggests that if fossil fuel assets are going to be retired in line with climate targets, additional incentives will be needed to break the prisoner's dilemma/tragedy of the commons and limit global warming to 1.5°C.

2.2.2 Long-term Risks for Fossil Fuel Exporters

Despite the short-term incentive to continue to maximise fossil fuel production, the literature shows that in scenarios where global emissions are reduced to be consistent with 1.5°C, fossil fuel exporters would face large economic losses in the long term. Studies by Mercure et al. (2018, 2021) and the IEA (2021b) have created net-zero emissions scenarios that estimate where the remaining oil and other fossil fuels still in use will be produced in 2050. Under net zero by 2050 scenarios and in scenarios in which the prices of renewable energy and storage continue to

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[5] An outcome where no player in the game has an incentive to switch stratedgy given the choices of the other players.

fall at recent historical averages, oil production will decrease significantly and move to countries with a low marginal cost of production.

A multi-model study by Rogeji et al. (2018) demonstrates that all scenarios consistent with limiting warming to 1.5°C include "a clear shift away from unabated fossil fuels [without carbon capture and storage]… and a phaseout of all fossil fuels" towards the end of the century (p.327). With our current economic structure, Mercure et al estimate this will leave many high-cost-per-barrel assets stranded leading to a global loss of wealth of US$ 1-4 trillion (at a 10% discount rate, over a 10–15-year investment horizon from 2020/21); or upwards of US$ 9 trillion when not discounted (Mercure et al., 2018) (p.588).

Even leaving aside the huge environmental cost of continued reliance on fossil fuels, Mercure et al.'s (2021) estimates predict that decarbonisation is a net-economic gain for fossil fuel importing regions whether or not the whole world follows a net-zero by 2050 pathway. To demonstrate the likelihood of this outcome, Mercure et al. (2021) use a two-by-two game theory framework that assumes energy policy decisions are based solely on GDP or employment outcomes that countries knew ahead of time. The game shows that the European Union and East Asia have a dominant strategy[6] to decarbonise; achieving net-zero in their domestic economies would create a Nash equilibrium (Mercure et al., 2021, p.7). At the same time OPEC and low-cost producers have a dominant strategy to "flood markets" and maximise short-term revenue before the oil importers reach net zero. This leaves high-cost producers to decide whether or not to decarbonise (Mercure et al., 2021, p.7). In the game and scenarios constructed by Mercure et al. (2021) the low-cost competition from OPEC causes high-cost fossil energy industries to recede, "but the economic benefits of low-carbon investment do not necessarily compensate for the high losses of output in high-carbon industries" (p.7). Mercure et al. (2021) argue that regardless of domestic policy it is likely "the creative destruction effect of the low-carbon transition [already] underway" will lead to "post-industrial decline" in high-marginal cost oil producing regions including the United States, Russia, Canada, and Brazil (p.7). The question these and other countries must consider is how best to minimise these declines and increase support for decarbonisation.

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[6] A strategy that a player would always choose regardless of the strategy of other players in the game.

Mercure et al. (2018) argue that that even if fossil fuel producing countries like Canada and the United States do not transition to low-carbon energy, their assets will become unviable, and they will end up importing cheaper oil from the Middle East without getting any of the benefits of the low carbon transition. Therefore, in the long-run fossil fuel exporting economies have an incentive to diversify their economies as “the ultimate safeguard against the energy transition” (Fattouh et al., 2018, p.3).

Due to the predicted decrease in demand from importing regions, some level of stranded assets is already inevitable (Mercure et al., 2018), and it will only increase as fossil fuel investment in producing nations continues while investment in renewables in importing nations increases significantly. The IEA’s NZE also noted, when the report was released in 2021 (International Energy Agency, 2021b), that no new exploration for new fossil fuel resources was needed and that fossil fuel infrastructure expansion should be stopped at the fields already approved for development. Nevertheless, new fossil fuel field expansion continues to be approved around the world.

Modelling by Way et al. (2021) and Mercure et al. (2021) demonstrate that low carbon investment is not an economic cost to be born or avoided but an economic opportunity that should be embraced, especially by importing countries and fossil fuel producing regions with high marginal costs of production. This marks a fundamental shift in global economic conditions from fossil fuel infrastructure being an asset to it being a potential liability. Mercure et al. (2021) argue that, at least in the long term, the strategic economic incentive for oil-producing regions is to invest in decarbonisation technology rather than to ‘free ride’ on the mitigation efforts of others.

2.2.3 Misalignment Between Short- and Long-term Incentives for Fossil Fuel Exporters

As described above, the literature on energy transitions demonstrates that emissions “locked” into existing fossil fuel infrastructure are greater than existing 1.5°C carbon budgets and that fossil fuel energy incumbents are likely to delay the transition for perceived short-term benefits. At the same time, section 2.2.2 showed that even without the constraints of the 1.5°C carbon budget, fossil fuel exporting regions with high marginal costs of production are likely to face industrial decline.

This leaves a contradiction between the short-term economic incentives of fossil fuel producing regions which are subject to the traditional prisoner’s dilemma decision-making paradigm (Nordhaus, 2015) and the long-term incentive to decarbonise at least as fast or faster than the rest of the world so that they minimise stranded assets and can compete in a reshaped global economy (Mercure et al., 2018).

This long-term incentive does not guarantee that fossil fuel exporting regions will not jeopardise the remaining carbon budget for limiting warming to 1.5°C. Despite the large potential for stranded fossil fuel assets "public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation" (IPCC Working Group 3, 2022b, p.17). McCollum et al. (2018) note that while a transition to a 1.5°C consistent energy system will require an increase of over one-quarter in total energy investment, a reallocation of the current energy investment portfolio is what is primarily needed to limit global warming (p.589-590).

Markets in most regions do not yet recognise Mercure et al.'s (2018) conclusion and global investment flows are not in line with McCollum et al.'s (2018) 1.5°C scenario. Therefore, better market incentives must be created to reduce the misalignment between capital flows, future energy needs, and the remaining limited carbon budget. Unless markets can properly internalise the cost of greenhouse gas emissions, fossil fuel exporting regions will continue to manifest the tragedy of the horizon. The likely continued political opposition from fossil fuel exporting regions to the economic transition required to limit global warming to 1.5°C is why this paper not only considers a high carbon tax scenario, but also opens the discussion to the new economic paradigm of carbon rewards.

2.3 Aligning Fossil Fuel Exporters' Incentives with Global Climate Goals

This section will start by reviewing the standard theory for internalising the negative externality associated with greenhouse gas pollution: carbon price theory based on the *social cost of carbon* (SCC) (section 2.3.1). Section 2.3.2 will discuss the political, ideological and economic shortcomings of carbon taxes based on the social cost of carbon. Section 2.3.3 will introduce the *risk cost of carbon* (RCC) as an additional *positive* externality to be considered if we are to meet the Paris goal.. Section 2.3.4 introduces the policy mechanism, called the global carbon reward (GCR), that has been proposed by Chen et al. (2017, 2019) to internalise the RCC into the world economy. Further explanation of the GCR can be found in Appendix A. The goal of the policy is to create a global market-based reward price for the mitigation and reduction of carbon dioxide and other GHGs. Section 2.3.5 will argue that RCC and GCR present as a novel theory that should be considered because they may be able to address the short comings of SCC based carbon taxes.

2.3.1 Carbon Taxes and the Social Cost of Carbon

The SCC is the marginal damage to society of one additional ton of CO_2 emissions in a given period (Metcalf & Stock, 2017, p.80). Current economic theory identifies CO_2 and other forms of GHG pollution as the cause of a negative externality and proposes a market price on these emissions equal to the estimated SCC. The SCC is often assessed using a method called cost-benefit analysis. The SCC is widely used by leading economists such as Nobel Memorial Prize-winners William Nordhaus (1992, 2015, 2019) and Joseph Stiglitz (2006), as well as Nicholas Stern (2006), although there is disagreement about how it should best be estimated.

Metcalf and Stock (2017) describe the two principal methods for shifting the private marginal-cost-of-pollution curve to the social-marginal-cost-of-pollution curve:

> a Pigouvian tax—a tax on pollution that is set equal to its social marginal damages—or by establishing property rights to pollution through a cap and trade system… in which the equilibrium trading price of emissions is determined by the intersection of the demand for emissions and the fixed supply of emission allowances set by policy (p.80).

The property rights strategy, most often called “cap and trade,” has been adopted in jurisdictions such as the European Union and China. The Pigouvian tax strategy is employed in most of Canada and other jurisdictions around the world. Both policies have produced positive results, but all countries have struggled with political acceptance and global scalability for limiting global warming to a safe level. Governments can also use command and control incentives to fund decarbonising activities. The latter allows for the establishment of standards for specific emissions outcomes and the development of early-stage technologies; however, market-based policies can usually achieve these at a lower cost.

This section will focus on the Pigouvian tax (hereafter referred to as a carbon tax) because it is more directly associated with the SCC and discussions on climate change economics. Nordhaus (2019) argues that a carbon tax has four main purposes: (1) to signal to consumers “which goods and services are carbon-intensive and should therefore be used more sparingly;” (2) to signal “to producers about which inputs are carbon-intensive… and which are low-carbon…, thereby inducing firms to move to low-carbon technologies;" (3) to signal to investors and innovators that there will be long-term demand for low carbon goods, therefore, boosting private research and development; and (4) to compile all the information required to complete these tasks in market price signals (p.2003).

Economist Joseph Stiglitz (2006) argues that "not paying the cost of damage to the environment is a [perverse] subsidy" (p.2). Therefore, imposing a carbon tax would have no negative effect on social welfare. However, the carbon tax does redistribute social welfare based on the policy design and can appear economically damaging to current generations (the tragedy of the horizon) and domestic populations when they are only applied in limited jurisdictions (free-riding and carbon leakage) despite its clear benefits over the medium to long term.

This leads to a debate over the best use of carbon tax revenues. The main uses of carbon tax revenues include: (1) transferring revenues back to the taxed population (revenue-neutral taxes) through a rebate based on household income, (2) as an investment in accelerating the decarbonisation of the economy, (3) carbon tax revenues are recycled to reward negative emissions through a reverse carbon tax.

Revenue-neutral carbon taxes have been adopted at the national level in Canada (Department of Finance Canada, 2020). This has the advantage of not reducing the welfare of low-income households and has been found to have a progressive effect on wealth distribution (low-income households receive larger relative returns than high-income households) in a study of British Columbia's 2008 carbon tax (Beck et al., 2015, p.57). There are a large number of policy options for recycling carbon tax revenues to boost incentives for other mitigation/abatement activities. For example, energy efficiency subsidies in the residential sector were found to provide additional mitigation and reduce energy poverty among homeowners (Bourgeois et al., 2021, p.9).

A third carbon tax revenue recycling scheme is the use of carbon tax revenues to provide a subsidy for negative carbon emissions. Daggash and Mac Dowell (2019) argue that a positive incentive for CDR equal to the negative incentive of the carbon tax could achieve deep decarbonization at "lower (and more politically feasible) carbon prices" than a carbon tax-only scenario in the United Kingdom (p.2127). The study found that when incentives for CDR were implemented sooner, the risk of overbuilt fossil fuel and CDR infrastructure systems were reduced; total system costs were reduced by 18% between 2015 and 2100 compared to scenarios that did not incentivise CDR (Daggash & Mac Dowell, 2019, p.2129). A comparison of the household welfare implications of a CDR revenue recycling scheme and a revenue-neutral carbon tax is needed to compare the equity implications of the two policies.

The use of a negative incentive (carbon tax) to punish emitters and a positive incentive to reward emission removers with the Global Carbon Reward has some similarities to the revenue recycling schemes to incentivise negative emissions activities (refer to section 2.1). These proposals both include mechanisms for boosting the deployment of negative emissions, which may be necessary to limit global warming to 1.5°C between now and 2100 due to residual emissions from hard-to-abate sectors and existing fossil fuel infrastructure (IPCC Working Group 3, 2022b, p.32; Luderer et al., 2018, p.267). As Daggash and Mac Dowell (2019) argue, incentivising negative emissions can lower the total system costs of the energy transition.

Finally, there is a case for strong mitigation policies that can address the planetary boundaries given the risks that the surpassing of these boundaries poses to humanity and the biosphere. In Engstrom et al.'s (2020) analysis of carbon pricing and the planetary boundaries, they found that a higher carbon price may reduce almost all planetary pressures including the degradation of climate change, ocean acidification, biodiversity, aerosol loading, and chemical pollution directly; most of the other planetary boundaries were at least indirectly positively impacted. By not properly pricing the negative externality of carbon emissions, the global economy is perversely undermining itself, operating in an inefficient and systemically risky manner.

2.3.2 Shortcomings of the Social Cost of Carbon Theory

There are two problems with the SCC approach that have prevented it from mitigating emissions in line with the Paris Agreement goals. First, a series of theoretical and political factors have meant that countries and regions around the world have not adopted a carbon price sufficient to prevent climate catastrophe. Second, even if the carbon prices were set to the socially optimal level, alone they would not necessarily prevent dangerous global warming because they do not directly value the mitigation of carbon or the inherent value of a stable climate system.

There are immediate and practical political impediments to the adoption of the SCC. In many countries, politicians face elections every 3-5 years, and in others, they must maintain their social legitimacy through popular support. To bolster their chances of re-election and boost social legitimacy they have an incentive to increase GDP in the short run even if it incurs long-term costs. On the whole, voters still discount the future costs of carbon in favour of maintaining or increasing their current standard of living. In other words, there are short-term political costs to increasing carbon prices even if it is a sound method for preventing climate catastrophe.

In a study of the United Kingdom (U.K.) decarbonisation pathway using a national-scale power systems model, Daggash and Mac Dowell (2019) argue that high carbon prices may decarbonise the U.K. economy temporarily, but would be unable to maintain it for the long term (p.2126). They also argue that the high carbon tax decarbonisation pathway is not the lowest cost pathway because it does not spur the near-term development and deployment of CDR technology (Daggash & Mac Dowell, 2019, p.2129). Given the political opposition to higher carbon taxes, the level of carbon taxes required to deliver on warming well below 2°C would likely be politically infeasible. Daggash and Mac Dowell (2019) conclude that the high carbon tax model "may be unable to deliver the climate mitigation objectives set out in the Paris Agreement" (p.2126). Their study reinforces the need to consider alternative carbon pricing regimes, including mechanisms that incentivise the development and deployment of negative emissions technologies (NETs).

The SCC also has ideological limitations. What meets neoliberal efficiency does not consider the almost unlimited value in maintaining a stable and livable climate. This is because most SCC calculations include a time-discounted cost-benefit analysis (comparing the value of future consumption to current consumption), assuming that in the future, society will be wealthier and therefore better placed to pay for the costs of climate change.

Stern argues that SCC calculations are often based on unethically high discount rates[7] (Stern, 2006, p.31-33). This means SCC estimations are frequently lower than would be consistent with the mitigation required to limit global warming to 1.5°C. Stern believes that many discount rates used in IAMs are too high because they don't take into account ethical considerations of "our duties to future generations;" those who use higher discount rates are intending to account for the present generation's "moral right to prioritize its own well-being" (Wagner et al., 2021, p.550). High discount rates can hide the significant of potential losses from high-warming scenarios: unmitigated climate change is estimated to reduce global average income by more than

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[7] There is significant debate over discount rates of 1-2% (a higher value for future consumption) and 5% (a higher value for current consumption) between Stern (Stern, 2006, p.31-33) and Nordhaus (Nordhaus, 2019, p.2005).

23% compared to non-climate change scenarios (Burke et al., 2015, p.238). This demonstrates that the SCC calculations often do not account for the ethical/ideological principles that need to be considered to allow future generations to live within low levels of global warming based on measures like the planetary boundary (itself an ideological priority, although considered one of utmost importance by this study).

When SCC calculations are based on certain climate damage functions, country-level analysis can also produce negative SCC values in northern and fossil fuel exporting countries like Canada and Russia (Ricke et al., 2018, p.897). In Ricke et al.'s (2018) reference scenario, these negative SCC results occur because current temperatures in these countries fall below what is considered to be 'economically optimal' (p.897). While this may be possible under the assumptions of some economic efficiency calculations, it is not logical from an earth systems or planetary boundaries perspective.

There are also two large impediments with macroeconomic incentives identified in the literature that prevent widespread coordinated action on more aggressive emissions reductions policies through carbon taxes: (1) the fear of carbon leakage (when emission reductions from domestic policies are offset by emission increases outside the carbon restricted area from domestic firms moving or other firms filling the same market) (Michalek, 2016, p.324); and (2) the free-rider problem (countries benefit from the emission reductions elsewhere and may not act themselves) (Hillman, 2013, p.4). For carbon taxes to be implemented widely at any level reasonable enough to limit warming to 1.5°C, these issues would need to be addressed through a coercive global climate regime (see Nordhaus 2015, 2019 on climate clubs).

2.3.3 The Risk Cost of Carbon

Chen et al. (2017) define the risk cost of carbon (RCC) as "the market price of each metric tonne of additional CO_2e [carbon dioxide equivalent] mitigation service that is needed to reduce climate systemic risk to an agreed limit" (p.273). The RCC was proposed by Chen et al. as the marginal cost of reducing and removing GHGs to limit the climate risk in terms of an average level of allowable global warming, the certainty of remaining below this warming, and the associated carbon budget. The RCC is the financial reward that is sufficient to create enough demand for low carbon goods and services that can achieve the agreed climate objective.

By pricing the RCC into the financial system (refer below), the GCR aims to create new demand for services that can mitigate GHG emissions (reduce or remove GHGs) measured in CO_2e mass; the goal is to create a market in which producers and consumers seek to supply carbon mitigation sufficient to meet the goals of the Paris Agreement.

The economic theory for the RCC is based in part on the "preventative insurance principle" which Chen (2022a) proposes as the counterpart to the "polluter pays principle" that is used to justify the carbon tax. Chen (2022a) describes the preventative insurance principle as the principle "that humanity should be protected from dangerous climate change by funding climate mitigation with rewards." This links the economy to the planetary boundaries that are impacted by the carbon cycle; therefore, current costs can be transferred away from stakeholders through the RCC while remaining efficient. This aligns with economics within planetary boundaries. A formal definition of the RCC from Chen et al. (2019) is:

> the average market price of voluntary mitigation (\$US per t CO_2e) that is sufficient to ensure that a certain level of global warming, ΔT, will not be exceeded within a risk tolerance of R (%). ΔT is defined as a global average surface temperature change (C) relative to a preindustrial baseline, and ΔT and R are applied over a rolling 100-year planning horizon denoted by the end-year, Y (p.194).

The positive externality that the RCC represents is needed to account for the embedded carbon in anthropogenic systems, and to respond to climate feedback loops (e.g. melting sea ice, thawing permafrost).

