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Biophysical, political and economic challenges to achieving Paris climate targets

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Thesis Summary

Climate change has arguably become the most urgent global environment issues of our times. After decades of ineffective climate policy, global greenhouse gas emissions have continued to rise. Rapid reductions in these emissions are now required to prevent the serious consequences of a global temperature rise of over 2°C. In response to this challenge, the Paris Agreement, the first truly global framework to combat climate change, was signed in 2016. Although it was welcomed as a landmark achievement in setting a clear goal of limiting the rise in global temperatures to 2°C, early signs suggest that it will be ineffective at achieving this aim. In this thesis I explore the aspects that make climate change a unique challenge among other environmental issues, which provide inherent barriers to achieving effective climate policy. To understand this better I separate the problem into three distinct aspects: biophysical, political and economic challenges. Each of these is explored through one detailed case and its likely impact on meeting the Paris Agreement's 2°C goal.

The biophysical challenge of climate change focused on is reducing fossil fuel consumption while maintaining the flow of energy for sufficient global economic growth and maintenance of current lifestyles. I investigate the particular biophysical factor of energy supply through the concept of Energy Return on Investment (EROI). This is a measure of how useful a particular energy source is to society by transforming gross energy to net energy. In order to stay within the 2°C carbon budget, a rapid transition from fossil fuels will be necessary. However, typical analyses of such transitions overlook the challenge that renewables generally have lower EROI values than the fossil fuels they replace, and the EROI values of fossil fuels, particularly oil and gas, are themselves declining. By using these to correct from gross to net energy, I show how renewables would have to grow two to three times faster than currently believed to meet to maintain society's energy needs.

The political challenge focused on concerns climate change being a classic case of the 'free-rider' problem, as countries have an incentive to not reduce emissions themselves at the expense of their economic growth and development, while hoping others do so. Moreover, the expected impacts of climate change and historical responsibility for emissions are very asymmetric among countries. Here I investigate a political factor behind why the Paris Agreement was unable to produce strong enough ambition in the commitments of parties of sufficient ambition to match its overall goal. Specifically, I look at how a lack of consistency and transparency in the process for countries submitting pledges has produced targets of widely differing ambition that may not have been apparent in the original submissions. This is done by categorising the countries' submissions and performing a normalisation against a consistent base year, which allows for direct comparability.

The economic challenge of climate change is seen through considering greenhouse gas emissions as a negative externality, which is an unaccounted-for social cost arising from economic activity. The most straightforward way to correct for such an externality is to place a price on it, such as through taxation. There are therefore strong arguments that setting a carbon price would be one of the most effective and efficient methods at attempting to control climate change. However, a challenge arises from the fact that economic decisions are increasingly made at the global level, and the Paris Agreement was unable to set a global carbon price. Here, I investigate how this is likely to lead to carbon leakage. If climate policy is not coordinated to be homogeneous or uniform across countries, or otherwise leading to consistent implicit carbon prices of national policies, those with weaker climate policy will become more competitive than others with respect to carbon-intensive economic activity and associated export of goods. This will result in a change in trade flows and a relocation of industry from countries with stronger policies to those with weaker policies. In effect, some of the emission reductions are 'lost' through resultant growth in other countries. My analysis suggests that the rate of leakage in the Paris Agreement could range from 1-9% and roughly double if the US were to withdraw from the Agreement.

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Chapter 1

Introduction

1.1 Background and motivation

Climate change seems quickly to have become the most pressing and dominant environmental issue of our times. While global temperatures have always fluctuated through natural cycles, expected temperature rises during the 21st century are considered unprecedented in rate and scale (Pachauri et al. 2014). There is now widespread agreement within the scientific community that the primary driver of recent temperature rises is anthropogenic in nature due to the release of greenhouse gases (Cook et al., 2013; Cook et al., 2016). The impacts of such rapidly rising temperatures are broad and present a fundamental threat to sustainability (Yohe et al., 2006). In response to growing concern about the danger posed by climate change, in 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was established with the overall objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The focus of the UNFCCC can be divided into adaptation, which aims to manage the impacts of climate change; and mitigation, which aims to prevent climate change primarily through a reduction in greenhouse gas emissions.

The first attempt by the UNFCCC at creating an international climate change mitigation agreement was the Kyoto Protocol, which was signed in December 1997. The Protocol was based on the concept of common but differentiated responsibilities, by acknowledging that some countries had partly owed their historical economic development to greenhouse gas-emitting activity. It required the 43 most industrialised nations to reduce their greenhouse gas emissions relative to 1990 levels. These industrialised countries were designated as Annex I countries, and accounted for 55% of total greenhouse gas emissions in 1990 (Breidenich et al., 1998). The non-annex I countries had no commitments to reduce greenhouse emissions, nor did they have limits to their growth. For these countries continuing economic development was seen as the priority.

The overall success of Kyoto at reducing global emissions has been questioned (Almer & Winkler, 2017; Böhringer, 2003). Although it can certainly be argued that emissions would be at a higher level if Kyoto had never been implemented, it is undisputable that the Protocol was incapable at reversing the trend of rising absolute emissions at the global level. Figure 1.1 shows the pattern of greenhouse gas emissions from 1990 to 2015, taken from the PRIMAP database (Gütschow et al., 2018). In the eighteen years following the signing of the Kyoto Protocol in 1997, emissions grew by 29%. We see that, although the emissions in the Annex-I countries did slightly decline over this period, it was more than offset by the growth in emissions from non-Annex I countries. The problem is exemplified by the rapid industrialisation of China in this timeframe, heavily fuelled by coal, which resulted in a 152% increase in its emissions.