Chen et al. call the new theory for the RCC market failure the *holistic market hypothesis* (HMH). The HMH states that "the total externalized cost of the market failure is significantly underestimated when the RCC is ignored" (Chen et al., 2019, p.184) (see Chen et al. 2017, 2019 for development of the HMH). The HMH argues that there are two externalized costs of carbon (the SCC and the RCC) that need "to be internalized into the economy to manage the climate problem;" the HMH states that each "externalized cost is assessed from a unique frame of reference: the SCC is assessed from a… neoclassical perspective; and the RCC is assessed from a… biophysical perspective" (Chen et al., 2019, p.192).

Therefore, the RCC is not meant to replace the SCC. Chen et al. (2019) indicated that the HMH implies that the total externalized cost of carbon (TCC) is a vector based on the SCC and the RCC for a given period t (see eq. 2.1)[8] (p.195).

(2.1) $TCC(t) = SCC(t)\,\hat{\imath} + RCC(t)\,\hat{\jmath}$

The SCC has units of $US per tonne of CO_2e emitted in a given year, whereas the RCC has units of $US per tonne of CO_2e mitigated for a 100-year duration. In terms of their temporal units, the SCC refers to a time-discounted value, whereas the RCC refers to a rolling 100-year planning horizon without time-discounting (D. Chen et al., 2019, p.195). The RCC, unlike the SCC, does not refer to marginal social costs because it is quantified using cost-effectiveness and does not involve a social discount rate. The 100-year planning horizon of the RCC is justified in terms of the global warming potential of GHGs and the timeframe required for civilisation to respond effectively with new technologies. Therefore, the SCC and RCC are complementary externalities because they address two optimisations based on two economic systems: (1) the SCC associates with the existing economy for the production of goods and services, and (2) the RCC associates with a parallel economy specifically for carbon mitigation on a global scale.

Chen et al. propose that the RCC and SCC operate together in a carrot and stick approach. This means that a carbon emitter could, in certain circumstances, be taxed for its remaining emissions (SCC negative incentive) while being rewarded for its mitigation activities (RCC positive incentive). Chen et al. (2017, p.245) cite Andreoni et al.'s (2003) principle of the "carrot" and the "stick" to show that, on their own, both rewards and punishments are less effective than when they are applied together. Combining the SCC and the RCC creates "a new paradigm of complementary market pricing for the dual objectives of improving market efficiency and managing systemic risk, respectively" (Chen et al., 2019, p.183).

Given the urgency of action on climate change, it is worth investigating multi-dimensional price signals such as the SCC and RCC that punish emitters and reward CO_2e mitigation through technology and behaviour change; this system may improve market and socioeconomic cooperation on mitigation.

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[8] Chen (Chen, personal communication, July 25, 2022) argues that it is not possible to simply add the RCC to the SCC, because these metrics have different units and they associate with different economic systems that are linked by exchange rates. The SCC refers to the optimisation of the mainstream economy under cost-benefits analysis, whereas the RCC refers to the optimisation of a new mitigation economy under cost-effectiveness analysis. For this reason, the TCC may be viewed as a two-dimensional vector, as indicated in eq. 2.1.

2.3.4 Global Carbon Reward

Chen et al. (2019) propose that the positive externality (represented by the RCC) should be internalised into the economy with a global carbon reward (GCR) that "manages the trade-off between market efficiency and climate certainty" (p.183). The GCR is a market-based policy that combines with monetary policy to create a scalable and debt-free pathway to the Paris targets (Chen, 2022b). This section outlines some basic principles of the GCR; more details on how the policy internalises the RCC can be found in Appendix A and in Ch.3 Methodology (section 3.2).

Chen et al. (2019) define the carbon reward as "a positive carbon price that is offered as an ex-post payment for verified carbon mitigation, and when the reward payment is (a) made with a parallel currency denominated in carbon by mass, and (b) provided with conditions for the awardees to maintain an agreed standard of service" (p.186).

The proposed GCR policy would provide a reward of 1 carbon currency (CC) for every ton of CO_2e mitigated for a 100-year duration. The unit of account of the CC will allow the currency to act as (1) a global ledger to track the mass mitigation of greenhouse gasses and (2) establish a predictable long-term incentive for mitigating greenhouse gases (Chen, 2022b). The CC will not be (1) "a carbon credit for the offsetting of greenhouse gas emissions;" (2) "a medium-of-exchange for the purchase of goods and services;" (3) "prone to high-risk speculative trading like a 'cryptocurrency;'" or (4) "require energy-intensive computer 'mining' to maintain data security" (Chen, 2022b).

According to Chen (personal communication, April 4, 2022) the value of CC should equal the marginal cost of removing 1 metric ton of CO_2e from the atmosphere at a rate that can limit global warming to the chosen climate objective. The intention is to create a new global market that supports the necessary development and deployment of carbon dioxide removal (CDR) and incentivises accelerated mitigation. The CC floor price is the lower bound of the CC exchange rate when compared with a representative basket of national currencies. The floor price will be defined for 100 years into the future to provide "forward guidance" to markets. The CC floor price will result in the CC being a stable financial asset and an investment-grade currency. The long-term nature of the CC floor price will provide certainty regarding the value of the carbon reward, it will encourage more long-term investment in low-carbon projects, and it might resolve the intergenerational equity problem that has been called the 'tragedy of the horizon' (Carney, 2015, p.3).

To manage the CC so that it has a stable and growing value relative to national fiat currencies Chen et al. (2018) propose that an international institution for the GCR policy set a CC floor price and then enforce this floor price with an international central bank protocol called *carbon quantitative easing* (p.8). The international institution would issue the CC as a reward for mitigated carbon and provide a public finance guarantee that the spot value of the CC would remain above the floor price that is calibrated annually to be in line with the world's climate targets. The CC will be traded in the open market, such that the spot price of the CC will move higher than the CC floor price as a result of market-driven supply and demand. The trading of the CC by private investors and central banks will redistribute the mitigation cost in a way that should achieve a Pareto optimal outcome.

Chen proposes that the CC floor price should be calibrated for incentivising sufficient greenhouse gas (GHG) removal from the ambient atmosphere (i.e. negative emissions) because many modelled pathways overshoot the 1.5-2°C carbon budgets and require net-negative emissions to limit global warming to a safe level (IPCC Working Group 3, 2022b; Luderer et al., 2018).

The CC supply will be proportional to the mass of carbon mitigated. The CC will be issued for carbon that is mitigated through (1) cleaner energy supplies, (2) cleaner business practices, and (3) the removal of carbon from the ambient atmosphere, also known as CDR (see below for base formulas provided in Chen, 2022b, personal communication, April 4, 2022). In this analysis I look only at the first of these—cleaner energy supplies—by applying the CC as a means of incentivizing low-carbon energy systems.

Even though this study examines only the reward for cleaner energy supplies, the combination of the three rewards can address different aspects of the carbon budget as understood using the Kaya identity.[9] Chen (personal communication, April 4, 2022) modified the Kaya identity to further explain how the GCR policy and the reward rules may be conceptualised. The GCR policy, with its three reward rules, offers significant mitigation possibilities for both the supply and demand of carbon-intensive goods.

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[9] The original Kaya identity shows that global greenhouse gas emissions are driven by population growth (P), GDP per-capita (G/P), the energy intensity of GDP (E/G), and greenhouse gas (CO_{2e}) intensity of energy (F/E) (Kaya & Yokobori, 1997).

Chen has proposed a self-funding administration system for the GCR to ensure compliance with qualifying mitigation activities. Leyre (2021) calls the policy's administrative body the *Carbon Exchange Authority* (CEA). The CEA would be responsible for the operationalisation of the GCR policy, including all measurement, reporting, verification, and reward payments (i.e. with the CC). For example, the CEA might be established under the United Nations Framework Convention on Climate Change (UNFCCC). The CEA would be financed through fees and commissions, and it should be self funding (D. Chen, personal communication, April 4, 2022).

Awardees will be required to sign a service-level agreement (SLA) with the CEA that defines their emissions baseline and the appropriate standard for measurement, reporting and verification; the SLAs will also include provisions for responding to carbon leakage and defaulting (Chen, 2022b, p.1). It is important to note that only mitigation with corresponding SLAs will be rewarded.

The CEA would have a governing board of scientific and economic experts and community consultants for establishing how the CC rewards would be adjusted to further incentivise co-benefits and disincentivize harms of mitigation activity. Reward adjustments can be used to incentivise: "(a) energy reliability; (b) community wellbeing, such as clean air and green jobs; and (c) ecological health, including the protection of biodiversity and the regeneration of habitats" (Chen, 2022b, p.1). The reward adjustments for co-benefits and harms would always sum to zero over a given assessment period so that the total supply of the CC remains proportional to the carbon stock take (see eq. 3.8). Chen proposes that the carbon intensity baselines for projects are calibrated by the CEA to ensure that the aggregate of all mitigation is sufficient to achieve the chosen climate goal (Chen, 2021).

The equations in Appendix A and section 3.2.2 show that the rule for cleaner energy would provide incentives to reduce the carbon intensity of energy commodities relative to a carbon intensity baseline ($CIE_{i,r,b},$). The aim is to shift energy supplies towards non-fossil fuel sources. As a starting point for analysis, the clean energy rule may pay out the CC to companies or governments that control the production of energy commodities if (1) the carbon intensity of energy production is reduced, (2) if the producer commits to retiring fossil fuel energy reserves and related assets ahead of schedule and to producing a minimum amount of clean energy for selling in the marketplace. Chen proposes that the carbon intensity baselines for projects are calibrated by the CEA to ensure that the aggregate of all mitigation is sufficient to achieve the chosen climate goal (Chen, 2021). A more complete – though not comprehensive – explanation of the GCR policy can be found in Appendix A.

2.3.5 Considering Carbon Rewards

If we accept the principle that global warming should be limited to as close to 1.5°C as possible, we must now ask if it is better to make high emitting sectors pay for their mitigation through a carbon tax and offsets, or to reward them (and all other sectors of the global economy) for their mitigation efforts. There is a strong argument to be made for the polluter-pays principle which states that it is morally and legally preferable to ensure that those responsible for the pollution pay for it. This may even make sense if a price signal effective enough to achieve the global climate targets could be implemented at the domestic level. Although, as we have seen in the CT-NDC scenario, it would have to be quite high.

If we consider future mitigation at the global scale based on negative incentives, one possibility is that countries that are successfully decarbonising domestically create a “climate club” to overcome the issues of free-riding and carbon leakage (Nordhaus, 2019, p.2010). Nordhaus (2019) defines a climate club as a set of countries that agree, out of mutual benefit, to limit their domestic carbon emissions through a unified carbon price; the club members would also agree to a tariff on imported goods from non-club countries to ensure they were penalized for not joining the ‘club’ (p.2011). Many countries may join a scheme and create a large market based on low carbon exchanges of goods and services. However, if carbon prices were set too high, only countries already on track to decarbonise would agree to join the club, and the carbon border tariff would create overly high barriers to trade with non-club members. Global trade might split into two “islands” of low and high carbon trade (Tsafos, 2020). High emitters would refuse to participate in a scheme so costly to their economies and would simply establish a parallel global trade system with other high emitters. Therefore, emissions might not be controlled, and global trade might bifurcate with both effects leading to lower long-run output and higher prices on both “islands.”

The urgency of limiting the risks of a fossil fuel economy and creating a system that operates within planetary boundary’s calls for the consideration of new market-based policies such as the GCR. The principals of meta-design show that in the context of the climate crisis it is important to identify and study novel policies so that even if they seem improbable now they will be 'future-possibles' (Wood, 2022, p.17). By ignoring the positive externality for addressing carbon emissions embedded in current infrastructure, transportation, agriculture and human systems, economists are not attributing economic value to the *prevention* of climate change.

The GCR is considered here over other novel policies such as carbon-tax revenue recycling schemes that incentivise negative emissions because of its three main advantages. The RCC applies to all mitigation activities and is therefore paid out for mitigating pollution that the SCC taxes (it does not just reward NET like the revenue recycling proposals) creating a carrot and stick approach to speed mitigation (Chen, 2022b). This would lower reliance on negative emissions technologies to hold global warming to 1.5°C. The IPCC notes these scenarios are "subject to increased feasibility concerns… and greater social and environmental risks" (IPCC Working Group 3, 2022b) and reduce (although not eliminate) the moral hazard problem associated with CDR incentives (Daggash & Mac Dowell, 2019, p.2130). Second, the RCC can be set at a level that rewards mitigation activities enough to provide preventative insurance against catastrophic climate change (Chen et al., 2018, p.6). A carbon tax revenue recycling scheme would lose the ability to fund CDR as net-zero was approached because carbon tax revenues would drop; therefore, it would not be able to incentivise long-term net-negative emissions if they were required to draw down carbon to limit warming to 1.5°C. Finally, the GCR provides debt-free funding for mitigation activities with zero direct cost to stakeholders; the carbon reward is different from a subsidy because the reward is supported by monetary policy and not by fiscal policy. Therefore, carbon tax revenues can be used for equity purposes to support a just transition so that low-income households do not face wealth reductions.

Chapter 3: Methodology

Section 3.1 will introduce the IMED|CGE model used to create the NDC scenario for current policies and the CT-NDC scenario which imposes additional high-carbon taxes on to near "gross zero" emissions and limit global warming to 1.5°C (>50%) by 2100. Section 3.2.1 will describe how this study estimates the GCR floor price. Section 3.2.2 will discuss how that floor price is integrated with results from the CT-NDC scenario to provide an estimate for the debt-free financing available to fossil fuel exporters.

3.1 IMED|CGE Model Selection, Features and Scenarios

This study uses the Integrated Model of Energy, Environment and Economy for Sustainable Developed/Computable Equilibrium Model (IMED|CGE) developed by the Laboratory of Energy & Environmental Economics and Policy (LEEEP) at Peking University (PKU) as the basis for its empirical investigation of the effects of decarbonisation on economies reliant on fossil fuel exports. The IMED|CGE model has been used to analyze the changes in investment, carbon emissions, output, value-added and other macroeconomic indicators in China and around the world (Dai et al., 2020; Z. Li et al., 2018; Peng et al., 2020; Qi et al., 2018).[10] To date, IAMs are the most popular approach for investigating potential changes in economic structures that result from carbon prices as well as for estimating the SCC.

Depending on research objectives, the IMED|CGE model is flexible and allows for different regional coverage, base-year data, sectorial classification, and time step calculation (Dai et al., 2020, p.259). For this study, the IMED|CGE global model is used. The IMED|CGE global model covers 14 regions and 18 sectors (table A.1). It uses baseline GTAP data from 2014 (*GTAP 10 Data Base*, n.d.) and is calculated at a 5-year time step. Projections are made through to 2055.[11] The IMED|CGE global model is employed in this study because its output data was generously made available through the Peking University MSc. Environmental Management program. Other IAM's may be more appropriate or better calibrated for a preliminary investigation of the GCR, but the author did not have time or the access to comprehensively consider alternative possibilities.

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[10] More papers are available on the LEEEP website (*LEEEP Publications*, 2022).

[11] See Appendix B for more information on the IMED|CGE model relevant to the results of this study and Dai (2018) for a full explanation of the IMED model system.

Table 3.1 IMED|CGE baseline annual autonomous energy efficiency improvement (AEEI)

Energy Type	Developed Countries	Developing Countries
Solid and liquid fuels	1%–2%	3%–5%
Gaseous Fuels	0%–1%	2%
Electricity	0.5%	3%

Table 3.1 describes the assumed annually AEEI or energy efficiency improvements in the IMED|CGE model. Developing countries display higher AEEI rates because they are not at the technological frontier and can more rapidly adopt more energy-efficient technologies.

The IMED|CGE model has been designed to reflect the past and future development of regional economies included in the model. Data points were adjusted to match historical statistics of population, GDP growth, energy usage and pollutants as much as possible. The baseline for future data is based on the SSP2 (shared socio-economic pathway) scenario (Fricko et al., 2017). SSP2 is chosen because it represents a middle-of-the-road estimation for key metrics (population, nominal GDP growth, etc.) that influence climate change mitigation and adaptation. It also represents "an extension of historical experience, particularly in terms of carbon and energy intensity improvements in its baseline" (van Vuuren et al., 2017).

The population in the 14 modelled regions follow the SSP2 scenario (Kc & Lutz, 2017) and grows from 6.9 billion in 2014 to around 8.3 billion in 2055. Population growth rates vary by region based on the middle-of-the-road trends in SSP2. In the base year about 205 million people, mostly in high fertility low-income and developing countries, are not included in the IMED|CGE Global Model's regions. Therefore, the total population is lower than the global population in SSP2. The model assumes that without carbon constraints (the NDC scenario) GDP growth rates are fitted to be similar to those seen in Dellink et al.'s (2017) estimations of SSP2. Global energy demand in SSP2 grows to about 640 exajoules/yr by 2050 (Fricko et al., 2017, p.260).

In the IMED|CGE baseline assumptions, autonomous energy efficiency improvement (AEEI) [12] is set to be consistent with SSP2 assumptions on GDP and energy demand (table 3.1). In the IMED|CGE model, carbon emissions and energy consumption are driven by the

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[12] The AEEI is the energy input per economic output or energy efficiency improvement.

"complicated mechanism of economic growth, energy efficiency improvements, and relative prices of energy" (Dai, 2018).

Finally, trends in carbon emissions reflect the environmentally extended input-output tables developed by the LEEEP to reflect CO_2 emissions from energy combustion and industrial processes in the base year data (see section 3.1.2 for an explanation of annual carbon mitigation rates in the CT-NDC scenario).

The rest of this section explains the scenarios used in this model to investigate the economic consequences of a transition to gross zero (it is gross zero, rather than net zero, because the model does not account for negative emissions) driven by a carbon tax, and the emissions and energy data used to calculate the GCR potential financing. The NDC scenario is the baseline scenario that represents current climate policy, as explained below. The NDC scenario is compared with the CT-NDC scenario, which represents a carbon tax that is high enough to address the exogenously inputted carbon budgets for 1.5°C of maximum global warming, as explained in section 3.1.2 (see table 3.1 for relevant carbon budgets).

3.1.1 The Nationally Determined Contributions Scenario

This study will use two different scenarios modelled by the IMED|CGE with data provided by the LEEEP. A Nationally Determined Contributions (NDC) scenario is adjusted to include climate policies implemented and committed to before COP26, including the NDCs to the Paris Agreement and current climate policies. This is done by limiting the carbon budget to the level the LEEEP approximated as consistent with global climate policy from 2020-2100 (with emissions being allocated from the 2014 base year data). The assessed carbon budget from 2014-2100 in this scenario is 1539 $GtCO_2$.