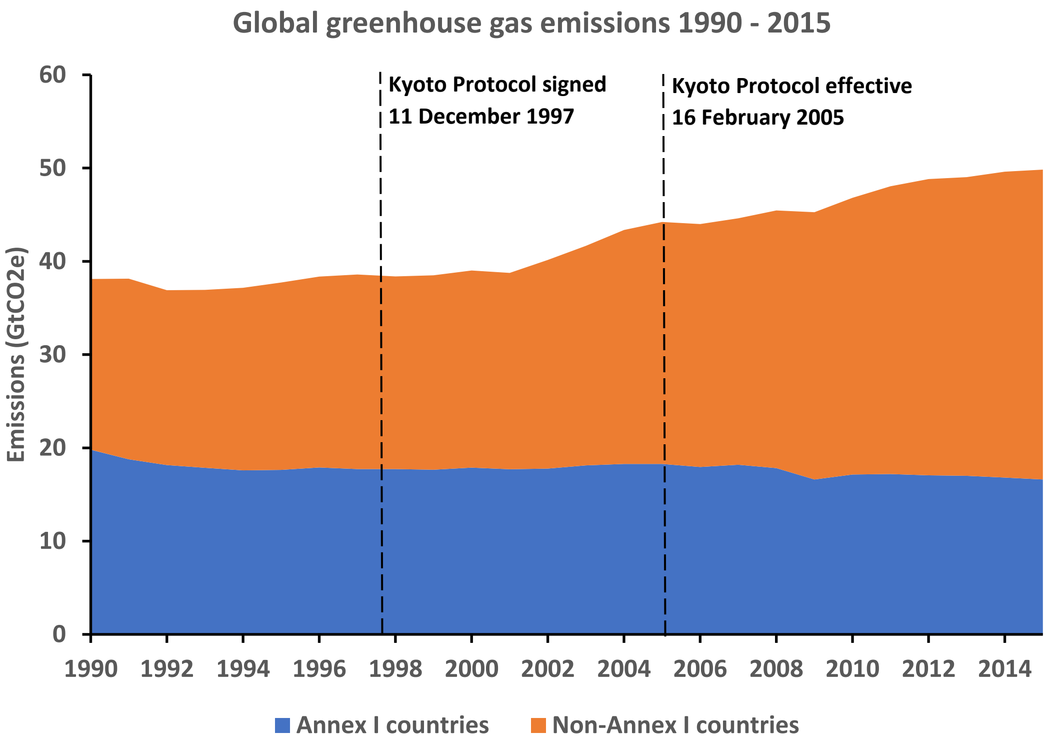

Fig 1.1. | Global greenhouse gas emission trends 1990 - 2015

In 2015, the successor to the Kyoto Protocol, the Paris Agreement, was adopted (UNFCCC, 2015). It had a clear aim to "limit the increase of the global average temperature to 2°C relative to pre-industrial levels". Importantly, and unlike Kyoto, the Paris Agreement covers almost all global emissions, and could therefore be seen as the first truly global climate change agreement. As of July 2020, 188 states and the EU have ratified the Agreement, covering almost 97% of global emissions. Iran, Turkey and Iraq are the most significant emitters who have signed, but not ratified the Agreement. An important difference to Kyoto, however, is that the Agreement takes the form of a bottom-up approach to tackling climate change, reliant on voluntary commitments in the form of nationally determined contributions (NDCs), which are publicly accessible through the NDC registry (UNFCCC, 2018). The NDCs are subject to regular review and updated every five years, implying a system of 'pledge and review' with civil society holding countries to account instead in the absence of direct enforcement mechanisms (Jacquet & Jamieson, 2016).

Although admirable in its ambition, the primary issue of achieving the Paris Agreement's goal is that there simply is not much time left to achieve the emission reductions needed to stay within 2°C. One method of looking at this problem is through the concept of a carbon budget. This is based on the idea that to limit anthropogenic warming to a certain level, cumulative emissions of greenhouse gases need to be capped at a certain level (Rogelj et al., 2016). Estimates of the size of the remaining budget vary widely, but for a >66% of keeping emissions below 2°C, the most appropriate estimates are 590-1,240GtCO$_2$ from 2015 onwards. Taking the midpoint of this range (900GtCO$_2$), and approximate current emission levels of 40GtCO$_2$ per year, we can estimate that the carbon budget would be consumed within 20 years if emissions remain at their current level.

Initial studies suggest current NDCs are insufficient at meeting the top-down goal as they imply a warming of 2.6°C–3.1°C (Höhne et al., 2017, Schleussner et al., 2016, Rogelj et al., 2016a). Even limiting the warming to this level is seen as overly optimistic by some, as it would be dependent on speculative negative emission technology (Anderson & Peters, 2016). It is clear that the Paris Agreement has so far been unable to produce the type of ambition that would be required to stay within the relevant carbon budget. There have also been indications that countries are likely to fail at fulfilling pledges they have made, with all major industrialised currently falling short of their targets (Victor et al., 2017). The reasons behind this are complex and numerous.

In this thesis I attempt to address three types of challenges which the Paris Agreement faces: biophysical, political and economic challenges. In the following sections, I discuss each of these challenges, translate them into research questions for this thesis, and describe how I will address these questions in later chapters.

1.2 Biophysical challenges

Economies have traditionally been modelled as flows of income between producers and consumers where economic decisions are shaped by prices. However, more recently the branch of biophysical economics has developed, where the flows of energy and natural resources in the economy are studied from a systems perspective, taking into account indirect energy use and related embodied energy (Cleveland, 1999; Hall & Klitgaard, 2011). Associated researchers argue that growth in energy production has been a fundamental driver of economic growth (Ayres et al., 2013; Chontanawat et al., 2008), and there is little evidence to suggest that strong decoupling between economic growth and energy use per capita has been achieved (Csereklyei & Stern, 2015; Moreau & Vuille, 2018). A biophysical economics perspective thus becomes important in the context of climate change mitigation as energy production accounts for 72% of global greenhouse gas emissions (World Resources Institute, 2016).

Considering that energy is the largest contributor to global greenhouse gas emissions, transitioning from fossil fuels to sources of renewable energy with much smaller carbon footprints, such as solar and wind, is arguably the most important action towards limiting climate change. Although much effort has been put into developing renewable technologies, Figure 1.2 (IEA, 2002) shows how their growth in terms of overall global energy production has been slow. Significantly, the growth in renewables has been unable to displace fossil fuels but instead largely served to meet growing energy demand, and from 2000 to 2017, fossil fuel production grew by 42%. The biophysical challenge of climate change is therefore the obstacle of reducing fossil fuel consumption while maintaining the flow of energy for sufficient economic growth and maintenance of current lifestyles. In addition, this should take into consideration that investment in renewable energy capacity will in an initial phase heavily depend on fossil-fuel based energy inputs, which can only fall as the share of renewables in overall energy production increases.