The NDC could also be described as a current policy scenario because it assumes that many current policies (including the NDCs) continue without political disruptions. However, the NDC scenario is approximate because it is not possible to capture every country's specific climate policy.

It is important to note that the NDC scenario will have a significant mitigation effect because it assumes that carbon emissions will be 400 $GtCO_2$ lower than the output of the IPCC's relatively unrestricted CO_2 emissions scenarios such as the SSP3-7.0 (high CO_2 emissions) and SSP5-8.5 (very high CO_2 emissions) (IPCC Working Group 1, 2021, p.15). The carbon budget from 2014 used in the NDC scenario is similar to the emitted carbon in SSP2-4.5 if 2014-2020 emissions are added; the SSP2-4.5 was assessed to lead to between 2.5°C and 3°C of warming (IPCC Working Group 1, 2021, p.29). Therefore, it could be considered optimistic compared to other baseline pathways. Nevertheless, the policies in the NDC are insufficient to achieve a 1.5-2°C pathway.

3.1.2 Carbon Tax Plus Nationally Determined Contributions Scenarios

The CT-NDC varies from the NDC by adding to the IMED|CGE optimisation function the constraint of a carbon budget consistent with global warming of 1.5°C. This is done by using the cumulative carbon budget estimates from Raupach et al.'s (2014) 2°C carbon budget (p.874) and modifying it to be consistent with the ratio between the 2°C and 1.5°C carbon budgets established by the IPCC (Laboratory of Energy & Environmental Economics and Policy, personal communication, May 1, 2022). The global carbon budget (from 2014 to gross zero carbon emissions) assessed by the LEEEP to limit warming to 1.5°C (>50%) is 1152 $GtCO_2$.

This carbon budget is higher than the IPCC's most recent central carbon budget to limit warming to 1.5°C (>50%) of 510 $GtCO_2$ from 2020 until net zero (IPCC Working Group 3, 2022b, p.19). The carbon budget used in the CT-NDC differs from the latest IPCC estimate due to emissions from 2014 to 2019 (decadal average of 56±6.0 $GtCO_2e$ per year) (IPCC Working Group 3, 2022b, p.4) and changes in climate modelling since Raupach et al. (2014) was published. Therefore the 1.5°C carbon budget used in this paper from 2020 is closer to the upper end of the IPCC's assessed "no or limited overshoot" scenarios (710 $GtCO_2$) rather than the central estimation.

To allocate carbon budgets[13] in the CT-NDC scenario between regions this study uses Raupach et al.'s (2014) sharing formula (p.874) (see eq. 3.1).

$$(3.1)\ s_r(w) = (1-w)\frac{f_r}{F} + w\frac{p_r}{P}$$

Where $s_r(w)$ is the emissions allocation for region *r*; f_r and p_r are, respectively, the baseline (2014) emissions and population in region *r*; F and P are, respectively, the baseline global emissions and population. The IMED|CGE global model adopts that formula and uses the blended allocation (w=0.5) (regional carbon budget allocation is equally based on the 2014 emissions

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[13] The remaining carbon budget is the remaining cumulative amount of CO_2 to achieve a certain goal (Rogelj et al., 2019, p.335).

baseline and population size). The blended allocation is a compromise between the amount of mitigation required by a particular region *and* equity-based historic emissions allocations based on historic emissions per capita.

The model achieves the carbon budget in each region (r) by attaching a regional shadow carbon price (hereafter referred to as a carbon tax) that acts to alter the model's economic output in line with the regional carbon budgets. The carbon tax is an endogenous output of the IMED|GGE model and is set by exogenous and endogenous factors (Wu et al., 2016, p.1117). The main exogenous factor is the relation between the imposed carbon budget and the demand for CO_2 emissions. For example, if the imposed carbon budget is greater than the demand for CO_2 emissions then the carbon tax would be zero; as the demand for CO_2 emissions raises or the imposed carbon budget shrinks, the tax increases (Wu et al., 2016, p.1117). Factors that determine the carbon tax endogenous to the model are factors that come from the modelled sectoral carbon reductions, technological development, energy efficiency, etc. (Wu et al., 2016, p.1117). Since this thesis only compares a 1.5°C scenario to the CT-NDC policy scenario, the main factor determining the carbon tax is the exogenous carbon constraint and assuming zero carbon dioxide removal (CDR). Therefore, the price of the carbon tax in region (r) in year (t) is highly dependent on the allocated carbon budget in region (r) in year (t).

Developed countries are assumed to have higher annual mitigation rates and approach gross zero sometime before 2060 (in this study Canada and Australia & New Zealand) and therefore higher carbon taxes. Developing regions have lower annual mitigation rates that vary based on their level of economic development (in this study from earliest to latest gross zero dates: Former Soviet Union, Middle East, Africa).

This focus on the carbon constraint by the IMED|CGE model resolves the failure of IAMs to deal with the uncertain risk of the catastrophic effects of climate change and allows this study to focus on the economic impacts of limiting warming to 1.5°C rather than any kind of 'optimal warming' outcome.

3.2 GCR Scenario for Negative Emissions and Cleaner Energy

To investigate the feasibility of the GCR policy, this study examines the financial mechanism for rewarding negative emissions (i.e. carbon dioxide removal) and for rewarding

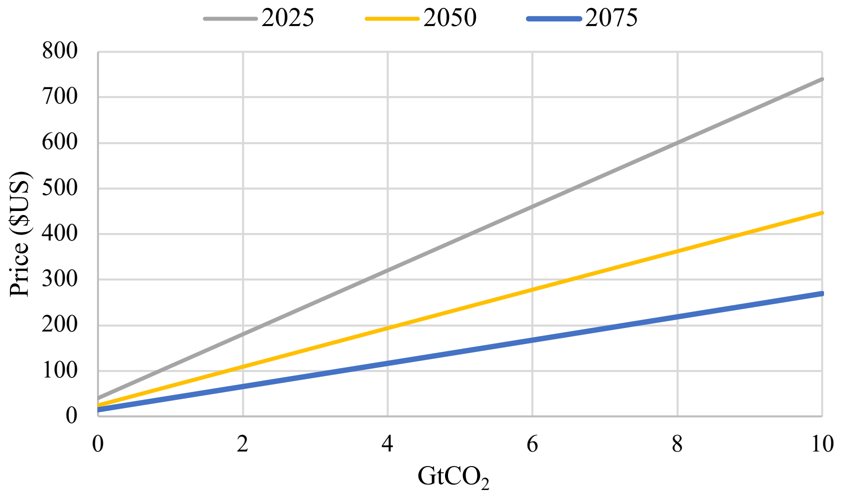

Figure 3.1 CDR estimated linear price vs quantity model

Figure 3.1 The estimated price quantity relationship of carbon dioxide removal in four chosen periods. The price and quantity estimates are based on interpreting the results of Fuss et al. (2018).

cleaner energy production at the speed and scale required to achieve the 1.5°C (>50%) goal. The study also examined the financial mechanism to support decarbonization of fossil fuel exporters when the GCR floor price is calibrated for a certain level of carbon direct removal (CDR). Due to time constraints the study did not consider the finance that could be offered through the GCR's rule for cleaner business and reward for negative emissions. The study is only of a preliminary nature, and the study approach was guided by the advice of Dr Delton Chen (personal communications between April-August, 2022).

There are two key parts to this preliminary study of the GCR: (a) the estimation of the floor price for the reward for negative emissions for achieving the 1.5°C goal (section 3.2.1 and appendix C); and (b) the review of the financial mechanism for incentivising fossil fuel producers to decarbonise energy production for achieving the 1.5°C goal (section 3.2.2).

3.2.1 GCR Floor Price

According to the GCR policy framework, the floor price of the Carbon Currency (CC) is to be defined by the marginal cost of each unit of negative emissions that is required to limit global warming to a specific level. The first necessary step is to develop a relationship between the price of negative emissions technologies and the quantity of carbon that is to be removed from the ambient atmosphere. The literature shows that estimates for the required amount of negative

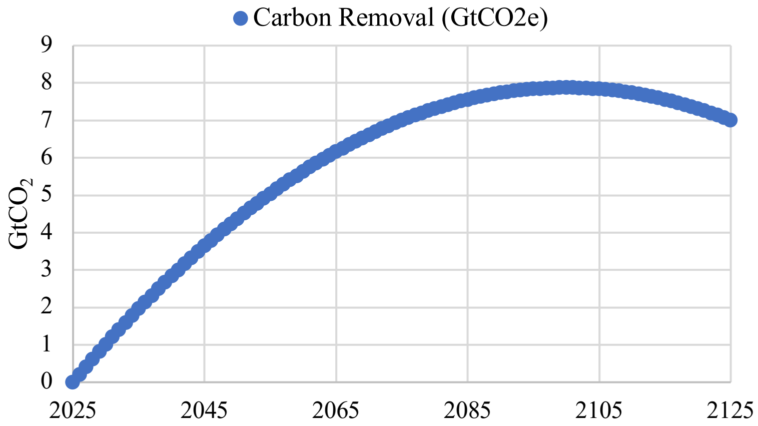

Figure 3.2 Estimated CDR target for GCR floor price calculation

Figure 3.2 represents the required carbon dioxide removal to stay below 1.5°C if the policies in the NDC scenario were implemented, but not the additional carbon tax. About 400 GtCO$_2$ is divided between 2025 and 2100.

emissions and the cost of negative emissions vary largely (Fuss et al., 2018; IPCC Working Group 3, 2022a; Strefler et al., 2021). This presents a challenge in the estimation of the floor price.

This paper does not look to provide a literature review of the possible development pathways for negative emissions technologies (NETs) and the associated costs. Therefore, to justify Chen's approach to the floor price, this study relies on the IPCC's estimate of the price-quantity relationship for CDR. Then it relies on the most comprehensive paper on negative emissions technologies cited in the IPCC Working Group 3's (2022a) discussion of NETs (p.12-35): Fuss et al. (2018) (see appendix C for further explanation). Finally, this study uses the difference in emissions between the NDC and CT-NDC scenarios to estimate the required negative emissions based on current climate policies so that is consistent with the mitigation CT-NDC scenario.

The IPCC defines carbon direct removal (CDR) as "anthropogenic activities that remove CO$_2$ from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products" (IPCC Working Group 3, 2022b, p.40). The NETs used in CDR vary significantly in terms of methods, storage location and technological maturity. Nevertheless, CDR will likely be necessary to counterbalance residual emissions from sectors that are hard to abate and existing fossil fuel infrastructure in scenarios where warming does not exceed 1.5°C between now and 2100 (IPCC Working Group 3, 2022b, p.28; Luderer et al., 2018, p.267). Chen has concluded that one way to determine the ideal GCR floor price, which is technically called the RCC, is to estimate the necessary level of CDR to achieve an agreed climate objective, such as the Paris Agreement goals (D. Chen, personal communication, April 4, 2022).

A price-quantity relationship for CDR has not been found in the literature that was reviewed in this study. A key finding is that the cost, externalities, and mitigation potential of CDR vary significantly based on the technology used, and future costs will vary greatly in accordance with technological breakthroughs (Fuss et al., 2018, p.1). Based on Fuss et al.'s review, this study estimates that in 2025 the lowest cost options for CDR will be approximately $US50 per tCO_2e for small amounts of sequestration. This quickly climbs to $US600-1000 for high levels of sequestration only. Costs then decline to a median price of about $US 200 tCO_2^{-1} for technologies with higher mitigation potential in 2050. To transition smoothly from the current 2025 curve to the mid-century estimates provided by Fuss et al. (2018) this study estimates an annual 3% compound decrease in the average price of deployed CDR because of economies of scale, the learn-by-doing effect, and technological improvements (while maintaining a positive price-quantity relationship in any given year); this was continued after 2050 for this review which ends with available IMED|CGE data in 2055.

To estimate the number of negative emissions required to limit global warming to 1.5°C this study considered several methods. The IMED Global Model relies exclusively on carbon pricing to mitigate emissions, so it was not able to provide a CDR estimate for this paper. A review by the IPCC found that the only CDR considered in a comprehensive IAM study was bioenergy carbon capture and storage (BECCS) (see Hilaire et al., 2019) and that only a limited number of other CDR technologies had been included in any integrated assessment models; the IPCC's review notes that the quantity of CDR required in different IAM's modelled pathways changes significantly "depending on the allowable overshoot of policy targets such as temperature or radiative forcing and the costs of non-CDR mitigation options" (IPCC Working Group 3, 2022a, p.220). Therefore, there was no obvious estimate for the required amount of CDR between 2020 and 2100 to use in this study to limit global warming to 1.5°C and the quantity of CDR required had to be assumed.

To provide the best comparison of the GCR and the modelled carbon tax in the CT-NDC scenario, this study assumes that the net-negative emissions required to limit global warming to 1.5°C between 2020 and 2100 are the difference in emissions between the NDC and the CT-NDC scenarios (around 400 $GtCO_2$ – see table 3.1). This may result in a more conservative floor price

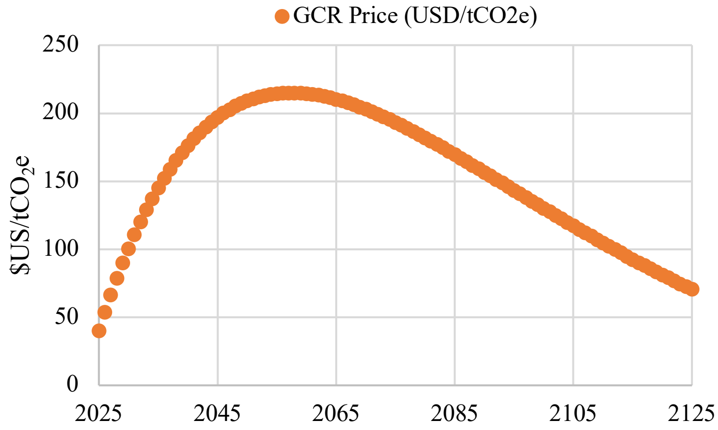

Figure 3.3 Estimated 100-year GCR floor price ($US/tCO2e)

Figure 3.3 represents the estimated GCR floor price calculated for this thesis. This is the estimated minimum spot price in $US for one Carbon Currency.

than alternative methodologies because the NDC scenario already assumes optimistic levels of mitigation based on the successful implementation of climate policy as discussed above.

The IMED-based targets result in demand for CDR that maxes out at about 8GtCO_2 /year in 2100 (figure 3.2) which, based on the estimations from Fuss et al, is significantly less than the likely technological frontier for NETs (Fuss et al., 2018, p.31-32). The amount of mitigated carbon per year was calculated by adjusting a CDR target model provided by Chen (personal communication, April 4, 2022) that provides smoothly rising and then falling levels of CDR aimed at maximizing the effects of economies of scale. This model assumes there will still be demand for CDR beyond 2100 (as is expected to hold global warming to 1.5°C), but that it will fall as the global economy decouples from carbon emissions and the risk of triggering catastrophic tipping points reduces.

Figure 3.3 represents the reward price (RP_t) in the equations below and is the exogenously established floor price of the CC set using estimates of the price-quantity relationship and the required amount of CDR in year *t*.

This model leads to a GCR floor price that starts at $US 40/t$CO_2$e in 2025 (the same year the IMED|CGE model introduces carbon prices), peaks at $US 215/t$CO_2$e just before 2060 and then would slowly decrease as the RCC declines due to the falling risk of irreversible climate tipping points and of exceeding global warming targets. The floor price change seen in figure 4.4 is consistent with the theory behind the RCC proposed by Chen et al. (2017, p.241).

3.2.2 Formula for the Rule for Cleaner Energy

This section explores the rule for clean energy, which is used to provide debt-free finance for incentivising decarbonisation of the energy sector at a rate sufficient to achieve the 1.5°C goal. Two simplifying assumptions are made in the examination of the financial mechanism: (1) the entire reward is paid out through the rule for cleaner energy and (2) it was not possible to estimate potential low-carbon feedback loops that may be able coordinate efficient market activity towards decarbonisation. In practice, the GCR would provide incentives for both supply and demand-side mitigation that might provide more mitigation for a similar reward price.

Because the IMED|CGE model imposes a carbon budget on each region in the model, we can use the carbon budget in the CT-NDC scenario to estimate the payout each region would receive at a macroeconomic level. Calculations represent how much aggregate compensation is available to fossil fuel exporting nations.

Below is the equation proposed by the GCR for the cleaner energy reward (Chen, 2021; personal communication, April 4, 2022) with some minor modifications so that it can be calculated using the IMED|CGE model results for an industry (i), in region (r), in year (t).[14] The reward for cleaner energy is calculated for ($Rbase_{i,r,t}$) – the initial reward for the ith sector/technology in the rth region in year t and then it is adjusted for co-benefits and administrative fees. The final reward to each sector is called the net reward ($Rnet_{i,r,t}$). The reward is calculated as follows.

(3.2) $Rbase_{i,r,t} = {}^{q_{i,r,t}}/_{Unit\ of\ Account}$

For the rule for cleaner energy $\Delta q_{i,r,t}$ is the change in carbon intensity (CI) between the baseline carbon intensity ($CIE_{i,r,b}$) and the carbon intensity in period t ($CIE_{i,r,t}$) times the total energy production ($E_{i,r,t}$). CIE and E must be in equivalent energy units to cancel out. For example, in this calculation, they must both be in tons of oil equivalent (toe).

(3.3) $\Delta q_{i,r,t} = (CIE_{i,r,b} - CIE_{i,r,t})\ E_{i,r,t}$

(3.4) $Unit\ of\ Account = CC = ton\ of\ CO_2e\ mitigation\ for\ 100\ years$

When denoted in $US $Unit\ of\ Account = \frac{CC}{USD}$. Therefore:

(3.5) $RP_t = Unit\ of\ Account = \frac{CC}{USD}$

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[14] See Appendix A for a complete set of formulas related to the GCR policy.

Where RP_t is the exogenously determined floor price of the CC (figure 3.3). By combining equations 3.2, 3.3, 3.4 and 3.5 we can calculate $Rbase_{i,r,t}$.

(3.6) $Rbase_{i,r,t} = (CIE_{i,r,b} - CIE_{i,r,t})\, E_{i,r,t} * RP_{i,r,t}$

To calculate $Rnet_{i,r,t}$ the GCR policy adjusts ($Radj_{i,r,t}$) for the co-benefits (positive and negative externalities) of ($a_{i,r,t}$) energy reliability; ($b_{i,r,t}$) community wellbeing, such as clean air and green jobs; and ($c_{i,r,t}$) ecological health that is created by the mitigation activity (see Appendix A for more details).