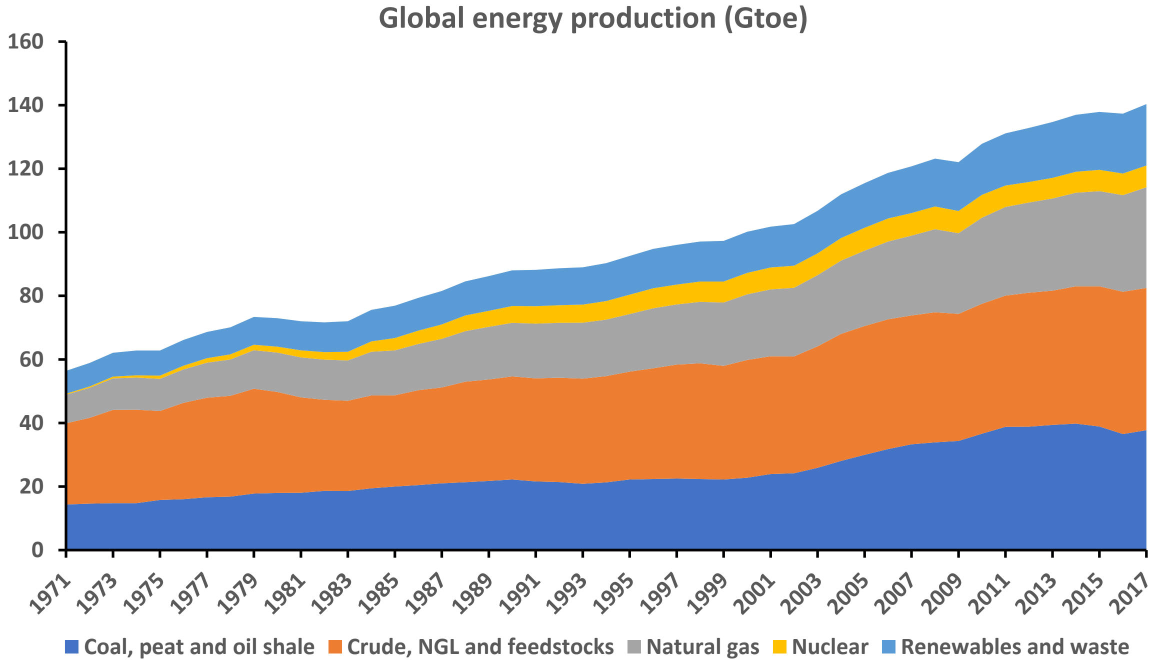

Fig 1.2. | Global energy production 1971-2017

In Chapter 2 I investigate the particular biophysical factor of energy supply, through the concept of Energy Return on Investment (EROI). This is a measure of how useful a particular energy source is to society by transforming *gross* energy to *net* energy. It is calculated as a ratio of the net energy supplied to society over the energy input to produce it. High EROI energy sources are therefore desirable as they provide more *net* energy to society, which is useful for purposes outside of the production of more energy. The average EROI of an economy's overall energy mix can therefore provide an indication of opportunities for economic activity which is free from the distortion caused by prices (Fagnart & Germain, 2016).

In order to stay within the 2°C carbon budget, a rapid transition from fossil fuels will be necessary. Some studies have suggested that such a transition is at least conceptually possible (IEA & IRENA, 2017; Jacobson et al., 2017)). However, such studies overlook the challenge that renewables generally have lower EROI values than the fossil fuels they replace, and the EROI values of fossil fuels, particularly oil and gas, are themselves declining (Hall et al., 2014). The challenge here is if we can still provide enough net energy to meet society's demand as we transition from fossil fuels to renewables, and do so at a rate that would stay within a 2C carbon budget. To analyse this challenge, I look at historical trends in net energy per capita based on estimated EROI values of different fuels, and project these into the future under a number of future energy supply scenarios.

1.3 Political challenges

Despite the widespread acknowledgement that climate change is an important issue that needs to urgently be mitigated against, there is still a vast political challenge. Unlike some environmental issues such as air pollution in cities, the effects of climate change are not localised to the source of pollution, and instead have consequences at the global level. Moreover, the expected impacts of climate change are expected to vary widely among countries, with some being affected much more than others (Mendelsohn et al., 2000). Climate change therefore becomes a classic case of the 'free-rider' problem, as countries have an incentive to not reduce emissions themselves at the expense of economic growth and development, while expecting or at least hoping others to do so. A globally-inclusive climate agreement that assures all parties are fully committed to a global emissions reduction target, or better even to a consistent emissions reduction policy, is therefore essential (Nordhaus, 2015).

The Kyoto Protocol failed at being the globally-inclusive climate agreement that the world needs, largely due to the decision that it should only cover the emissions of already economically developed countries. Although this decision was understandable, it illustrates another aspect of the political challenge. Countries have vastly different historical contributions to cumulative emissions and there is a debate around fairness if countries with low historical emissions are unable to use fossil fuels to aid their development as other countries did in the past (Neumayer, 2000; Peters et al., 2015). The Paris Agreement was however a step in the right direction, with almost all countries signing it and agreeing to its overall goal. However, the lack of coordinated policy and genuine enforcement mechanisms, the insufficiency of current pledges at meeting the overall goal, and the potential withdrawal of the US, the largest cumulative emitter of CO_2, demonstrate that the political 'free-rider' challenge persists post-Paris.

In Chapter 3 I investigate a political factor behind why the Paris Agreement was unable to produce strong enough ambition in the commitments of parties of sufficient ambition to match its overall goal. Specifically, I look at how a lack of consistency and transparency in the process for countries submitting pledges has produced targets of widely differing ambition that may not have been apparent in the original submissions. Countries were given much freedom to submit their pledges in a format of their choosing. These fell into four main categories: i) percentage reductions relative to a historical base year, ii) percentage reductions against a projected business-as-usual scenario, iii) reductions in emission intensity of GDP, and iv) pledges without a clear emission target. To make the pledges more comparable I perform a normalisation of all countries' submissions relative to a consistent base year. By doing so I illustrate how pledges vary widely in ambition both among categories and between categories, and discuss how this lack of transparency and consistency in the process challenges the potential efficacy of the Agreement. Integrating this approach into the Paris Agreement would promote more effective NDCs upon revision as is foreseen to happen every 5 years under the 'ratcheting mechanism' of the agreement.

1.4 Economic challenges

While both the biophysical and political factors are largely driven by the pursuit of economic growth, systemic factors arising from having a globalised, market-based economy are an additional aspect of the challenge. Economic decisions are regulated by prices that are determined by interactions between supply and demand; however, these are susceptible to a variety of market failures. The failure of climate change from an economic perspective would be to consider greenhouse gas emissions as a negative externality, which is an unaccounted-for social cost arising from economic activity (Nordhaus, 2019). After stating that climate change was the greatest and widest-ranging market failure ever seen, Stern (2006) estimated that each tonne of carbon dioxide was causing at least US$85 worth of unaccounted for damage to the global economy. Other studies have also tried to estimate the social cost of carbon, but there is a large degree of variance dependent on various assumptions used, particularly the discount rate applied to future climate impacts. Based on aggregating existing studies and accounting for overlooked impacts, it has been argued that a lower bound to the social cost of CO_2 might be at least US$125 per tonne (van den Bergh & Botzen, 2014).