(3.7) $Radj_{i,r,t} = Rbase_{i,r,t} + a_{i,r,t} + b_{i,r,t} + c_{i,r,t}$

Since the adjustments sum to zero at the geographic level of administration (for this calculation regional), the following condition holds in any period *t*:

(3.8) $\sum_{i,r}^{n} a_{i,r,t} + \sum_{i,r}^{n} b_{i,r,t} + \sum_{i,r}^{n} c_{i,r,t} = 0$

Therefore, for this macroeconomic regional analysis:

(3.9) $Radj_{i,r,t} = Rbase_{i,r,t}$

To calculate $Rnet_{i,r,t}$ the administrative fee, F, is subtracted from the $Radj_{i,r,t}$.

(3.10) $F = 0.03Radj_{i,r,t}$

Therefore:

(3.11) $Rnet_{i,r,t} = Radj_{i,r,t} - 0.03Radj_{i,r,t} = 0.97Radj_{i,r,t}$

The final calculation for $Rnet_{i,r,t}$ combines equations 3.6 and 3.11.

(3.12) $Rnet_{i,r,t} = 0.97(CIE_{i,r,b} - CIE_{i,r,t})\, E_{i,r,t} * RP_{i,r,t}$

$E_{i,r,t}$ is found using data from the IMED|CGE CT-NDC scenario for primary energy supply. $CIE_{i,r,t}$ and $CIE_{i,r,b}$ are calculated using $E_{i,r,t}$ and CO_2 emissions ($F_{i,r,t}$) data from the IMED|CGE CT-NDC scenario. $CIE_{i,r,t}$ is calculated from data in year t as follows:

(3.13) $CIE_{i,r,t} = \frac{F_{i,r,t}}{E_{i,r,t}}$

Recall from section 3.3.2 that Chen's proposal includes $CIE_{i,r,b}$ calculations based on a complex administrative process. Therefore, a simplified equation was required. There were several possibilities considered for the $CIE_{i,r,b}$ calculation (see section 5.4). For the consistency of calculation and the available data, this study chose to base $CIE_{i,r,b}$ on the two time periods before the enaction of the policy (2015 and 2020) as follows:

(3.14) $CIE_{i,r,b} = \frac{\frac{F_{i,r,2015}}{E_{i,r,2015}} + \frac{F_{i,r,2020}}{E_{i,r,2020}}}{2}$

Chapter 4: Results

Section 4.1 will discuss the quantitative results of the IMED|CGE model comparing the carbon emissions, GDP and energy usage in the NDC and CT-NDC scenarios in Canada, the Middle East, the region of the Former Soviet Union, Africa and Australia & New Zealand. Section 4.2 will identify the carbon prices that the model produces to limit global warming to 1.5°C. Section 4.3 presents the debt-free financing available through the GCR rule for cleaner energy as described in section 3.2.

4.1 Quantitative Effects of Decarbonisation

4.1.1 Global Trends

Figure 4.1 demonstrates the absolute change in emissions between the two scenarios. It is important to note that due to the 5-year time step of the model input and output and, since 2020 is fitted to match the reductions in economic activity that resulted from the pandemic, the total emissions reduction between 2015 and 2020 is much larger than we observed in the latest IEA estimates (International Energy Agency, 2021a). This is because the environmentally extended input-output tables read the decrease in economic activity as a drop in emissions from 2015, despite the average annual increase in missions of 1.3% during the 2010-2019 decade (IPCC Working Group 3, 2022b, p.10). Therefore, the scenario ultimately allows for emissions further into the century than if the 2020 data was fitted closer to the 30 $GtCO_2$ estimated by the IEA (International Energy Agency, 2021a). The NDC scenario emissions bounce back to above 2015 levels (33.7 $GtCO_2$ at its 2035 peak), however the CT-NDC scenario emissions peak at about 24 $GtCO_2$ in 2030. This suggests that the economic losses, as well as the reductions in GHG emissions and carbon intensity discussed in the rest of this section, would be even greater if 2020 emissions better reflected the IEA's estimated total. This also implies that the potential financing provided by the GCR would be higher since the rate of decline in the carbon intensity of energy would be higher (unless carbon reductions were driven only by decreased primary production of energy).

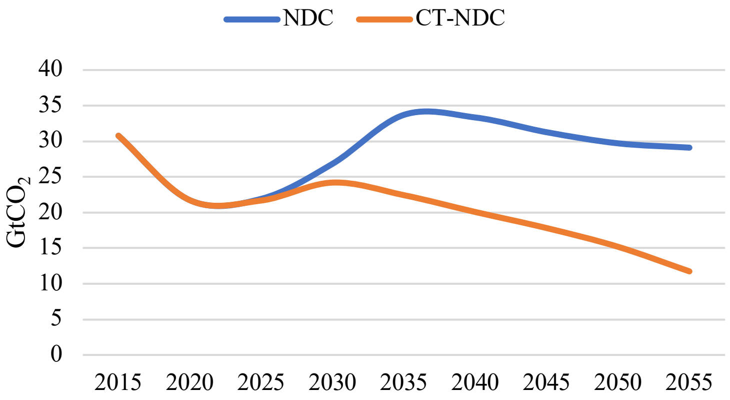

Figure 4.1 Global CO$_2$ emissions by scenario (GtCO$_2$)

Emissions in 2055 remain well above gross zero in both scenarios. In the CT-NDC, global CO2 emissions remain at 11.7 GtCO2 having declined over 50% from their 2030 peak. In 2055 the NDC scenario emissions are almost triple those in the CT-NDC at 29.1 GtCO2. The average year-over-year declines in CO2 emissions from the scenarios' respective peaks are 2.1% and 0.84% in the CT-NDC and NDC.

Global GDP continues to grow from the base year in both scenarios; however, as annual carbon budgets become stricter from 2055, some regions contract in absolute terms in the CT-NDC scenario. Figure 4.2 demonstrates the percentage of global GDP reductions between the scenarios. Global GDP generally grows more slowly throughout the CT-NDC than in the NDC scenario. In 2055 global GDP is 8.9% less in the CT-NDC than in the NDC. The largest relative decrease between 2050-2055 is driven by developed regions, including Canada and Australia & New Zealand, approaching gross zero in the CT-NDC. Under the NDC scenario, only regions that had the strongest climate policies, such as Western Europe, approached gross zero that early. The 8.9% relative decline in GDP represents a global economy that does not transition proactively to renewable energy and other low carbon technologies but is still constrained to gross zero. This may be a slightly extreme outcome as it does not account for negative emissions or rapid renewable energy development, but it highlights the cost to the global economy imposed by the strict limitation of global warming through regional carbon taxes.

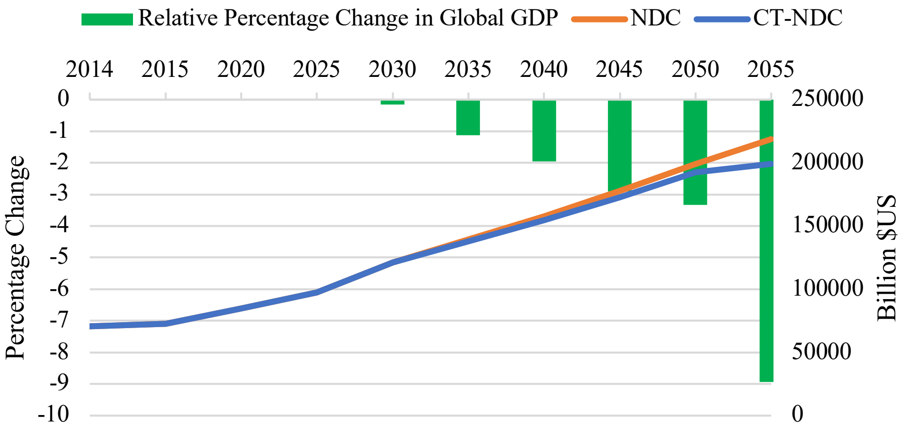

Figure 4.2 Global change in GDP between the NDC and CT-NDC scenarios

On the left vertical axis figure 4.2 demonstrates the relative percentage change in World GDP emissions between the NDC and the CT-NDC. The percentage change in GDP is calculated for each period relative to the GDP in the NDC scenario for that period. On the right vertical axis figure 4.2 demonstrates the absolute growth in GDP in both scenarios measured in $US billions.

Table 4.1 Fossil fuel industries: 2014 net exports (bil$US)

	Petrol Oil	**Crude Oil**	**Natural Gas**	**Coal Mining**	**Net Fossil Fuel Exports**	**GDP**	**Net Fossil Fuel Export % of GDP**
Canada	1.83	59.62	22.35	5.38	89.18	1651.30	5.40
Africa	-35.96	184.11	41.43	6.18	195.76	2245.28	8.72
Australia & New Zealand	-14.82	-9.49	10.37	56.33	42.4	1526.78	2.78
Former Soviet Union	89.46	217.23	62.96	17.35	386.99	2304.78	16.79
Middle East	60.41	580.46	45.12	-5.6	680.39	3335.23	20.40

Table 4.1 shows the net exports of each fossil fuel industry used in this study. It uses the IMED Global Model base year data to determine net exports for each industry and the GDP of each region.

4.1.2 Macroeconomic Trends in Fossil Fuel Exporting Regions

In 2014, exports from the fossil fuel industry represented a significant share of the GDP in all of the regions in the case study, however, the structure of that share varied greatly in both composition and magnitude (Table 4.1). Australia & New Zealand saw the lowest share of exports of the five regions at 2.8% of GDP. These net exports were driven primarily by coal ($US 56.3

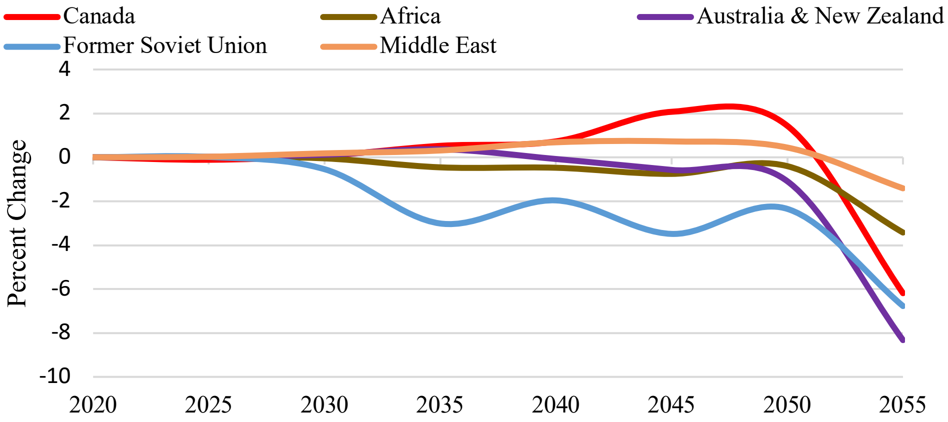

Figure 4.3 Fossil fuel exporters relative change in GDP

Figure 4.3 demonstrates the relative percentage change in GDP emissions between the NDC and the CT-NDC. The percentage change in GDP is calculated for each period relative to the GDP in the NDC scenario for that period.

billion) and they imported over $US 20 billion of petrol oil and crude oil. On the upper end of the spectrum, the Middle East and the Former Soviet Union saw the highest share of GDP attributed to fossil fuel exports at 20.4% and 16.4% respectively with both driven primarily by crude oil. Canada and Africa's exports were also both dominated by crude oil, with Africa still relying on petrol oil imports from elsewhere.

Like the rest of the world, fossil fuel exporting regions observe a lower GDP in 2055 in the CT-NDC scenario than they do in the NDC scenario alone (figure 4.3). Nevertheless, the pathway experienced by fossil fuel exporters between 2020 and 2055 is not uniform in the CT-NDC.

The emissions declines shown in figure 4.4 show that in the CT-NDC, the regions with the largest emissions reductions also experienced the largest relative declines in GDP (figure 4.3). These regions also experienced the greatest decreases in the carbon intensity of their primary energy supply. Canada and Australia had the lowest emissions and carbon intensities in 2055 but experienced by far the largest declines in GDP. The Middle East was the only region to see a relative increase in emissions, likely due to the increased output of petrol oil (figure 4.7) resulting from its low production costs and because its remaining carbon budget is larger than that of developed countries (based on Raupach et al.'s (2014) sharing formula).

The Middle East, identified by Mercure et al. as a low-cost oil producer, has a higher petrol output and sees a higher GDP throughout the first half of the century in the CT-NDC scenario.

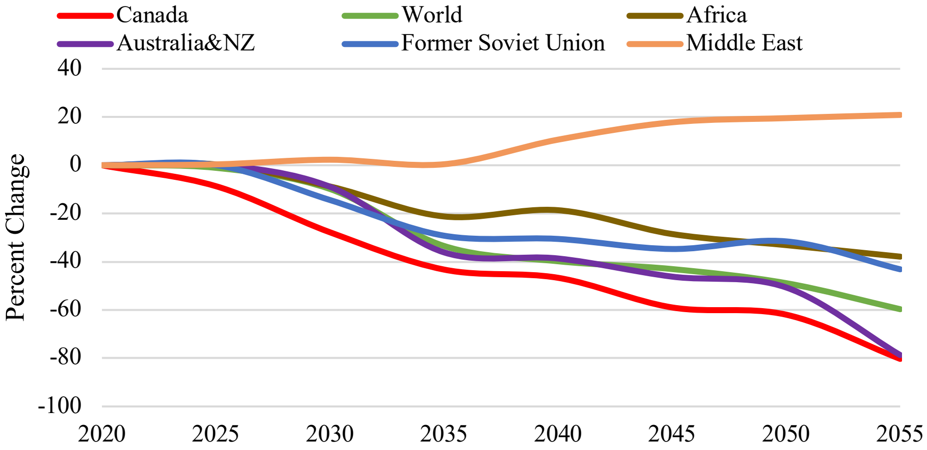

Figure 4.4 Percentage change in CO_2 emission between the NDC and CT-NDC

Figure 4.4 demonstrates the relative percentage change in CO_2 emissions between the NDC and the CT-NDC. The percentage change in emissions is calculated for each period relative the emissions in the NDC scenario for that period.

GDP drops below the NDC scenario after 2050; even the Middle East, which has higher relative CO_2 emissions in 2055 in the CT-NDC (see figure 4.4), has a $US 91 billion (1.4%) reduction in GDP between scenarios. Africa, another low-cost producer with low historic emissions, faced the second-lowest decline as a percentage of GDP in 2055 (3.4%). Both of these countries had relatively low carbon taxes compared to developed regions, demonstrating how in a high-carbon tax scenario economic activity slows even in regions that don't adopt such aggressive mitigation policies.

Behaving as expected for a high-cost fossil fuel producer, the Former Soviet Union saw a consistently lower GDP between 2020 and 2055; the region ultimately had a GDP that was $US 288 billion (6.8%) lower in the CT-NDC scenario. The regions with the largest decreases in both relative emissions and relative GDP are the highly developed and high-cost producers (Canada and Australia & New Zealand). They approach gross zero at earlier dates and therefore have higher carbon taxes which restrict economic activity. Canada saw an increase in relative GDP between the two scenarios until 2050 with relative GDP change peaking at $US 63 billion in 2045 (2.1% of GDP). However, as the carbon budget runs out and the carbon tax increases (see table 4.3) Canada's economy ends with a relative loss of 6.2% in 2055 compared to the NDC scenario.

Most regions saw at least minor declines in fossil fuel primary energy supply from the base year in both scenarios (figure 4.5). The major exception is Africa which saw a rise in coal,

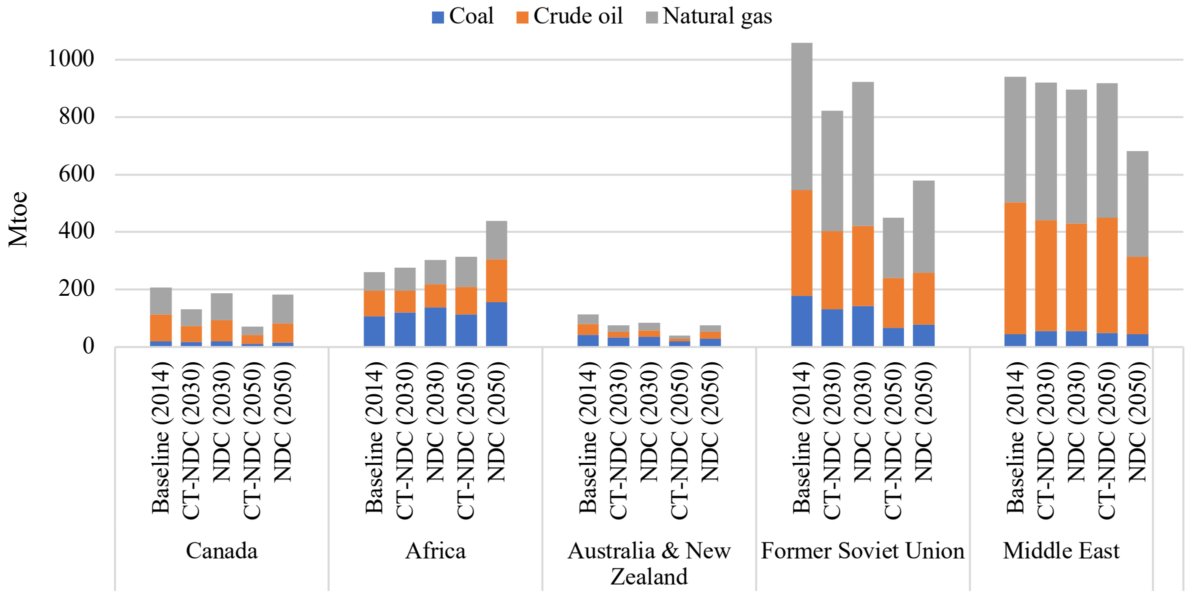

Figure 4.5 Fossil fuel primary energy supply in selected years (Mtoe)

Figure 4.5 compares the regional fossil fuel primary energy supply in 2014, 2030 and 2050 between the CT-NDC and NDC scenarios. Primary energy production from coal (blue), crude oil (orange) and natural gas (orange) is represented in Mtoe on the vertical axis. Data is grouped by region on the horizontal axis.

crude oil and natural gas energy production in 2050 compared to the base year in both scenarios. This was driven by increases in population and GDP growth as well as a less stringent carbon budget than developed countries in the CT-NDC. Fossil fuel primary energy supply was lower across most regions in the CT-NDC scenario than the NDC scenario due to the implementation of carbon taxes and the resulting drop in energy demand. However, the Middle East saw a higher primary fossil fuel energy supply in the CT-NDC in both 2030 and 2050. This reflects a far higher petrol oil output in the CT-NDC than in the NDC (see figure 4.7). Canada and Australia & New Zealand saw fossil fuel primary energy supply fall by more than 50% by 2050 in the CT-NDC, compared to the baseline and the NDC. The Former Soviet Union saw fossil fuel primary energy supply decrease across both scenarios in 2030 and 2050. In the NDC scenario, the decrease in fossil fuel primary energy supply is at a higher rate than any other country when compared to the baseline; this means there would have been significant regional mitigation even without a carbon tax in the Former Soviet Union.