The most straightforward way to correct for such an externality is to place a price on it, such as through taxation. There are therefore strong arguments that setting a carbon price would be one of the most efficient methods at attempting to control climate change (Baranzini et al., 2017; Hagmann & Loewenstein, 2019). However, a challenge arises from the fact that economic decisions are increasingly made at the global level, illustrated by how exports as a percentage of global GDP have risen from 23% in 1997, when the Kyoto Protocol was signed, to 30% in 2018 (World Bank, 2020). Unless there is a serious, globally homogenous carbon price, systemic effects will occur that will undercut the ability to reduce emissions. These effects include carbon leakage (Babiker, 2005; Dröge et al., 2009), carbon rebound (Antal & van den Bergh, 2014; Druckman et al., 2011), and the Green Paradox (Sinn, 2012). The Paris Agreement failed at setting a global carbon price, and initial studies of the Paris Agreement NDCs show that there is a wide discrepancy of the indicative implicit carbon prices of countries' policies (Aldy et al., 2016; Fujimori et al., 2016). This indicates that the economic challenges facing climate change mitigation will persist post-Paris.

In Chapter 4 I investigate the specific economic factor of carbon leakage. This is a systemic issue arising from having a globalised economy. If climate policy is not coordinated to be homogeneous or uniform across countries, those with weaker climate policy will become more competitive than others with respect to carbon-intensive economic activity and associated goods. This will result in a change in trade flows and relocation of industry from countries with stronger policies to those with weaker policies. In effect, some of the emission reductions are 'lost' through resultant growth in other countries. Previous studies have shown that this carbon leakage was a significant contributor to why Kyoto was unable to reduce emissions at the global level (Babiker, 2005; Palstev, 2001). I analyse to what extent carbon leakage may be a relevant factor under the Paris Agreement, despite being a more globally-inclusive agreement than Kyoto. To do this I use a computable general equilibrium model (GTAP-E) which models how the global economy responds to policy shocks. Using a range of potential scenarios, I use the model to quantitatively estimate the level of carbon leakage we could conceivably expect post-Paris. This follows similar approaches to analysing the carbon leakage from the Kyoto Protocol, but is novel in being the first study of its kind to quantitively analyse the potential for carbon leakage to arise in the Paris Agreement.

In Chapter 5 I provide a summary of the chapters and overall conclusions. This includes discussing how the multifaceted challenges behind climate change policy are likely to come together and may seriously undermine the effectiveness of the Paris Agreement. I argue that unless it is seriously reformed, such as through the implementation of a globally-harmonised carbon price, overshooting the 2°C is likely to be inevitable.

Chapter 2

Biophysical Challenge: Implications of net energy-return-on-investment for a low-carbon energy transition[1]

2.1. Introduction

The role of energy in maintaining or improving lifestyles tends to be strong and fundamental, though frequently underestimated (Ayres et al., 2013; Chontanawat et al., 2008; Cleveland et al., 1984; Stern, 2011). Precise accounting of energy requirements is critical for accurately assessing the impact of potential transitions to a low-carbon economy. Following the Paris Agreement, several global energy transition scenarios have been presented, which tend to be analysed in terms of gross energy, and aimed at maintaining past rates of economic growth (IEA & IRENA, 2017; Jacobson et al., 2017). However, the literature on energy return on investment (EROI) argues the importance of distinguishing between net and gross energy when making judgments about energy and lifestyles (Hall, 2017; Murphy & Hall, 2010). Expressed as a ratio, EROI signifies the amount of useful energy yielded from each unit of energy input to the process of obtaining that energy. The lower an energy source's EROI, the more input energy is required to produce the output energy, resulting in less net energy available for consumption.

Although there is some debate around the appropriate calculation and boundaries of EROI (Mulder & Hagens, 2008; Murphy et al., 2011), it serves as a reasonable proxy for the biophysical utility of any particular energy source to society. It provides, at least in theory, a more objective, stable and future predictive assessment than information about costs and prices, as this is strongly influenced by erratic and short-term factors, such as subsidies, market power, strategic behavior of suppliers, and emotional responses by market participants. The average EROI of an economy's overall energy mix can therefore provide an indication of opportunities for economic activity (Fagnart & Germain, 2016).

Here, we analyse low-carbon energy transitions by considering net energy per capita as the basis of lifestyles. By accounting for differences between gross and net energy, we evaluate the potential consequences of a low-carbon energy transition on future lifestyles. This allows us to analyse different energy pathways in combination with optimistic and pessimistic estimates of EROIs in the literature.

Our results indicate that net energy per capita is likely to decline in the future without substantial investments in energy efficiency. To maintain net energy per capita at current levels, renewable energy sources would have to grow at a rate two to three times that of current projections. We propose an 'energy return on carbon' (EROC) indicator to assist in maximizing potential net energy from the 2 ºC carbon budget.

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2.2. Illustrating the importance of EROI for lifestyles

To illustrate the economic and welfare importance of EROI, we analyse and compare two hypothetical high- and low-EROI economies. As illustrated in Figure 2.1, both economies produce the same 550 EJ of gross energy. This approximates the level of current global production in IEA world energy balances (OECD & IEA, 2017). The high-EROI economy has an average EROI equal to 20:1, which represents the present state. The low-EROI economy has an average EROI equal to 3:1, a level insufficient to operate societies at the current level of affluence in the Global North (Hall et al., 2009), which might be interpreted as a hypothetical tar sand economy (Poisson & Hall, 2013) or a severe peak oil scenario. Both economies suffer subsequent (downstream) proportional losses from transformation and end use losses of 58%, based on rates of 2011 'rejected energy' in world energy flow charts (Lawrence Livermore National Library, 2011). Assuming that both societies first meet their requirements for essentials, such as food and water, which we are keeping constant at an illustrative value of 100 EJ, we calculate that the low-EROI economy would have less than half (54 EJ vs. 119 EJ) the net energy of the high-EROI economy available for consumption and production of all 'non-essential' goods and services. This would have significant implications for lifestyles, and limit the ability to invest energy for future economic growth.