A surprising result is that the share of coal as a percentage of fossil fuel primary energy supply was higher in 2050 in the CT-NDC than the NDC in all regions except the Middle East. In Canada and Australia & New Zealand, the share of coal in the fossil fuel primary energy supply

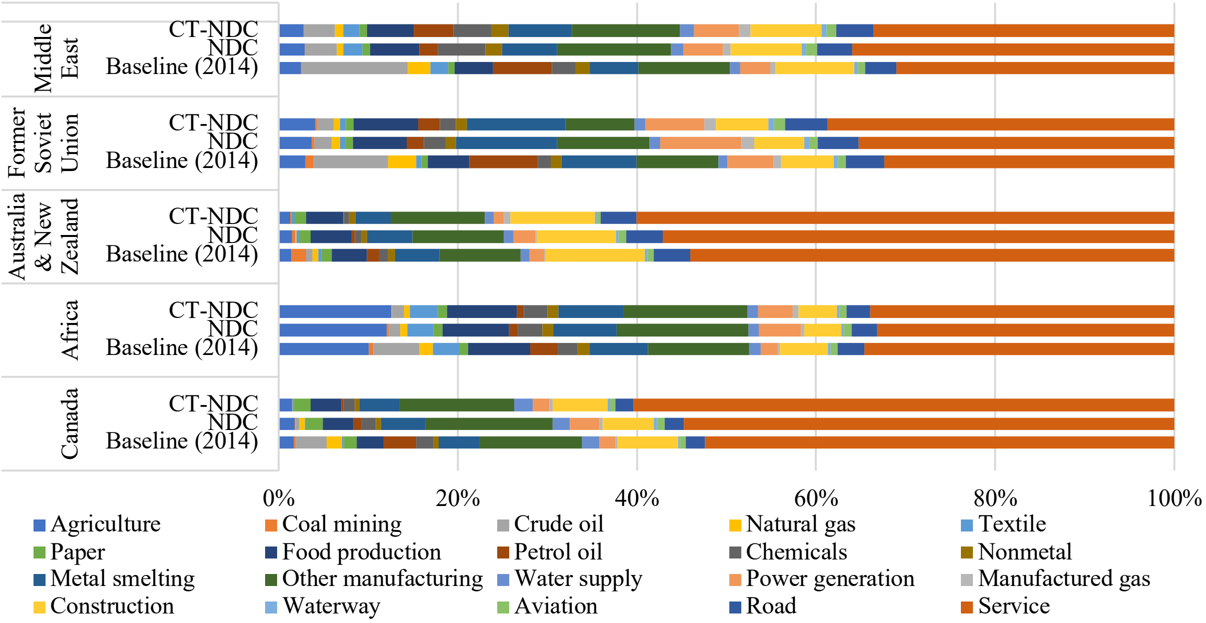

Figure 4.6 Output share by sector in base year (2014) and 2055

Figure 4.6 compares the share of sectoral output in 2014 and 2055 in the CT-NDC and NDC scenarios. Share of output is represented by percentage on the horizontal axis and data is grouped by region on the vertical axis.

was also higher than it was in the baseline. This demonstrates how a high carbon tax, applied on its own, results in lower emissions primarily through the reduction of primary energy supply and not through the incentivisation of alternative energy resources to replace existing fossil fuel infrastructure. Ultimately this results in the large economic losses seen in figures 4.2 and 4.3.

Figure 4.6 shows that the importance of the fossil fuel industry as a share of output declined in every region in both scenarios between 2014 and 2055. There are large regional disparities in the changes in sectoral output between the baseline and 2055 and between the scenarios. Nevertheless, the service sector sees important relative growth in all regions but Africa by 2055. The changes in sectoral output in Africa represent the industrialisation of the economy and an increase in the importance of secondary industry (mostly manufacturing processes) and agriculture.

Figure 4.6 and 4.7 show that regardless of the decarbonisation strategy the world follows, most fossil fuel exporting economies can expect to see the size of their coal mining, crude oil, natural gas and petrol oil sectors decrease between the baseline (2014) and 2055, even as the size of their economies grow year-over-year. The important exception is Africa which sees the output

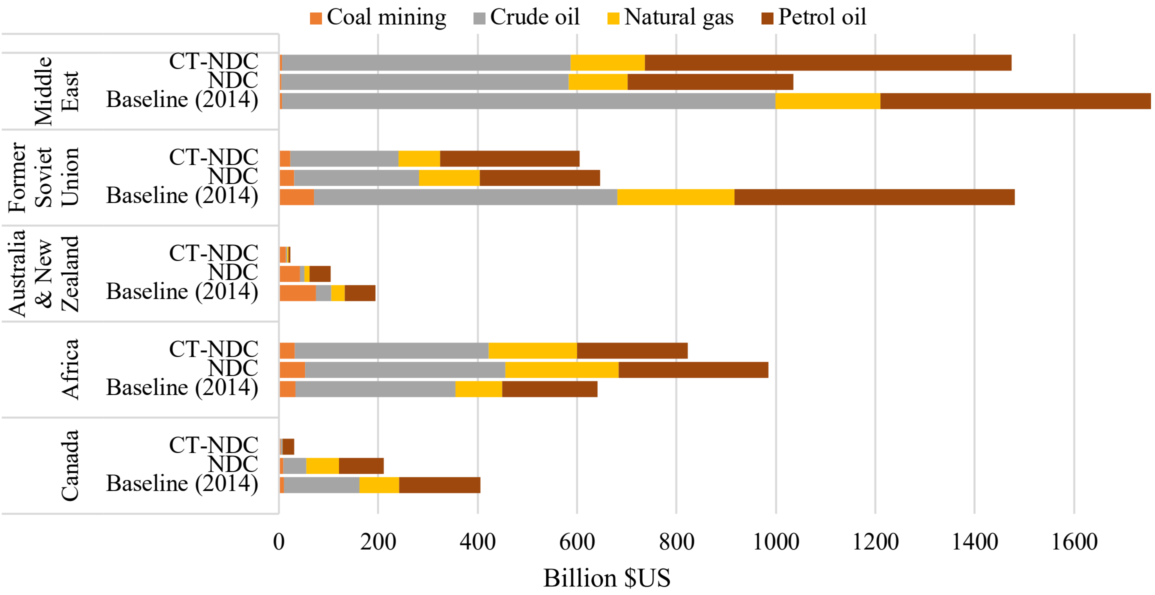

Figure 4.7 Fossil fuel sectoral output (billion $US) in base year (2014) and 2055

Figure 4.7 compares fossil fuel sectoral output in 2014 and 2055. Output is measured in billion $US on the horizontal axis and data is grouped by region on the vertical axis.

of almost all fossil fuel sectors grow in both scenarios (except the coal mining sector in the CT-NDC); nevertheless, the relative economic output of the fossil fuel industry still decreases (figure 4.6).

All regions except the Middle East also see a reduced fossil fuel sector in the CT-NDC compared to the NDC in 2055. The effects are most pronounced in developed countries and among high-cost producers. The Middle East sees a slightly larger output of crude oil and natural gas in 2055 in the NDC; however, the larger share of the fossil fuel sector in the 2055 CT-NDC sectoral share is driven almost entirely by the roughly 55% ($US 404 billion) increase in petroleum oil output compared to the NDC scenario. Petroleum oil output is also $US 188 billion higher in the 2055 NDC over the 2014 baseline.

4.2 Extreme Carbon Prices are Required to Limit Warming to 1.5°C

Table 4.2 Carbon price in fossil fuel exporting regions (US/tCO_2$)

	2025	2030	2035	2040	2045	2050	2055
Canada	75	323	605	847	1204	1621	12143
Africa	0	81	349	383	693	764	1868
Australia & New Zealand	0	112	579	916	1866	2585	19162
Former Soviet Union	0	106	312	367	513	480	1262
Middle East	0	0	66	0	4	0	46

Table 4.2 shows the regional carbon prices (in US/tCO_2$) that are required to limit each region to its respective 1.5°C carbon budget.

The IMED|CGE data shows that excessively high carbon taxes are needed to shift emissions in the historically exporting nations to a 1.5°C consistent pathway. These carbon taxes drive the large reductions in GDP demonstrated in section 4.1; regions with higher carbon taxes tended to see greater reductions in relative GDP. Table 4.3 shows that carbon taxes in $US/ton would have to be deployed at a much higher rate and far more broadly than currently in fossil fuel exporting regions. For the global economy to function within planetary boundaries a carbon tax of well over $US 10,000/ton in 2055 would be required in Canada and Australia & New Zealand. Another set of IMED|CGE results showed that if these high carbon taxes were removed after regions such as Canada and Australia & New Zealand reached gross zero, GDP would rebound, but so would CO_2 emissions. Therefore, the high carbon taxes seen in 2055 could not be eliminated when gross zero is achieved without a subsequent rise in emissions. In these fossil fuel exporting countries, the required carbon taxes grow almost exponentially as gross-zero is approached.

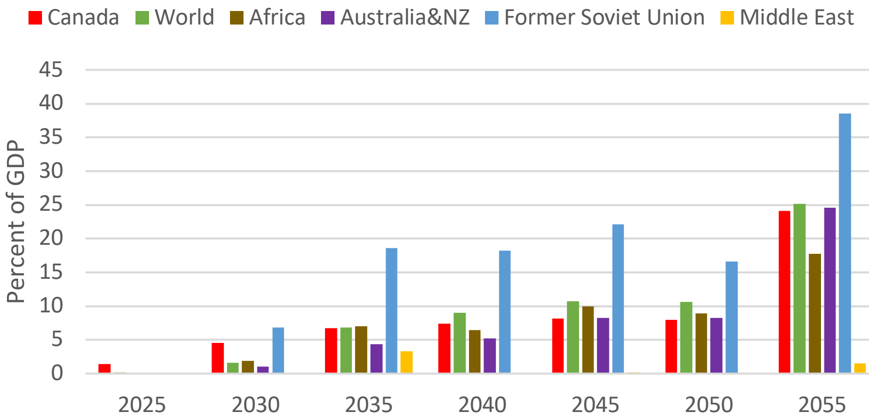

Figure 4.8 Carbon tax revenues as a share of GDP in the CT-NDC

Figure 4.8 demonstrates the carbon tax revenues presented in table 4.3 as a percentage of regional GDP in year t. The carbon tax revenues are proportional to the carbon prices that the IMED|CGE calculated to hold regions within the 1.5°C carbon budget.

Because emissions are embedded in their economic structures and are hard to abate and because the model does not account for potential changes in the price of renewable energy, drastic economic losses are seen in section 4.1.2.

Figure 4.6 demonstrates that the level of carbon tax collection in the CT-NDC scenario reaches as much as 24.1% of global GDP. The highest share of global GDP consumed by carbon tax revenue collection occurs in 2055, the period before many developed regions achieve gross zero in the model. The fossil fuel exporting region that pays the most total carbon tax, by a wide margin, is the Former Soviet Union, which sees the carbon tax consume over 15% of GDP from 2035 and as much as 38.6% of GDP in 2055. The only region where carbon tax revenues don’t exceed 5% of GDP after 2040 is the Middle East. This is likely because the emissions quota gives the Middle East a carbon budget through to the end of the century due to the lower historic emissions and high population of the region. More granular country data may present a different picture. Some wealthier, but low-population OPEC countries which have high per capita emissions may also be subject to higher carbon prices and emissions reductions if this were the case.

4.3 Carbon Reward Financing Available to Fossil Fuel Exporting Regions

Table 4.3 GCR Cleaner energy rule available financing (bill $US)

	2025	2030	2035	2040	2045	2050	2055
Canada	4.85	12.92	18.89	30.24	41.11	53.70	38.91
World	240.19	662.66	1026.21	1747.77	2361.14	3132.72	2939.71
Africa	7.17	22.10	26.06	42.25	88.34	112.83	178.96
Australia & New Zealand	3.18	8.20	9.63	14.27	22.22	24.46	16.28
Former Soviet Union	7.19	17.09	20.43	35.22	62.18	81.18	81.92
Middle East	5.99	21.09	18.79	37.86	104.10	104.42	125.87

Table 4.3 shows the available debt-free financing from the GCR in each region in each period. These levels of financing are consistent with this study's calculations for limiting warming to 1.5°C. As noted these are likely conservative estimations for total levels of GCR financing available.

This section provides estimates for the total GCR payouts provided by the rule for cleaner energy in the CR pathway modelled in this study. This estimate is necessarily preliminary because a) it is impossible to know how individual countries and industries would react to the GCR, b) this study's GCR price estimate is made with only 'best estimate' knowledge of the future cost developments of carbon removal technology and c) it is unclear how the markets would react to establish the final price of the GCR. However, this model provides each region with an order-of-magnitude estimation, likely on the lower end, of the financial benefits they could receive in a scenario where global warming was limited to 1.5°C through the GCR.

To understand the differences in rewards, recall from section 3.2 that RP_t is the same across all regions. Since RP_t is set at the global level, the regionally calculated $Rnet_{i,r,t}$ will depend on two factors: the difference between the baseline carbon intensity and the carbon intensity $(CIE_{i,r,b} - CIE_{i,r,t})$; and the total energy production $(E_{i,r,t})$.

Table 4.4 demonstrates that significant funding for mitigation would be made available to fossil fuel producers between 2025 and 2055 with funding totals generally growing steadily from $US 240.19 billion until the peak of $US 3,132.72 billion in 2050. Global total compensation then starts to decline. This is because by 2050 a significant degree of mitigation would already have

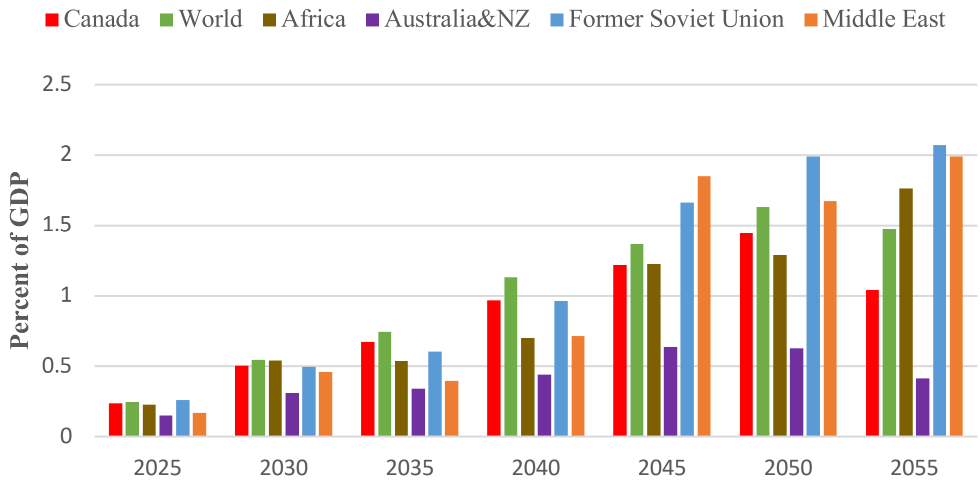

Figure 4.9 GCR regional payment as a percentage of GDP

Figure 4.9 demonstrates the GCR rule for cleaner energy rewards presented in table 4.4 as a percentage of regional GDP in year t.

been achieved in this scenario. As the risk of the global economy surpassing 1.5°C of warming declines, so does the total reward at the global level.

At the regional level, there are some differences as to when total reward peaks (see figure 4.9 and table 4.4). In regions with higher historic emissions and lower populations (and therefore lower carbon budgets), such as Canada and Australia & New Zealand, compensation peaks earlier in 2050 (1.4% of GDP) and 2045 (0.64% of GDP) respectively. Australia & New Zealand likely have the lowest compensation because their CO_2 reductions were driven more by a decline in the primary energy supply ($E_{i,Aus\&NZ,t}$) rather than a decline in the carbon intensity of energy ($CIE_{i,Aus\&NZ,t}$).

The less developed fossil fuel exporting regions with lower costs of production and which will continue to decarbonise for longer see rewards higher than the global average from 2040 onwards. This suggests that the GCR would provide debt-free financing for mitigation to regions that most need it to decarbonise, as long as they are consistently lowering their carbon intensity of energy.

An interesting result is that the Middle East ends up being one of the largest collectors of the GCR, peaking at 2% of GDP in 2055; this is despite having higher relative CO_2 emissions in the CT-NDC. They still demonstrate a decline in CO_2 emissions of 10.4% compared to the base year (2014) in 2055 and their emissions reductions are driven by decreases in carbon intensity of energy. If the GCR were implemented in a CR pathway, the Middle East's energy and emissions structure would likely be different than in the CT-NDC scenario, although they would still probably grow their petroleum oil market share. Africa and the Former Soviet Union's available financing also peak in 2055 at 1.8% of GDP ($US 252.36 billion) and 2.1% of GDP ($US 81.92 billion) respectively.

Limiting global warming to 1.5°C through a carbon tax could take up to 6.8% of GDP by 2035 and 25.1% of GDP in 2055. By contrast, it is estimated that financing available through the GCR peaks at 1.6% of global GDP in 2050. The cost of the carbon taxes as a share of GDP in the CT-NDC scenario is far too great to be a feasible way to limit global warming to 1.5°C. Therefore, it is not consistent with planetary boundaries. On the other hand, the order of magnitude for the GCR reward price is far more realistic based on the required financing to transition the global energy system (as well as other aspects of the global economy) to limit warming to 1.5°C by 2100.

These results show that limiting global warming through a reward-based system for mitigation like the GCR is less costly to the global economy. This is an important finding, however, the methodology employed in this paper only provides an order-of-magnitude estimate for the GCR. Further qualitative discussion is needed to draw conclusions on the likely effects of the GCR on the global economy and its ultimate feasibility to limit global warming to 1.5°C compared to a carbon tax-based approach.

4.4 Testing the GCR Calculations

Because the GCR is a novel policy whose financing has not been estimated before it warrants using additional data to calculate the potential reward funding provided by the rule for cleaner energy. This is important to demonstrate the sensitivity of the GCR calculations to its key assumptions. It is also important because the IMED|CGE global model used in this thesis does not include negative emissions or include a mechanism for more rapid deployment of renewable energy resources and because the calibration is biased by pandemic-impacted economic data that resulted in relatively low carbon emissions in 2020. Chen (personal communication, July 25, 2022) argues that the GCR rule for cleaner energy reward should be calibrated to represent the funding needed to decarbonise each energy commodity. This section presents a calculation that fixes the total reward ($Rnet_{i,r,t}$). This allows for the calibration of the carbon intensity baseline ($CIE_{i,r,b}$)

as proposed by Chen (2021). One important difference is that in this calculation the preliminary assessment of the $CIE_{i,r,b}$ was only provided in terms of global averages. Chen (2021) proposes that it the $CIE_{i,r,b}$ should be calibrated at the project level and the actual $CIE_{i,r,b}$ will be individually calibrated for each energy company or project, so as to provide a cost-effective incentive for decarbonation.

This section presents two calculations to show how important the assumptions are for the results of the policy and to highlight the need for careful consideration when implementing such a reward. The first calculation fixes $Rnet_{i,r,t}$ based on the total required energy investment in McCollum et al.'s (2018) 1.5°C scenario (hereafter called “total investment”) and the second calculation fixes $Rnet_{i,r,t}$ as the difference between energy investment in McCollum et al.'s (2018) current policy scenario and their 1.5°C scenario (hereafter called “additional investment”). Both of these calculations use Gambhir et al.’s (2019) paper to estimate primary energy output and carbon intensity in their 1.5°C scenario. For consistency with the calculation that used the IMED|CGE data to estimate $Rnet_{i,r,t}$, the floor of the reward price (RP_t) is the same as it was in section 3.1.[15] This calculation is only done at the global level as comparable regional calculations for fossil fuel exporters are not available using the data from the literature.

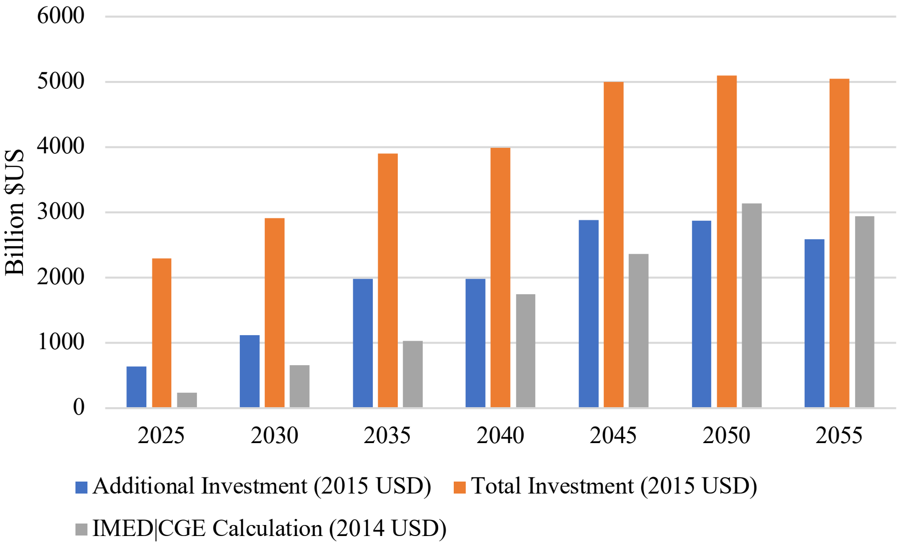

Figure 4.10 Total GCR financing in the three different calculations

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[15] Calculations which use IPCC Working Group 3's (2022a, 2022b) mean negative emissions estimates for 1.5°C consistent scenarios to set RP_t are available upon request to the author and show a similar $CIE_{i,r,b}$.

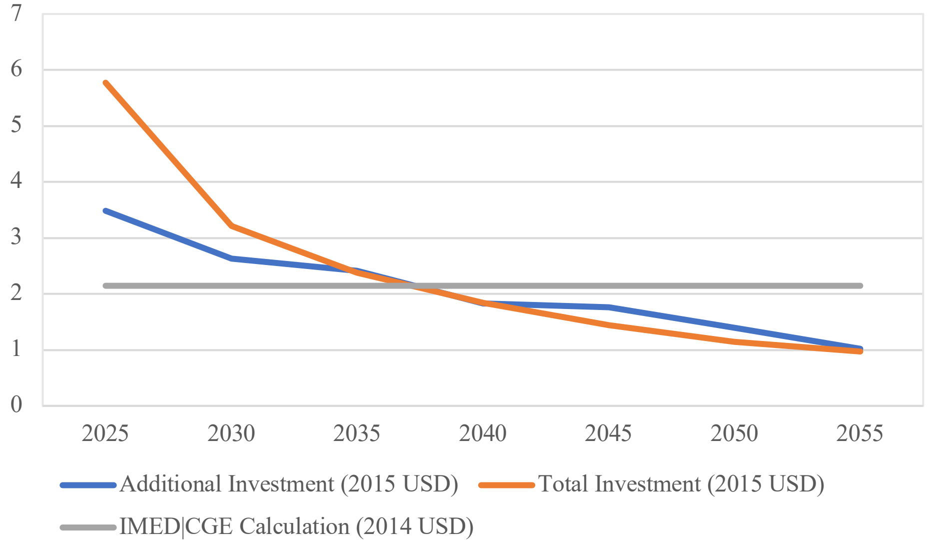

Figure 4.11 Carbon intensity of energy baselines

The “total investment” calculation represents a scenario where the GCR rule for cleaner energy would be calibrated to provide financing for the entire energy transition to ensure that global climate change remains below 1.5°C. The “additional investments” calculation represents a scenario where the GCR rule for cleaner energy would be calibrated to improve the marginal profitability of renewable energy investment compared to fossil fuel energy investment.

Figure 4.10 highlights the difference between the total energy investment in McCollum et al.'s (2018) 1.5°C scenario (orange bar) and the investment gap (blue bar) that needs to be closed to shift us from their current policy scenario to their 1.5°C scenario. We can see that the estimation of the rule for clearer energy based on the that the IMED|CGE data reaches the required level of investment as we approach mid-century; however it is not as front loaded as may be required to meet McCollum et al.'s (2018) 1.5°C scenario. Given the relative size of this financing relative to total energy investment,[16] the additional investment calculation and the IMED|CGE based calculation both offer finance that could work to incentivise the capital forecasted to be invested in fossil fuel energy to shift to low- and zero-carbon energy. These two calculations are provided simply to demonstrate the variability in the GCR rule for cleaner energy reward based on the

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[16] In this calculation the GCR rule for cleaner energy reward would range from 28% of total energy investment in 2025 to 52% of total energy investment in 2055.

assumptions used to calculate the RP_t and $CIE_{i,r,b}$ as well as the decarbonisation pathway that the world follows (which would determine $CIE_{i,r,t}$ and $E_{i,r,t}$).

Here this study notes that careful consideration must be given to the calibration benchmark. It may be preferable to calibrate the rule for cleaner energy based on the “investment gap” rather than the total required funding. This will provide an incentive for capital investment in low- and zero-carbon energy. The standard economic theory would suggest that this would move the highest return on energy capital away from fossil energy and towards lower-carbon energy sources. However, if the GCR rule for cleaner energy was calibrated for the total required energy investment in a 1.5°C scenario, there may be too many resources flowing into the energy industry. There is a potential for this to result in a very low return on new capital investment, too many real resources being shifted away from other important priorities and an unnecessarily high risk of inflation compared to the additional investment calibration. Another important consideration is the $CIE_{i,r,b}$ (see figure 4.11). It may also be preferable to have a consistently declining baseline over time as seen in the total investment and additional investment calculations; that will look to incentivise continuous energy improvements.

The $CIE_{i,r,b}$ that is shown for total investment in figure 4.11 is an important starting point for discussion, because it was calibrated to deliver around the additional US $2 to 5 trillion per year (between 2050 and 2055) for a clean energy transition to meet the 1.5C goal — which is the required amount of total finance (McCollum et al., 2018). The two other calibration measures should be considered as the policy is developed and discussions shifts from the global reward level to practical implementation at the project level.

As discussed above, Chen (personal communication, July 25, 2022) proposes that the rewards for cleaner energy will be conditional, as defined in individualised "service level agreements" (SLAs) that will define the awardee’s $CIE_{i,r,b}$, and will also introduce conditions for retiring fossil fuel assets and for producing a minimum amount of cleaner energy. The introduction of these SLAs (with a set $CIE_{i,r,b}$ to measure progress against) represents a major departure from conventional market pricing. The new approach could offer a global breakthrough for energy decarbonisation by providing scalable finance, and by providing a positive incentive for energy producers to rapidly retire their fossil fuel assets. There are still lots of unknowns with the GCR policy and how energy markets or energy infrastructure would evolve should the GCR be implemented. Nevertheless, as ‘meta-design’ shows us it is important that we question what is traditionally seen as ‘possible’ and properly consider all solutions, no matter how novel, to the massive problem of the climate crisis.

Chapter 5: Discussion

Chapter five discusses the results presented in section four in the context of the existing literature surrounding the modelling and economic theory of decarbonisation pathways. Section 5.1 argues that carbon taxes cannot hold the global economy within the 1.5°C carbon budget. Section 5.2 argues that the RCC and GCR may be able to align the short-term incentives of fossil producers with those of the global climate system. Section 5.3 argues that the rapid decline in renewable energy prices increases the likelihood that the GCR could incentivise the replacement of high-marginal cost fossil fuel infrastructure with low carbon energy sources. Section 5.4 discusses feasibility issues with GCR policy that have been identified in this paper and that merit further study and development.

5.1 Carbon Taxes are Helpful but Insufficient to Limit Warming to 1.5°C

As demonstrated by the IMED|CGE model, limiting global warming to 1.5°C through a carbon tax is unfeasible. It is too late to avoid exceeding planetary boundaries through incremental price changes representing the negative externality of each marginal unit of pollution; the regional carbon prices required to limit global warming to 1.5°C are higher than would be acceptable.

The sharp declines in relative GDP in 2055 (figure 4.3), as well as the sharp reduction in fossil output and primary energy support (figures 4.5 and 4.7) in Canada and Australia & New Zealand, represent the shortfalls of high-carbon tax-based mitigation pathways. No country would ever self-impose such a high carbon tax (see table 4.2) and in this scenario, these economies had little proactive structural transformation away from fossil fuels while carbon prices were still reasonable. Therefore, they were forced to reach emissions targets extremely quickly and cut energy supply (figure 4.5). Relying exclusively on a negative price signal to transition the global economy in the short period we have remaining to meet global carbon budgets will result in significant losses in developed countries, depressing developing countries' economic growth even with the relatively high carbon 1.5°C budget used in this study.

5.2 Bringing Fossil Fuel Exporters into a Decarbonised Future

The literature on energy transitions demonstrates that emissions “locked” into existing fossil fuel infrastructure are greater than existing 1.5°C carbon budgets and that fossil fuel energy incumbents are likely to delay the transition for perceived short-term benefits. At the same time, the CT-NDC and the and the modelling discussed in section 2.2.2 shows that with the constraints of the 1.5°C carbon budget, fossil fuel exporting regions with high marginal costs of production are facing industrial decline. This section argues that the reward for the positive externality associated with mitigation may be able to bridge the gap between global climate policy and the short-term market incentives of fossil fuel exporters.

The GCR does not replace all the losses experienced by the fossil fuel exporting regions between the NDC and the CT-NDC using the methodology in this paper. However, this is likely not a desirable policy outcome if there is not a requirement to use any payments to build out equivalent renewable energy resources. Instead, the proposed policy is meant to provide incentives to speed the pace of decarbonisation and allow those with the capacity and expertise to develop low- and zero-carbon energy resources to do so at a pace consistent with the Paris Agreement target.

By taking advantage of the policy, fossil fuel exporting regions could reduce the “post-industrial decline” that Mercure et al. (2021) argue is likely (p.7). The GCR could both boost the awards available to the regions analysed in the study and reduce their GDP losses because their economies will be better prepared for a 1.5°C consistent world. The main benefit of the GCR, however, is its ability to keep the global economy consistent with the planetary boundary framework.

Way et al. (2021) and Mercure et al. (2021) demonstrated that low carbon investment is not an unnecessary economic cost on which fossil fuel exporting regions can ‘free-ride’ on the efforts of others; fossil fuel exporting regions with high marginal costs of production need to invest in decarbonising their domestic economies to minimise industrial decline. Under a high-carbon tax, fossil fuel infrastructure is not retired until the point where it is completely economically unviable: it does not effectively incentivise its early retirement or permit its replacement by increasingly low-cost renewable energy. This would still leave high-cost fossil fuel producers with large amounts of stranded assets and no financing to create equivalent low-carbon energy supplies.

We saw that coal had a higher share of the primary energy supply in the CT-NDC scenario compared with the NDC scenario. This reflects the inability of a carbon tax alone to force a transition from high carbon-emitting energy sources to lower emissions alternatives. Instead, the CT-NDC achieved its emissions reductions through decreases in primary energy supply, resulting in large economic losses for fossil fuel exporting regions. With the GCR incentives described in section 4.3, the sooner fossil fuel exporting regions decouple their GDP from carbon emissions, the larger their share of the GCR payment becomes. If fossil fuel exporters agreed to decommission fossil fuel infrastructure ahead of schedule and substitute it for a clean power source, more financing would be available than modelled. This would allow the producer to recover some of the sunk costs of the fossil fuel infrastructure, purchase more efficient clean energy infrastructure, and provide employment for workers in the carbon-based industries that are being phased out.

In contrast to the sole use of carbon taxes, the complementary “carrot” and “stick” rewards could greatly improve social cooperation on mitigation and speed decarbonisation efforts. The GCR might address many of the issues associated with national and proposed international carbon pricing regimes. By proposing carbon quantitative easing as the main funding mechanism of the GCR, Chen et al. (2018) shift the burden of financing away from governments, citizens and corporations to central banks (Chen et al., 2018). This is a radical shift in central bank policymaking that recognises the role of climate stability in financial stability (Carney, 2015) and might increase the socioeconomic feasibility of mitigation. The GCR might improve the maintenance of domestic industry competitiveness by providing the same rewards globally. It might also address the free-rider problem because equivalent positive incentives for mitigation would exist globally so that there is an incentive for all firms and regions to increase their mitigation activities. However, unless very carefully constructed, the GCR could still face the problem of carbon leakage; if a certain firm or organisation were to be rewarded for their mitigation efforts, the same polluting activities could still be expanded elsewhere by a firm that chose not to benefit from the GCR. Nevertheless, the advantage of the GCR over most carbon taxes when addressing carbon leakage is that all firms globally would have an incentive to reduce emissions, not just those located in carbon-restricted jurisdictions. A reward may be the only way to entice both high- and low-emitting regions into the same low-carbon future.

The integration of the GCR into the economy could incentivise the development of low carbon energy over new fossil fuel infrastructure and also the early retirement of fossil fuel infrastructure while allowing fossil fuel energy suppliers to substitute their fossil energy reserves with comparable clean energy supply. This is important because maintaining the stability of the energy supply will be critical to human wellbeing and political acceptance during the transition to a net-zero carbon economy.

5.3 Low-cost Low-carbon Technology Make Rewards More Feasible

The feasibility of the GCR is enhanced by the large decreases in the cost of solar PV and wind energy as a result of technological improvements and economies of scale. Since 2010 prices have fallen by four-fifths for utility-scale solar PV models and by two-thirds for residential systems (International Energy Agency & International Solar Alliance, 2019, p.13). This section argues that financing provided through the GCR could allow for the rapid and orderly deployment of low-carbon energy supplies and associated energy distribution infrastructure.

During the last decade (2010-2019) the unit cost of solar and wind energy, as well as lithium-ion batteries, decreased by 85%, 55% and 85% respectively. This decrease in prices also saw an increase in deployment of these low carbon technologies. Solar and electric vehicle deployment increased by a factor of 10 and 100, respectively, but with wide regional differences (IPCC Working Group 3, 2022b, p.15). According to the IPCC, in 2020 the levelized cost of electricity (LCOE)[17] producing using renewable technologies is now competitive with that of comparable new fossil fuel installations in most regions (IPCC Working Group 3, 2022b, p.16). Analysis from the private sector firm Lazard reinforces this conclusion by demonstrating that in 2021 the LCOE for new installations of utility-scale solar PV-thin film (US$28-37), utility-scale solar PV-crystalline (US$30-41), and onshore wind (US$26-50) is cheaper in most cases than the LCOE of convention energy sources: new gas peaking (US$151-196), coal ($65-152) and gas-combine cycle (US$45-74) (Ray, 2021, p.3). What their analysis shows that is particularly important is that the LCOE of these renewable technologies is competitive with the marginal cost-

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[17] LCOE is a metric for comparing energy costs.

per-unit of energy of gas-combine cycle and cheaper than coal electricity generation on a global scale; when US government subsidies are included, the LCOE of onshore wind drops to US$9-40 generally making it cheaper than the marginal cost of gas-combine cycle (US$19-29) (Ray, 2021, p.8).

These price declines in the cost of solar, wind and other low-carbon technologies are expected to continue. In modelling by Mercure et al. (2021), in every scenario but the Investment Expectations (InvE) scenario (which is an unlikely scenario because it includes “lower than already-observed growth rates in solar, wind, electric vehicles (EVs) and heat pumps”), solar PV becomes the lowest-cost energy-generation technology by 2025-2030 (p.3). Way et al. (2021) argue that from a cost perspective, near-net zero emissions can be achieved in 25 years “if solar photovoltaics, wind, batteries and hydrogen electrolyzers continue to follow their current exponentially increasing deployment trends for another decade” (p.1). Therefore, it is likely that we have the technical capabilities and the required cost-effectiveness to decarbonise the global economy fast enough to limit warming to 1.5°C.

However, achieving such a rapid transition will be costly. As discussed in section 2.2 McCollum et al. (2018) indicated that more funding was needed to meet Paris goals for low carbon energy. McCollum et al. (2018) found that annual investments in low-carbon energy supply need to surpass fossil energy investments by 2025 to be able to limit warming to 1.5°C (p.589). McCollum et al. (2018) also found that to meet the Paris targets of limiting global warming by 2100 to 1.5-2°C, there was a significant investment “gap” between baseline total energy investment of $US 480 billion per year (to 2030) (p.590). In the CR pathway modelled in this paper, financing made available through the GCR at the global scale would be available to increase investment in renewable energy technology by $US 240 billion and $US 662 billion in 2025 and 2030 respectively. This does not equal the total global amount of funding needed for clean energy investment (about US$ 3.3 trillion annually between 2016 and 2050), but it represents a significant part of the investment gap and would provide and additional incentive for the baseline energy investment to transition from high- to low-carbon energy.

As we saw in the last section, the GCR’s financial mechanism could accelerate the retirement of fossil fuel infrastructure by acting as a complement to the carbon tax and by providing a new source of financial capital for a rapid energy transition. This transition will be aided by the continued decline in the prices of renewables plus storage.

5.4 Developing the Global Carbon Reward Policy

Throughout this research, several features of the GCR were identified as requiring further investigation and research. This section will briefly address: (a) the moral hazard associated with designing a policy for funding CDR, (b) some potential macroeconomic impacts of the GCR that require additional understanding, and (c) the baseline assumptions of the policy that should be carefully considered.