Should the low-EROI society wish to match the quantity of discretionary funding of the high-EROI society (119 EJ), it has, theoretically, three options: increase gross energy production to 785 EJ {(523x3)/(3-1)}, which would be a 43% increase from 550 EJ; improve end use energy efficiency in production and consumption of goods and services from 42% to 60% {(100+119)/367}; or improve the average EROI from 3 to 20 through technological improvements and investment in higher-EROI energy sources, such as coal. While these ambitious goals may not be achievable in practice, some lower-level combination of the three types of changes is likely to have compensated for the slowly declining global average EROI of oil and gas experienced in recent decades (Gagnon et al., 2009). For example, there has been a rapid growth of coal since 2000, which has one of the highest EROI values of current energy options (Hall et al., 2014). However, continuation of this strategy, at least without carbon capture and storage (CCS), is incompatible with the goals of the Paris Agreement (UNFCCC, 2015) which require the vast majority of fossil fuels to remain in the ground (McGlade & Ekins, 2015). The most significant challenge we face may therefore not be a declining EROI of fossil fuels itself, but continuing to supply enough net energy while investing in a new energy system with relatively low net energy yields (Hall et al., 2008). Moreover, population forecasts (United Nations, 2015) indicate the world population will be approaching 10 billion by 2050, so remaining fossil fuels will have to be spread among an even greater population. The challenge of a rapid transition to low-carbon energy is therefore twofold: staying within climate change targets while continuing to deliver net energy for the needs of a growing global society.

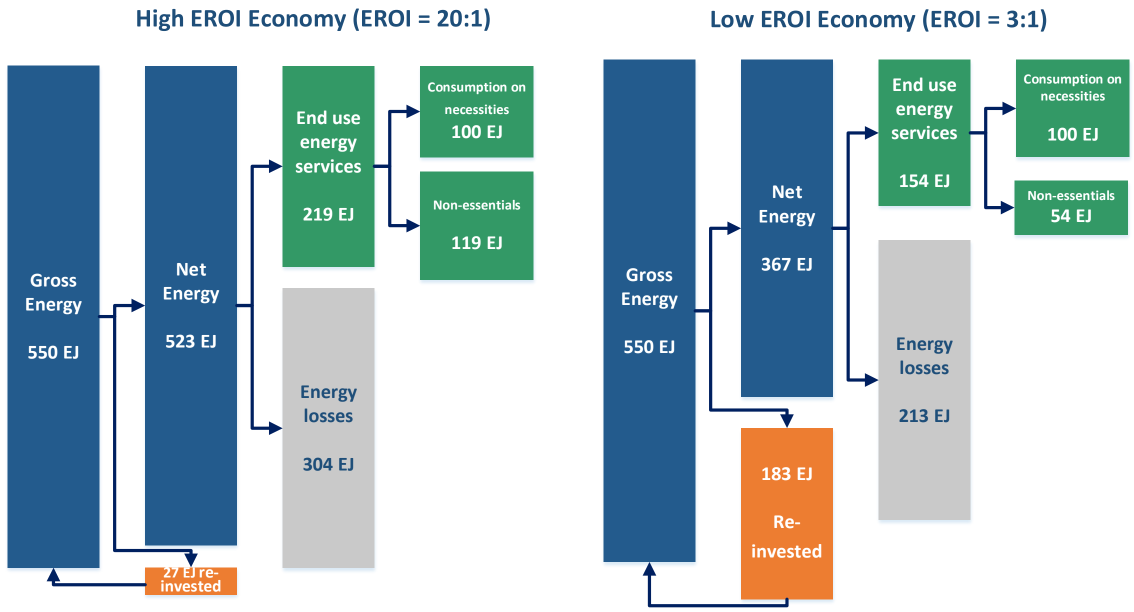

Figure 2.1. | Illustrative comparison of high and low EROI economies. Blue boxes illustrate flows of gross to net energy; green boxes illustrate end-use energy services; orange boxes illustrate energy used for reinvestment to produce more gross energy; and grey boxes illustrate process energy losses. The two alternatives (high and low EROI economies) are hypothetical, aimed at illustrating the impact of two very different EROI scenarios on lifestyles given end-use consumption on necessities fixed at 100EJ. The low EROI economy reinvests a far greater proportion of its gross production for future production than the high EROI economy. After accounting for downstream energy losses and consumption on necessities, this results in only around half of the net energy being delivered for non-essential energy services. Gross energy production of 550EJ is roughly consistent with that of the global economy (OECD & IEA, 2017) while energy losses are based on rates of 2011 'rejected energy' in world energy flow chart (Lawrence Livermore National Library, 2011).

2.3. Analytical approach

Our approach to analysing future net energy returns involves four stages: defining a carbon budget exclusively for energy based on current literature; defining three energy pathway scenarios to 2050; defining 'optimistic' and 'pessimistic' sets of EROI assumptions to capture the range of values in the current literature; and creation of an original, dynamic EROI model to produce net energy projections for the pathway scenarios, and an energy-return-on-carbon indicator.

2.3.1. Carbon energy budget

One of the most ambitious energy transition scenarios published in response to the Paris Agreement is the joint report, 'Perspectives for the Energy Transition' by the IEA & IRENA (2017). Compared to previous IEA scenarios (IEA, 2016a), it utilizes a more stringent probability, >66%, of staying within 2°C warming. Defining this carbon budget precisely is challenging, as calculation uncertainty has resulted in a wide variety of estimates, with a likely range of 590–1,240 $GtCO_2$ from 2015 onwards

(Rogelj et al., 2016). Moreover, this budget includes emissions from all sources (energy and non-energy). When focusing on energy policy, we need to derive a carbon *energy* budget, which corrects for non-energy emissions. The most significant of these are future emissions from land use change and industrial processes such as cement production. The IEA/IRENA study arrives at a carbon energy budget of 790 $GtCO_2$ (see Appendix 1.1 Methods section for details of the calculation) and presents a scenario to stay within it, primarily through strong growth in renewables, improvements in end-use energy efficiency, and deployment of CCS for coal and natural gas.

2.3.2. Energy pathway scenarios

We correct gross energy to net energy for three scenarios to 2050: LCT - a low-carbon transition consistent with >66% probability of limiting warming to 2 °C, using the IEA/IRENA scenario[5] as a reference; BAU - a ‘business as usual′ scenario based on current trends; and CNE - an optimised transition aiming to maintain current levels of net energy per capita. As we use global weis, it should be noted that many countries in the Global South wish to grow their energy use per capita. The CNE scenario may therefore imply a fall in net energy consumption within the Global North. We present per capita results as a proxy for lifestyle implications, which is important given the context of a growing global population. Details of the assumptions in each scenario are provided in the Appendix 1.1 Methods section.