The reward floor price (i.e. the RCC) of the GCR will be calibrated the level that will be needed to achieve the climate goal of the Paris Agreement. If the reward floor price is calibrated higher than is needed, then CDR would become a 'privileged technology,' and this could lead to an over-reliance on CDR to meet the Paris Agreement targets. Thus there is a need for some restraint with regards to the reward floor price so that there is not over-reliance on CDR. The IPCC is unsure of the plausibility of scenarios with such high reliance on removing carbon from the atmosphere (IPCC Working Group 3, 2022b, p.19). One important caution is the moral hazard that arises from CDR incentive schemes because CDR may prolong the global energy systems' reliance on fossil fuels by allowing for their continued use; Daggash and Mac Dowell (2019) found that "once the imposed CDR ''target'' [of the positive incentive policy] is met… further CDR deployment is limited and the system reverts to building the cheapest form of generation" (in their study it was combined cycle gas turbines) (p.2131). Therefore, while "carrots" are needed for CDR and to reduce the total systems cost of the energy transition, other policy mechanisms ("sticks") are also needed to prevent the resurgence of fossil fuel infrastructure once net-negative emissions are achieved. This is why a "carrot and stick" approach to climate mitigation is recommended. Relying too heavily on just "carrots" or just "sticks" should be avoided. Due to our limited experience with negative emissions technologies, care should be taken when estimating the GCR floor price. This floor price should be revised periodically in response to emerging social and technological trends.

This study did not attempt to examine inflation or global wealth distribution as a result of the GCR policy. The carbon quantitative easing that establishes the reward floor price will result in an increase in the supply of money in the world economy, which should lead to some monetary inflation. On the other hand, reducing the impacts of climate change will avoid cost-push inflation in goods and services that would otherwise be caused by more extreme weather, higher temperatures, higher sea levels, and more degraded ecosystems. It is therefore unclear if the GCR would put upward or downward pressure on real inflation over time. This study did not attempt to quantify the different kinds of inflation that could result with/without the GCR policy.

Chen (2021) proposes that the carbon intensity of energy baseline ($CIE_{i,r,b}$) should be monitored at the project level when implementing the reward rule for cleaner energy (section 2.2). This will require intensive information collection and administration making the policy less efficient than alternative market-based policies. However, the objective of the GCR policy is not to be efficient under a cost-benefit analysis; the objective of the GCR policy is to be effective in controlling the global carbon balance for achieving a specific climate objective. The results of this study suggest that the economy-wide $CIE_{i,r,b}$ is a simple-to-calculate metric, but the GCR authors argue that each energy project will be rewarded based on an individually prescribed carbon intensity of energy baseline that will be calibrated to be "cost effective" for achieving a prescribed energy transition. These details will be written into long-term service-level agreements for the awardees, and each awardee will be invited to sign on to their agreement on a voluntary basis. Less administratively burdensome solutions should be considered, at least in the short-term, because it may take a long time to establish those institutional capabilities.

Other methodologies that would have matched global GDP loss between the CT-NDC and NDC scenarios to the total GCR reward price were considered. However, they rely on a counterfactual calculation and was found to inject an overly large supply of financing into the global economy and provide rewards greater than the total value of GDP to some fossil fuel exporters, which was both unrealistic and not the point of the policy.

This study also considered other levels of negative emissions between 2020 and 2100 to test the sensitivity of the GCR floor price and the resulting carbon rewards. Other scenarios tested using the IPPC's mean estimate of 770 $GtCO_2$ of required negative emissions between 2020 and 2100 (IPCC Working Group 3, 2022b, p.29) resulted in a higher GCR floor price and higher potential costs of total negative emissions. Therefore, this study provides a conservative estimate for the available debt-free financing available through the GCR policy. Importantly, this demonstrates that the setting of the GCR floor price — called the RCC — is subject to uncertainty in relation to the cost of CDR over time.

Chapter 6: Conclusion

This study identified the misalignment between current global economic incentives and the goals of the Paris Agreement as a critical shortcoming in the environmental economics literature. Given the strong rational to take significant mitigation activity (Lenton et al., 2019, p.595) this thesis adopted the call of 'meta-design' to investigate novel policies and create 'future-possibles' to improve or transform the climate crisis (Wood, 2022, p.17). It assesses the feasibility of — and highlights the need for — new market-based policies to incentivise the rapid decoupling of carbon emissions from the global economy.

To improve the understanding of how market-based incentives could be used to limit global warming to 1.5°C, this study investigated the feasibility of both a high carbon tax pathway and a carbon reward pathway to reduce CO_2 emissions in fossil fuel exporting regions. Through the IMED|CGE model, out-of-model calculations and a qualitative discussion of decarbonisation, this study found that carbon taxes alone will fail in limiting global warming to 1.5 degrees because the pricing regime and model-simulated economic changes appear too dramatic to be economically or politically feasible.

This research affirms the results of Daggash and Mac Dowell's (2019) study which found that a carbon tax, when applied as the main economic tool for reaching 1.5°C, is not economically or politically feasible. In 2055 in the CT-NDC scenario, fossil fuel exporters faced carbon prices of up to $US 19,162/ton and relative GDP reductions of up to 8% compared to the NDC. It is important to note that the calculation of the carbon tax values has certain limitations and is based on the model's assumptions (as discussed above), and so is only a notional tax — as well as being interpreted as being "infeasible." If actually implemented, the carbon tax revenues modelled in the IMED|GGE global model would equal up to 25% of global GDP and 39% of GDP in the Former Soviet Union. To limit global warming to 1.5°C, it appears that the required carbon tax, and its associated share of regional and global GDP, are beyond the limits of what is politically feasible in terms of historical experience with carbon taxes.

By contrast, the carbon reward provides a direct incentive to reduce the carbon intensity of the energy supply while at the same time offering funding to close the gap between the cost of renewable electricity projects and the marginal cost of existing fossil fuel infrastructure. Unlike a carbon tax, carbon rewards can incentivise and fund the early retirement of fossil fuel infrastructure and thus reduce the financial risks associated with the stranding of otherwise valuable fossil fuel assets. The GCR provides financing of between 0.64% and 2.1% of GDP to fossil fuel exporting countries during their various peak years. The GCR rule for cleaner energy provided global debt-free financing of $US 240.19 billion in 2025 which grew until it peaked at $US 3,132.72 billion in 2050. This is estimated to be within range of the 'investment gap' that must be closed to achieve total energy investment to decarbonise global energy infrastructure to meet the Paris Agreement goals (McCollum et al., 2018, p.590). If the full reward was tested, GCR funding would be awarded for the three reward rules in contrast to the single one analyzed here, providing additional financing for decarbonisation across the economy.

The discussion section showed that by providing funds to transition energy infrastructure the carbon reward pathway offers an improved socioeconomic transition to a 1.5°C consistent economy. Some key conclusions of the study are: (a) the risk cost of carbon (RCC) may be a necessary metric to integrate into the global economy; and (b) the global carbon reward (GCR) shows promise as an effective means of properly pricing a new positive externality at the global scale, whereby the positive externality is defined as the new GCR marketplace, including the carbon currency instrument. The GCR marketplace is a positive externality because it is a proposed new global public good with a capacity to influence the global carbon budget and to "… … significantly reduce the risks and impacts of climate change…" (Article 2 Section 1(a); Paris Agreement, 2015); nevertheless, the policy is still within its early stages of development and needs additional research before it can be considered by governments for addressing the Paris Climate Agreement.

From this study, three broad socio-political emissions pathways are interpreted as possible futures. Either (1) fossil fuel exporters maintain their usage of their fossil fuel infrastructure, pushing us past our remaining carbon budgets for 1.5°C, and bringing us to 2°C or higher, more dangerous levels of global warming; (2) carbon tariffs on fossil fuel exporters are so high they ultimately reduce fossil energy trading through coercion, but net-zero would not necessarily be achieved because of rising domestic consumption in fossil fuel or through exports to other non-compliant regions; or (3) the international community develops a mechanism that supports the early retirement of fossil fuel infrastructure and its replacement by alternative energy sources. Scenario (1) risks catastrophic changes to the global climate system and therefore risks huge and uncertain economic losses in the long-term. Scenario (2) might destabilise the economies of fossil fuel exporting nations without actually providing a globally effective mitigation outcome. Only scenario (3) of those considered appears consistent both with the Paris goal and with the principles of Lenton et al. (2019) and Rockström et al.'s (2009a, 2009b) planetary boundary framework. Nevertheless, the policy has not been studied by major research institutions, and it deserves further detailed investigation in relation to its impact on the global financial system.

Of course, there are important limitations to this study. With the current evidence and the methodology employed, this study provides only a preliminary assessment of the high-tax scenario and the carbon reward scenario. With the limited time and resources available, this study relied on the existing IMED|CGE model. Future work could improve the calibration of this model for an investigation of the GCR. The IMED|CGE model, like all IAMs, cannot include yet-to-be-developed negative emissions technologies, called carbon dioxide removal (CDR), and nor does the IMED|CGE model factor CDR into its conceptual framework or calculations. Other limitations of the study are that: (i) the IMED|CGE global model is under continuous development and does not yet account for potential future increases in the rate of renewable energy deployment; (ii) some of the data used to calculate the carbon reward was based on estimates from preliminary literature; (iii) the study was limited to the impacts on fossil fuel exporting nations; (iv) welfare was measured simplistically in terms of GDP; and (v) the study did not examine the third GCR reward rule, which is the reward for "cleaner business," which implies offering carbon rewards for cleaner patterns of consumption at the level of individual businesses. For these reasons, the reader should treat the data with due care when referencing this paper.

Future research should address the shortcomings of the current study by using more precise methods and by experimenting with 'carbon rewards,' including, but not limited to: (a) exploring and justifying the theory for the positive externality associated with mitigating climate change; (b) considering how the GCR could be modelled in its entirety and compared quantitatively to other policy scenarios; (c) reviewing the GCR's carbon reward floor price and the carbon intensity baseline concepts; and (d) this paper did not consider the complicated administrative and monetary mechanisms required to implement the GCR.

While the data has limitations which affect the specific numerical outcomes, they do not affect the overall conclusions which are reliable and important. Most immediately this research suggests that positive incentives for carbon mitigation should be considered, assessed, and tested at whatever scale is practical. This might include policy assessments at the international, national, or sub-national level; and the detailed review of the concept of a "positive externality" being associated with the marginal cost of reducing carbon emissions and removing carbon from the atmosphere. The formalisation of this positive externality as the risk cost of carbon (RCC) represents a major new complement to the standard notion of the negative externality, denoted as the social cost of carbon (SCC). A new positive incentive has the potential to reduce the amount of carbon emissions 'locked in' to our current infrastructure and other anthropogenic systems.

The explicit economic damage of anthropogenic global warming requires us to re-conceptualise the negative externalities associated with carbon emissions and the (classical) market failure in carbon. The climate crisis, with the rising risk of unknowable future damages should drive policymakers and economists to consider the inherent validity of a new positive externality — the global public good — associated with the climate conditions that underpin the social, political, cultural, health, transportation and other human systems that are necessary for human wellbeing. If economists, environmental scientists, policymakers and citizens do not work together to design an economy consistent with our environmental constraints and social needs we will be, as the UN Secretary-General warned, "firmly on track towards an unliveable world" (United Nations, 2022).

References/参考文献

Beck, M., Rivers, N., Wigle, R., & Yonezawa, H. (2015). Carbon tax and revenue recycling: Impacts on households in British Columbia. *Resource and Energy Economics*, *41*, 40–69. https://doi.org/10.1016/j.reseneeco.2015.04.005

Bourgeois, C., Giraudet, L.-G., & Quirion, P. (2021). Lump-sum vs. energy-efficiency subsidy recycling of carbon tax revenue in the residential sector: A French assessment. *Ecological Economics*, *184*, 107006. https://doi.org/10.1016/j.ecolecon.2021.107006

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, *527*(7577), 235–239. https://doi.org/10.1038/nature15725

Carney, M. (2015, September 29). *Breaking the tragedy of the horizon—Climate change and financial stability Mark Carney*. https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability

Chen, D. (2021). *Cleaner Energy*. Global Carbon Reward. https://globalcarbonreward.org/introduction/carbon-rewards/cleaner-energy/

Chen, D. (2022a). *Pricing Theory*. Global Carbon Reward. https://globalcarbonreward.org/carbon-currency/pricing-theory/

Chen, D. (2022b). *Global Carbon Reward: Policy Summary* (March 23rd, 2022). https://globalcarbonreward.org/wp-content/uploads/2022/03/GCR-Four-Page-Summary-27Mar22-English.pdf

Chen, D. (2022, April 4). *Personal Communication: GCR-Variables+Formulas* [Personal communication].

Chen, D. (2022, July 25). *Personal Communication: GCR-Reward Rules* [Personal communication].

Chen, D., Beek, J. van der, & Cloud, J. (2019). Hypothesis for a Risk Cost of Carbon: Revising the Externalities and Ethics of Climate Change. *Understanding Risks and Uncertainties in Energy and Climate Policy*, 183–222. https://doi.org/10.1007/978-3-030-03152-7_8

Chen, D., van der Beek, J., & Cloud, J. (2017). Climate mitigation policy as a system solution: Addressing the risk cost of carbon. *Journal of Sustainable Finance & Investment*, *7*(3), 233–274. https://doi.org/10.1080/20430795.2017.1314814

Chen, D., Zappalà, G., & van der Beek, J. (2018). *Carbon Quantitative Easing: Scalable Climate Finance for Managing Systemic Risk - Working Paper*. https://globalcarbonreward.org/wp-content/uploads/2021/05/CLIMATE-RISK_Chen-Zappala-Beek_Paper_V2.17.pdf

Climate Action Tracker. (2021). *Canada*. Climate Action Tracker. https://climateactiontracker.org/countries/canada/

Daggash, H. A., & Mac Dowell, N. (2019). Higher Carbon Prices on Emissions Alone Will Not Deliver the Paris Agreement. *Joule*, *3*(9), 2120–2133. https://doi.org/10.1016/j.joule.2019.08.008

Dai, H. (2018). *Handbook of IMED Model Framework: A technical introduction*. Laboratory of Energy & Environmental Economics and Policy. https://www.jianguoyun.com/p/DZnI8a8QlL7CBhi913M

Dai, H., Hossain, S., & Liu, X. (2020). Chapter 8—The climate and economic benefits of developing renewable energy in China. In J. Ren (Ed.), *Renewable-Energy-Driven Future* (pp. 257–285). Academic Press. https://doi.org/10.1016/B978-0-12-820539-6.00008-X

Dellink, R., Chateau, J., Lanzi, E., & Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change*, *42*, 200–214. https://doi.org/10.1016/j.gloenvcha.2015.06.004

Department of Finance Canada. (2020). *Climate Action Incentive Payment Amounts for 2021*. Government of Canada. https://www.canada.ca/en/department-finance/news/2020/12/climate-action-incentive-payment-amounts-for-2021.html

Dilnot, C. (2022). Foreword: The Unthinkable Practice of Designing. In J. Wood (Ed.), *Metadesigning designing in the anthropocene* (pp. i–xxiii). Routledge. https://doi.org/10.4324/9781003205371

Fattouh, B., Poudineh, R., & West, R. (2018). *The rise of renewables and energy transition: What adaptation strategy for oil companies and oil-exporting-countries?* Oxford Institute for Energy Studies. https://doi.org/10.26889/9781784671099

Fouquet, R. (2016). Historical energy transitions: Speed, prices and system transformation. *Energy Research & Social Science*, *22*, 7–12. https://doi.org/10.1016/j.erss.2016.08.014

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M., Pachauri, S., … Riahi, K. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, *42*, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., Garcia, W. de O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., Dominguez, M. del M. Z., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

GTAP Data Bases: Detailed Sectoral List. (n.d.). Retrieved March 2, 2022, from https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector.asp

GTAP Data Bases: GTAP 10 Data Base. (n.d.). Retrieved April 21, 2022, from https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx

Hilaire, J., Minx, J. C., Callaghan, M. W., Edmonds, J., Luderer, G., Nemet, G. F., Rogelj, J., & del Mar Zamora, M. (2019). Negative emissions and international climate goals—Learning from and about mitigation scenarios. *Climatic Change*, *157*(2), 189–219. https://doi.org/10.1007/s10584-019-02516-4

Hillman, J. (2013). Changing Climate for Carbon Taxes: Who’s Afraid of the WTO? *German Marshal Fund Paper Series*. https://www.scribd.com/document/155956625/Changing-Climate-for-Carbon-Taxes-Who-s-Afraid-of-the-WTO

International Energy Agency. (2021a). *Global Energy Review: CO2 Emissions in 2020 – Analysis*. IEA. https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020

International Energy Agency. (2021b). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. IEA. https://www.iea.org/reports/net-zero-by-2050

International Energy Agency, & International Solar Alliance. (2019). *Solar Energy: Mapping the Road Ahead*. IEA. https://www.iea.org/reports/solar-energy-mapping-the-road-ahead

IPCC. (2018). *Global Warming of 1.5 ºC: Special Report*. https://www.ipcc.ch/sr15/

IPCC Working Group 1. (2021). The Physical Science Basis: Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, Ö. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC Working Group 2. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability* (p. 3675). Intergouvernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/

IPCC Working Group 3. (2022a). Chapter 12: Cross-sectoral perspectives. In *Climate Change 2022: Mitigation of Climate Change* (p. 12:1-12:220). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/

IPCC Working Group 3. (2022b). *Mitigation of Climate Change: Summary for Policy Makers* (pp. 1–52). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/

Kaya, Y., & Yokobori, K. (Eds.). (1997). *Environment, energy, and economy: Strategies for sustainability*. United Nations University Press.

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, *42*, 181–192. https://doi.org/10.1016/j.gloenvcha.2014.06.004

Laboratory of Energy & Environmental Economics and Policy. (2022, May 1). *Personal Communication: IMED Model Parameters* [Personal communication].

LEEEP Publications. (2022). [Academic]. Laboratory of Energy & Environmental Economics and Policy. http://scholar.pku.edu.cn/hanchengdai/publications

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points—Too risky to bet against. *Nature*, *575*(7784), 592–595. https://doi.org/10.1038/d41586-019-03595-0

Leyre, J. (2021, May). *Governance*. https://globalcarbonreward.org/carbon-currency/governance/

Li, M., Trencher, G., & Asuka, J. (2022). The clean energy claims of BP, Chevron, ExxonMobil and Shell: A mismatch between discourse, actions and investments. *PLOS ONE*, *17*(2), e0263596. https://doi.org/10.1371/journal.pone.0263596

Li, Z., Dai, H., Sun, L., Xie, Y., Liu, Z., Wang, P., & Yabar, H. (2018). Exploring the impacts of regional unbalanced carbon tax on CO2 emissions and industrial competitiveness in Liaoning province of China. *Energy Policy*, *113*, 9–19. https://doi.org/10.1016/j.enpol.2017.10.048

Lindsey, R. (2021, October 7). Climate Change: Atmospheric Carbon Dioxide. *National Oceanic and Atmospheric Administration*. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., De Boer, H. S., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., … Kriegler, E. (2018). Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nature Climate Change*, *8*(7), 626–633. https://doi.org/10.1038/s41558-018-0198-6

McCollum, D. L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., Fricko, O., Fujimori, S., Gidden, M., Harmsen, M., Huppmann, D., Iyer, G., Krey, V., Kriegler, E., Nicolas, C., … Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, *3*(7), 589–599. https://doi.org/10.1038/s41560-018-0179-z

Mercure, J.-F., Knobloch, F., Pollitt, H., Paroussos, L., Scrieciu, S. S., & Lewney, R. (2019). Modelling innovation and the macroeconomics of low-carbon transitions: Theory, perspectives and practical use. *Climate Policy*, *19*(8), 1019–1037. https://doi.org/10.1080/14693062.2019.1617665

Mercure, J.-F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., Salas, P., Sognnaes, I., Lam, A., & Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, *8*(7), 588–593. https://doi.org/10.1038/s41558-018-0182-1

Mercure, J.-F., Salas, P., Vercoulen, P., Semieniuk, G., Lam, A., Pollitt, H., Holden, P. B., Vakilifard, N., Chewpreecha, U., Edwards, N. R., & Vinuales, J. E. (2021). Reframing incentives for climate policy action. *Nature Energy*, 1–11. https://doi.org/10.1038/s41560-021-00934-2

Metcalf, G. E., & Stock, J. H. (2017). Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience. *Review of Environmental Economics and Policy*, *11*(1), 80–99. https://doi.org/10.1093/reep/rew014

Michalek, G. (2016). Progressive Optimal Technology-based Border Carbon Adjustment (POT BCA)—A New Approach to an Old Carbon Problem. *Environmental Modeling & Assessment*, *21*(3), 323–337. https://doi.org/10.1007/s10666-015-9484-0

Nordhaus, W. (1992). An Optimal Transition Path for Controlling Greenhouse Gases. *Science*, *258*(5086), 1315–1319. https://doi.org/10.1126/science.258.5086.1315

Nordhaus, W. (2015). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, *105*(4), 1339–1370. https://doi.org/10.1257/aer.15000001

Nordhaus, W. (2019). Climate Change: The Ultimate Challenge for Economics. *American Economic Review*, *109*(6), 1991–2014. https://doi.org/10.1257/aer.109.6.1991

Peng, W., Dai, H., Guo, H., Purohit, P., Urpelainen, J., Wagner, F., Wu, Y., & Zhang, H. (2020). The Critical Role of Policy Enforcement in Achieving Health, Air Quality, and Climate Benefits from India’s Clean Electricity Transition. *Environmental Science & Technology*, *54*(19), 11720–11731. https://doi.org/10.1021/acs.est.0c01622

Pye, S., McGlade, C., Bataille, C., Anandarajah, G., Denis-Ryan, A., & Potashnikov, V. (2016). Exploring national decarbonization pathways and global energy trade flows: A multi-scale analysis. *Climate Policy*, *16*(sup1), 92-. http://dx.doi.org/10.1080/14693062.2016.1179619

Qi, Y., Dai, H., Geng, Y., & Xie, Y. (2018). Assessment of economic impacts of differentiated carbon reduction targets: A case study in Tianjin of China. *Journal of Cleaner Production*, *182*, 1048–1059. https://doi.org/10.1016/j.jclepro.2018.02.090

Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D. P., & Le Quéré, C. (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, *4*(10), 873–879. https://doi.org/10.1038/nclimate2384

Raworth, K. (2017). *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*. Chelsea Green Publishing.

Ray, D. (2021). *Lazard’s Levelized Cost of Energy Analysis* (Version 15.0; p. 21). Lazard. https://www.lazard.com/media/451905/lazards-levelized-cost-of-energy-version-150-vf.pdf

Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, *8*(10), 895–900. https://doi.org/10.1038/s41558-018-0282-y

Rockstrom, J., & Gaffney, O. (2021). *Breaking Boundaries: The Science Behind our Planet*. DK.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., Lenton, T., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P., Costanza, R., Svedin, U., … Foley, J. (2009a). Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/ES-03180-140232

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009b). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J., & Séférian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, *571*(7765), 335–342. https://doi.org/10.1038/s41586-019-1368-z

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., … Tavoni, M. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, *8*(4), 325–332. https://doi.org/10.1038/s41558-018-0091-3

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Stern, N. (2006). *Stern review: The economics of climate change*. https://www.osti.gov/etdeweb/biblio/20838308

Stiglitz, J. (2006). A New Agenda for Global Warming. *The Economists' Voice*, *3*, 3–3. https://doi.org/10.2202/1553-3832.1210

Strefler, J., Kriegler, E., Bauer, N., Luderer, G., Pietzcker, R. C., Giannousakis, A., & Edenhofer, O. (2021). Alternative carbon price trajectories can avoid excessive carbon removal. *Nature Communications*, *12*(1), 2264. https://doi.org/10.1038/s41467-021-22211-2

Tsafos, N. (2020). How Can Europe Get Carbon Border Adjustment Right? *Center for Strategic and International Studies*. https://www.csis.org/analysis/how-can-europe-get-carbon-border-adjustment-right

United Nations. (2022, April 4). Secretary-General Warns of Climate Emergency, Calling Intergovernmental Panel's Report 'a File of Shame', While Saying Leaders 'Are Lying', Fuelling Flames | Meetings Coverage and Press Releases. *United Nations Press Release*. https://www.un.org/press/en/2022/sgsm21228.doc.htm

van Vuuren, D. P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., Kc, S., Kriegler, E., & O'Neill, B. (2017). The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, *42*, 148–152. https://doi.org/10.1016/j.gloenvcha.2016.10.009

Wagner, G., Anthoff, D., Cropper, M., Dietz, S., Gillingham, K. T., Groom, B., Kelleher, J. P., Moore, F. C., & Stock, J. H. (2021). Eight priorities for calculating the social cost of carbon. *Nature*, *590*(7847), 548–550. https://doi.org/10.1038/d41586-021-00441-0

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2021). Empirically grounded technology forecasts and the energy transition. *INET Oxford Working Paper*, *No. 2021-01*, 23.

Wood, J. (2022). *Metadesigning designing in the anthropocene*. Routledge. https://doi.org/10.4324/9781003205371

Wu, R., Dai, H., Geng, Y., Xie, Y., Masui, T., & Tian, X. (2016). Achieving China's INDC through carbon cap-and-trade: Insights from Shanghai. *Applied Energy*, *184*, 1114–1122. https://doi.org/10.1016/j.apenergy.2016.06.011

Appendices

A. Global Carbon Reward Rules

The intention of the GCR is to create a new global market that supports the necessary development and deployment of carbon dioxide removal (CDR). To create this market the policy is split into three rules based on the Kaya identity.

The original Kaya identity shows that global greenhouse gas emissions are driven by population growth (P), GDP per-capita (G/P), the energy intensity of GDP (E/G), and greenhouse gas (CO_{2e}) intensity of energy (F/E) (Kaya & Yokobori, 1997). Chen et al. add a decoupling factor ($w\Delta Q$) where w is the economic decoupling factor and ΔQ is the global mitigated CO_2e that is rewarded by the CC.(Chen et al., 2019)

(A2.1) $F = P * \frac{G}{P} * \frac{E}{G} * \frac{F}{E} - w\Delta Q$

Where at the global scale:

(A2.2) $\Delta Q = \sum_{i,r}^{n} q_{i,r,t_{(energy)}} + \sum_{i,r}^{n} q_{i,r,t_{(buisness)}} + \sum_{i,r}^{n} q_{i,r,t_{(removal)}}$

Where $\sum_{i,r}^{n} q_{i,r,t_{(energy)}}$, $\sum_{i,r}^{n} q_{i,r,t_{(buisness)}}$, and $\sum_{i,r}^{n} q_{i,r,t_{(removal)}}$ represents the sum of all tCO_2e mitigated for a 100-year duration across all regions (r) and industries (i) in a period (t) by the reward for cleaner energy, a reward for cleaner business and the reward for CDR respectively.

The reward is paid out relative to the difference between the current carbon intensity (CIE_t) and the carbon intensity baseline (CIE_b). This baseline is established differently depending on the reward. The CIE_b in the reward for the reduction in the carbon intensity of energy production is proposed to be determined as a unique value "for each energy commodity and for each unique energy market… so that the computed financial reward is sufficient to justify a rate of decarbonisation that is aligned with the Paris goal" (Chen, 2022b). This would likely create an information burden far too great for any government organisation and risks causing the same issues associated with command-and-control mitigation policy. This study will use a simplified calculation discussed in section 4.3.2, based on a rolling average of historic energy intensity, so that continuous improvement would be promoted with a low administrative burden. The rule for cleaner energy aims to reduce (F/E) from the modified Kaya identity and can be expressed at the global level as follows (Chen, personal communication, April 4, 2022):

(A2.3) $\sum_{i,r}^{n}\ q_{i,r,t_{(energy)}} =\ (CIE_b - CIE_t)E_t$

For the rule for cleaner business, where energy production is not a primary activity, "the emissions baseline will be framed by the emissions intensity of their outgoing cash flow—to encourage perpetual decarbonisation" (Chen, 2022b). In other words, they will be encouraged to reduce the carbon embedded in their products and services. The reward rule for cleaner business aims to reduce (E/G) in the modified Kaya identity and can be represented at the global level as (D. Chen, personal communication, April 4, 2022):

(A2.4) $\sum_{i,r}^{n}\ q_{i,r,t_{(buisness)}} = (CIC_b - CIC_t)C_t$

Where CIC_b and CIC_t respectively represent the baseline and current cashflow intensity of carbon; and C_t represents the cash flow in period *t*.

For CDR projects, the CIE_b is zero and the negative emissions per unit of carbon emissions are subtracted to calculate the base reward. It addresses the decoupling factor in the modified Kaya identity. It represents the total mass removed from the atmosphere and stored, taking into account the storage period and life cycle analysis of the CDR project.

(A2.5) $\sum_{i,r}^{n}\ q_{i,r,t_{(removal)}} = w\Delta Q$

B. IMED|CGE Model Specifications

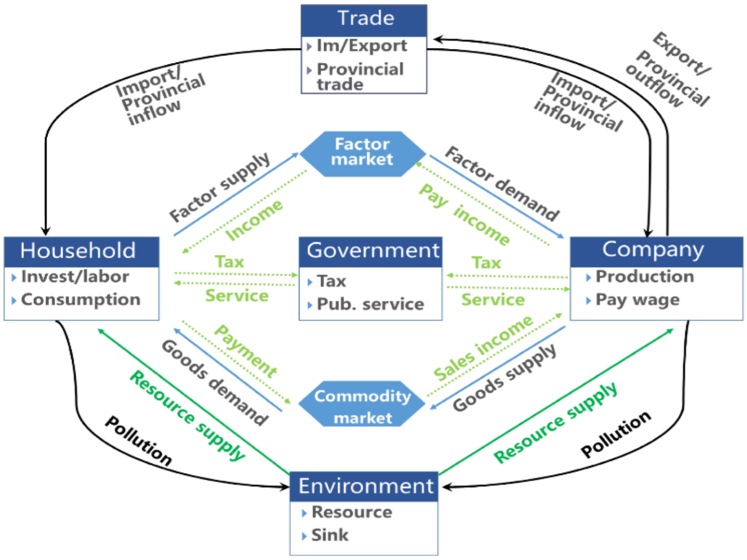

Figure A.0.1 CGE conceptual framework (borrowed from Dai, 2018)

The IMED|CGE model uses the Mathematical Programming System for General Equilibrium under General Algebraic Modeling System (GAMS/MPSGE) to solve its optimisation functions. The model includes “a production block, a market block with domestic and international transactions, as well as government and household incomes and expenditures blocks” (Dai, 2018).

Environmentally extended input-output (IO) tables are used to plot the relationship between required direct and indirect inputs into each economic sector and the associated environmental impacts. Production functions subject to certain constraints are optimised based on the market clearance hypothesis (at the end of each time step the market is in equilibrium and all resources in the economy have been allocated) to produce the results. The IMED|CGE model uses a constant elasticity of substitution (CES) production function to determine sector activity output. The CES production function inputs are categorized into “material commodities, energy commodities, labor, capital and resources” (Dai, 2018). The highest nesting level is a Leontief production function (Dai, 2018).

Table A.1 IMED Global Model regions and sectors

Regions	Sectors
China	Agriculture
India	Coal mining
Japan	Crude oil
South Korea	Natural gas
Other Asia	Textile
Australia & New Zealand	Paper
Canada	Food production
United States	Petrol oil
Latin America	Chemicals
Africa	Nonmetal
Middle East	Metal smelting
Western Europe	Other manufacturing
Eastern Europe	Water supply
Former Soviet Union	Power generation
Rest of the World	Manufactured gas
World Total	Construction
	Waterway
	Aviation
	Road

Figure D.1 presents the conceptual model for the IMED|CGE. It is a circular flow diagram that combines trade ("provincial" should be replaced with "national" for the global model), household, the private sector (company) and the government. In addition to usual circular flow models, the IMED|CGE framework includes the environment as a source of resources and a sink for pollution.

The IMED|CGE model is an equilibrium model, which means it is a supply-led model where the representative agents maximise utility under constrained optimisation problems; in equilibrium models, the economy is at an optimal equilibrium under the conditions of the model at every point in time and is therefore driven by its ability to produce and optimally distribute the production (Mercure et al., 2019). The equilibrium model is most appropriate for this study

Table A.2 Comparing IMED sectors and GTAP definitions

IMED Sector	GTAP Code	GTAP Definition
Petrol Oil	p_c	Petroleum & Coke: manufacture of coke and refined petroleum products
Coal Mining	coa	Coal: mining and agglomeration of hard coal, lignite and peat
Crude Oil	oil	Oil: extraction of crude petroleum, service activities incidental to oil and gas extraction excluding surveying (part)
Natural Gas	gas	Gas: extraction of natural gas, service activities incidental to oil and gas extraction excluding surveying (part)

Table A.2 compares the industry definitions used in the IMED Global Model with the corresponding input data from the GTAP database. GTAP definitions are found in: *(GTAP Data Bases: Detailed Sectoral List*, n.d.).

because it is driven by profit maximisation for producers. Looking at the output from a producer's perspective is most appropriate when discussing the potential losses of fossil fuel exporting regions and the feasibility of the GCR's supply-focused *rule for cleaner energy* as a financial incentive to transition production to non-fossil fuel energy.

The model accounts for other factors such as the depreciation rate of capital which it sets at (5%). The discount rate is 5% which is widely used in IAMs such as Nordhaus's DICE (Stern and others argue for a discount rate of 1-2%) (Nordhaus, 2019). A complete description of the IMED model can be found in the IMED Handbook (Dai, 2018).

The model's output can be broken down into 14 different regions and 13 different sectors of economic activity (see table A.1). The IMED|CGE Global Model is supported by data from the Global Trade Analysis Project (GTAP). The GTAP data's latest version is from 2014, meaning that the base year for the model is 2014 (*GTAP 10 Data Base*, n.d.). Data from 2015 and 2020 have been fitted to reflect real-world data.

The IMED Global Model's definitions of sectors are also based on GTAP definitions. The sectors investigated in this study and their definitions are described in Table A.2.

C. Calculating the Global Carbon Reward Floor Price

A price-quantity relationship for carbon direct removal (CDR) has not been established in any reviewed literature. In ch.3.2.1 we saw that the IPCC defines CDR as “anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products” (IPCC Working Group 3, 2022a). The consensus was that the cost, externalities and mitigation potential of CDR vary significantly based on the technology used and future costs will vary greatly based on technological breakthroughs (Fuss et al., 2018). For example, soil sequestration is very cheap at low levels ($US 0-100 tCO_2^{-1}), but will eventually become saturated and can be reversed, whereas direct air carbon capture and storage (DACCS) and to a lesser extent bioenergy carbon capture and storage (BECCS) is very expensive at low levels (currently estimated at $US 600-1,000 tCO_2^{-1}) but has a high potential for considerable innovation cost decreases (Fuss et al., 2018; IPCC Working Group 3, 2022a).

To estimate the price-quantity relationship this study relies on Fuss et al.’s (2018) assessments. The authors note that the cheaper, mature, but low-volume capacity (0-5$GtCO_2$/year with a saturation point) NETs options currently have a median price of $US 0-100 tCO_2^{-1}. The more expensive mitigation options, but with much higher volume potentials by the end of the century (BECCS and DACCS) currently cost upwards of $US 600 tCO_2^{-1} and are expected to drop to $US 100-300 tCO_2^{-1} by mid-century. BECCS and DACCS have further potential for significant cost decreases and they mature (Fuss et al., 2018). To go smoothly from the current low-volume low-cost estimates to the mid-century higher volume medium estimates for DACCS and BECCS, this study estimates a 3% annual compound decrease in the average price of deployed CDR. This seems to align best with the central estimates for the price of CDR from Fuss et al., but it is difficult to determine the accuracy at lower or higher annual levels of CDR.

There is also currently no accurate way to determine how CDR prices will vary over time. Decreases in average cost are expected for some technologies as research and development are conducted and the scale of deployment increases (innovation effect and economies of scale). However, given biophysical limitations and opportunity costs of certain NETs, this study assumes that there are significant diseconomies of scale (the price of the marginal ton mitigated will increase) at higher levels of sequestration (Fuss et al., 2018). This effect will be particularly strong until technologies like BECSS and DACCS can mature (expected sometime in the second half of the century) when they may be able to provide scalable lower cost CDR; nevertheless, both technologies are not mature and have significant limitations (Fuss et al., 2018). Given the uncertainty over the impact of diseconomies of scale for the currently available CDR technologies and the unknown strength of the economies of scale for DACCS and BECCS or other novel technologies, this study estimates a linear price-quantity curve.

With only these limited data points for CDR prices through to 2050 and very few quantitative estimates after mid-century, this simply represents a best-guess effort to model the GCR floor price. Considering this, alternative estimation techniques for the GCR floor price or a highly sophisticated inventory of various NETs will be required to provide more accurate estimations in the future. It is also possible CDR cost reductions would follow an 'S' curve once a breakthrough in technology is reached, however, there is no accurate way to estimate what the shape of this curve might be. Therefore, the linear price-quantity relationship and the compound rate of cost improvement are used for simplicity and clarity of analysis.

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