2.3.3. EROI assumptions

EROI values for different energy sources vary considerably from study to study. A recent meta-analysis (Hall et al., 2014) attempted to produce mean values of EROIs for thermal and electrical energy sources. However, there is much debate, particularly around EROI values for renewable sources, due to differing perspectives on calculation methods (Raugei et al., 2012), and whether energy costs of storage and intermittency should be accounted for (Raugei, 2013; Raugei et al., 2015; Weißbach et al., 2013). This has led to a range of EROI values for solar PV from as low as 0.8:1 (Ferroni & Hopkirk, 2016) to over 60:1 (Leccisi et al., 2016). Respecting the various positions in this debate, we employ two sets of EROI perspectives, ‘optimistic’ and ‘pessimistic’, to produce an uncertainty range in our results. The latter perspective includes lower EROI values for biofuels and renewables and a declining EROI of oil and gas, in line with recent trends (Hall et al., 2014). More details are provided in Appendix 1.1 Methods.

Table 2.1. | Comparison of Mean EROIs for different energy sources

Energy source			Optimistic EROI	Optimistic net energy percentage	Pessimistic EROI	Pessimistic net energy percentage
Coal	*Thermal*		46:1	98%	46:1	98%
	Electricity		17:1	94%	17:1	94%
	Electricity with CCS		13:1	92%	13:1	92%
Oil	*Thermal*		19:1	95%	19:1*	95%
	Electricity		7:1	85%	7:1*	85%
Gas	*Thermal*		19:1	95%	19:1*	95%
	Electricity		8:1	88%	8:1*	88%
	Electricity with CCS		7:1	86%	7:1*	86%
Biofuels & waste	*Solids*	*Thermal*	25:1	96%	25:1	96%
		Electricity	10:1	90%	10:1	90%
	Gases & liquids	*Thermal*	5:1	80%	3:1	67%
		Electricity	2:1	50%	1.2:1	17%
Nuclear			14:1	93%	14:1	93%
Hydroelectric			84:1	99%	59:1	98%
Geothermal			9:1	89%	9:1	89%
Wind			18:1	94%	5:1	80%
Solar PV			25:1	96%	4:1	78%
Solar thermal			19:1	95%	9:1	89%

Thermal EROI values for oil and gas are identical as the data from which they are derived is normally aggregated. Optimistic EROI values are taken from Hall et al. (2014), except for solar thermal and solar PV. Solar thermal was not included in the meta-analysis, so we use an estimate from Weißbach et al. (2013). Optimistic values for solar PV are based on the median values in Leccisi et al. (2016) which rely on more recent data. There is significant variance in the EROI between each particular biofuel; Hall et al. (2014) calculate a mean of 5, but it is skewed by several large outliers. Biofuels refers to all solid, liquid, and gaseous fuels from any biomass source, which has then been split into 'solids' and 'gases and liquids' subcategories to account for considerably higher EROIs of solid biomass e.g. 25:1 for wood (Pandur et al. 2015). Pessimistic EROI values for renewables are adjusted downwards in line with Weißbach et al. (2013) to account for 'buffering' through energy storage. *Under pessimistic EROI assumptions, oil and gas follow a trend of -0.357 from a starting value of 35.4 in 1971, extrapolated from oil and gas EROI trends between 1992 and 2006 (Hall et al. 2014).

The relationship of EROI to net energy is non-linear, and consequently its impact can potentially be misjudged, particularly at very high and very low EROI values. To illustrate this, Table 2.1 also provides the 'net energy percentage', equal to $1 - \frac{1}{EROI}$, to represent more clearly the amount of net energy obtained. The difference between coal and wind for instance – with EROIs of 46 and 18 – becomes far less pronounced according to this metric: 98% and 95%, respectively. The net energy percentage begins to reduce rapidly below EROIs of 5:1, so the significance of an EROI below this value is especially great. This non-linear relationship is commonly termed the 'net energy cliff', a concept first attributed to Euan Mearns (2016).

EROI figures for thermal fuels are often calculated at the mine mouth, not at the point of use. This makes comparisons with renewables difficult as they supply electricity directly, and for this reason some argue that renewables should be adjusted upwards (Raugei et al., 2012). Our approach to this problem here is to adjust the EROIs for fossil fuels that are used for electricity generation downwards, based upon efficiency percentages for power plants by the IEA (2017). Utilization of carbon capture and storage (CCS) technology will further decrease these net energy returns significantly, although very little research to date has looked at the effect of CCS on EROI. The IPCC special report on CCS (IPCC 2005), however, suggests the capture energy requirement is 16% and 31% for natural gas and coal respectively, so we have produced CCS EROI estimates based on these figures. Although subject to some debate (Anderson, 2015; Anderson & Peters, 2016), an additional proposal to mitigate climate change is bio-energy with carbon capture and storage (BECCS) to produce net negative carbon dioxide emissions. The low EROI of most biofuels before trying to capture and store emissions presents an additional challenge, as the additional energy costs due to CCS would result in at best negligible, and conceivably negative, net energy to society. For this reason, BECCS is not considered in our analysis.

2.3.4. Dynamic EROI model

The relationship between EROI, gross energy and net energy for an individual energy source is represented by equation (2.1) from Murphy (2013):

$$Net\ Energy = Gross\ Energy\ \left(1 - \frac{1}{EROI}\right) \tag{2.1}$$

The total net energy delivered to society can be calculated by summing net energy across all energy sources, as in equation (2.2):

$$E^N = \sum_{i=1}^{n} \left[Q^i \left(1 - \frac{1}{EROI^i}\right)\right] \tag{2.2}$$

Here E^N = net energy delivered to society and Q^i = gross production of energy source *i*. However, this equation presents a static view of the net energy in society and thus fails to capture the dynamics during a rapidly changing energy transition. Importantly, this would overlook an additional challenge with converting to renewables. The growth rate of solar and wind renewables is limited due to the majority of energy costs being borne upfront in production and installation (Louwen at al., 2016). If the rate of growth is too fast, it would create a short-term net energy sink effect. To capture the resulting dynamics, we model net energy supplied to society by separating EROI into operational (maintenance) and investment costs, captured by equation (2.3).

$$E_t^N = \sum_{i=1}^{n} \left[Q_t^i - \frac{\alpha Q_t^i}{EROI_t^i} - \frac{(1-\alpha) L^i Max\left\{0, Q_t^i - Q_{t-1}^i + Q_{t-L^i}^i - Q_{t-L^i-1}^i\right\}}{EROI_t^i} \right] \tag{2.3}$$

Here E_t^N = net energy delivered to society at time t, Q_t^i = gross production of energy source i at time t, L^i = lifetime of capital of energy source i, α = proportion of energy costs attributable to operations and maintenance, and 1-α = proportion of energy costs attributable to investment. Energy investment costs in each time period are calculated by summing the growth of an energy source in this period $(Q_t^i - Q_{t-1}^i)$ plus the growth at $t - L^i$, which represents the investment needed to replace the capital that has now reached the end of its lifetime. The sum $(Q_t^i - Q_{t-1}^i + Q_{t-L^i}^i - Q_{t-L^i-1}^i)$ therefore represents total needed investment, which is subject to the Max$\{0,\cdot\}$ function as it is only applicable when investment needs are positive. The value of α is typically larger for non-renewable than renewable energy sources, based on data by Weißbach et al. (2013). See Appendix 1.1 Methods for more details of assumptions used in the dynamic EROI model. Historical and projected net energy supply per capita is calculated by dividing Equation (3) by the population in each time period, giving Equation (2.4):

$$E_t^{Npc} = \frac{E_t^N}{P_t} \tag{2.4}$$

Here P_t = population at time t. Per capita figures are considered in our analysis to measure the effect on lifestyles in the context of a growing global population. Assumptions used in the dynamic EROI model are summarised in Table 2.2, while details are provided in Appendix 1.1 Methods.

Table 2.2. | Model assumptions

Energy source			Optimistic EROI assumptions	Pessimistic EROI assumptions	Lifetime (years)	Investment proportion of energy costs $(1-\alpha)$	Operation & maintenance proportion of energy costs (α)
Coal	*Thermal*		46	46	45	0.086	0.914
	Electricity		17	17	45	0.086	0.914
	Electricity with CCS		9	13	45	0.086	0.914
Oil	*Thermal*		19	19*	35	0.019	0.981
	Electricity		7	7*	35	0.019	0.981
Gas	*Thermal*		19	19*	35	0.019	0.981
	Electricity		8	8*	35	0.019	0.981
	Electricity with CCS		4	7*	35	0.019	0.981
Biofuels & waste	*Solids*	*Thermal*	25	25	40	0.003	0.997
		Electricity	10	10	40	0.003	0.997
	Gases & liquids	*Thermal*	5	3	40	0.003	0.997
		Electricity	2	1.2	40	0.003	0.997
Nuclear			14	14	50	0.168	0.832
Hydroelectric			84	59	75	0.961	0.039
Geothermal			9	9	25	0.900	0.100
Solar PV			25	4	25	0.900	0.100
Solar thermal			19	9	25	0.743	0.257
Wind			18	5	20	0.977	0.023

*Under pessimistic EROI assumptions, oil and gas follow a trend of -0.357 from a starting value of 35.4 in 1971 (extrapolated from oil and gas EROI trends from 1992 to 2006 (Hall et al., 2014).

2.4. Model output for energy pathway scenarios

Figure 2.2 illustrates the historical trend and future projections of net energy supply per capita under the three energy pathway scenarios. Key indicators from the model output are also summarized in Table 2.3. As we are considering the potential impact on lifestyles under a growing population it is pertinent to focus on per capita metrics. From 1990 to 2014, net energy supply per capita rose at around 0.5% per annum, with particularly high growth seen post-2000 as a result of a boom in coal production. However, under the LCT scenario, there is a strong reversal of this trend, with net energy supply per capita declining, between 24% and 31% from 2014 levels. To maintain or improve lifestyles there would therefore need to be unprecedented improvements in end use efficiency to reduce energy demand per capita. If efficiency improvements on this scale are unachievable, net energy supply per capita will decline and be insufficient to meet demand. Supply of net energy may then become a limiting factor to maintaining or improving lifestyles for a growing global population.

The BAU scenario shows net energy per capita continuing to increase at current rates until 2050. However due to continued growth in fossil fuels, the carbon budget for 2 ºC will have already been exhausted by 2022. The CNE scenario maintains net energy per capita roughly constant at 2014 levels. However, this does not necessarily imply stagnation in lifestyles, as there is considerable potential for improvements in end use efficiency to facilitate this (IEA, 2016b). Note that over the period 1990 to 2000 net energy supply per capita was rather constant, despite global economic growth over this period. Figure 2.2d compares the growth of gross solar and wind production in the LCT and CNE scenarios. To achieve a stable net energy supply, the rate of growth of solar and wind renewables would have to grow to a capacity level by 2050 that is 2.2 to- 3.0 times that suggested by the LCT scenario. Table 2.4 summarizes the change in gross energy for the three scenarios from 2014-2050.

Under the LCT and BAU scenarios, we see a widening gap between gross and net production, while the uncertainty range for net energy also increases. The latter is not seen for the CNE scenario, as increased gross production compensates for the lower EROI values. If the pessimistic assumptions are correct, it would imply 10% less net energy being delivered in 2050 than if the optimistic assumptions hold. There is thus a strong argument for continued research into the EROI of future energy options.

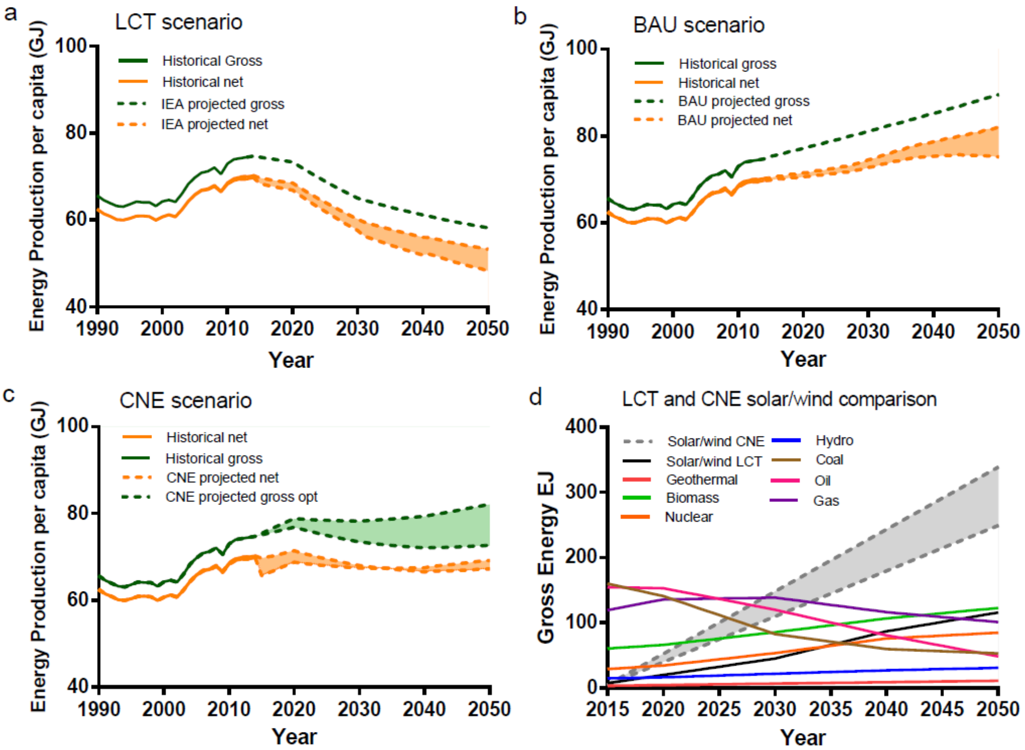

Figure 2.2. | Model output. a-c, Gross and net energy production per capita for **(a)** LCT scenario, **(b)** BAU scenario, **(c)** CNE scenario. **(d)** Comparison of gross energy product by energy source between LCT and CNE scenarios. The black line in panel (d) represents the projected energy production under the LCT scenario of solar PV, solar thermal and wind combined. The grey area represents the comparative growth of these three energy sources in the CNE scenario, to keep net energy per capita roughly constant. The CNE scenario requires growth of these to be 2-3 times that of the LCT scenario. The shaded areas in all graphs denotes the uncertainty range between optimistic and pessimistic EROI assumptions. In the CNE scenario gross energy has an uncertainty range as it is endogenous here, whereas gross energy is exogenous in the LCT and BAU scenarios.

Table 2.3. | Model output illustrating a trade-off between stabilizing climate and continuing current lifestyles

Scenario	**EROI assumptions**	**Growth in solar and wind renewables by 2050**	**Average net energy per capita 2015-2050 (GJ)**	**Net energy percentage of gross energy in 2050**
2ºC transition scenario (LCT)	*Optimistic*	2754%	60.4	91.5%
	Pessimistic	2754%	57.3	82.9%
Business as usual scenario (BAU)	*Optimistic*	553%	75.8	93.5%
	Pessimistic	553%	73.2	85.7%
2ºC constant net energy (CNE)	*Optimistic*	6228%	68.3	92.5%
	Pessimistic	8500%	67.8	84.2%

Results show a trade-off between climate and lifestyles. LCT scenario sacrifices net energy per capita while BAU sacrifices climate goals. CNE scenario attempts to balance both objectives, at the cost of much more rapid growth in solar and wind. The lower net energy percentage of the LCT and CNE scenarios indicate their less favourable energy mix from a net energy perspective compared to BAU. In 2014 the net energy percentage was 94.0% and 93.3% for optimistic and pessimistic EROI assumptions respectively. We see a considerable decline by 2050 for all scenarios under pessimistic EROI assumptions.

Table 2.4. | Changes in gross energy for the three energy pathway scenarios

Energy source			Gross Energy in 2014 (EJ)	Change in gross energy from 2014 to 2050 (EJ)		
				TRA Scenario	BAU Scenario	CNE Scenario
Coal	*Thermal*		68.5	-40.1	+15.3	-40.1
	Electricity		95.2	-95.2	+70.7	-95.2
	Electricity with CCS		0.0	+24.3	+24.3	+24.3
Oil	*Thermal*		144.0	-95.8	+33.9	-95.8
	Electricity		10.9	-10.9	-0.5	-10.9
Gas	*Thermal*		70.7	-2.6	+42.3	-2.6
	Electricity		45.2	-24.7	+38.7	-24.7
	Electricity with CCS		0.0	+12.3	+12.3	+12.3
Biofuels & waste	*Solids*	*Thermal*	48.4	0.0	0.0	0.0
		Electricity	4.1	0.0	0.0	0.0
	Gases & liquids	*Thermal*	4.4	+37.7	+22.4	+37.7
		Electricity	2.3	+25.7	+9.6	+25.7
Nuclear			27.7	+56.9	-14.7	+56.9
Hydroelectric			14.0	+16.7	+16.0	+16.7
Geothermal			3.0	+7.8	+2.2	+7.8
Solar PV			0.7	+29.0	+6.3	+ (65.1–88.8)
Solar thermal			1.3	+40.8	+4.4	+ (92.0–125.6)
Wind			2.6	+41.2	+11.2	+ (94.5–129.4)

Under the CNE scenario growth in solar PV, solar thermal and wind are exogenous model variables which are dependent on the EROI assumptions used. The model output therefore produces a range of gross energy for these energy sources. BAU scenario gross energy is produced by extrapolating trends based on 2005-2014 data.

2.5. Energy return on carbon

Our analysis suggests that net energy is likely to move from an abundant to a scarce resource if effective measures are taken to remain within a 2°C carbon budget. As in any economic problem of scarcity, efforts should be made to ensure the most efficient use of resources. We therefore examine the strategy of maximizing the net energy obtained from fossil fuels within the constraint of the carbon budget. To achieve this, we propose a measure of 'energy return on carbon' (EROC), using a metric of net energy per tCO_2, which allows comparison of the performance of different energy sources under the constraint of climate change targets. EROC is calculated as [(1-1/EROI)/(Carbon emission factor)]. The EROC takes into account both the net energy potential of a fossil fuel and its carbon emissions in order to produce a metric of the fuel's overall utility under climate change policy. Table 2.5 illustrates this indicator for the combustion of various fossil fuel options. It shows that tar sands and oil shale, for instance, represent inefficient usage of our carbon budget.

Table 2.5. | Energy return on carbon of combusting different fossil fuels

Energy source	EROI	Carbon emission factor[37] ($kgCO_2/TJ$)	EROC ($EJ/GtCO_2$)
Coal	46:1	94.6	10.3
Coal with CCS	9:1	9.5	65.1
Oil	19:1	73.3	12.9
Oil shale	7:1	107.0	8.0
Tar sands	4:1	107.0	7.0
Natural gas	19:1	56.1	16.9
Natural gas with CCS	4:1	5.6	101.9

CCS carbon emission factors are based on capturing 85% of CO_2 emissions the midpoint of 80-90% range stated in the IPCC special report on carbon capture and storage (IPCC, 2005).

This metric supports current prioritisation of fossil fuel reductions in the order of coal, oil and then gas. Their net energies per $GtCO_2$ are 10.3 EJ, 12.0 EJ and 16.9 EJ respectively. Gas thus provides a significant 64% more net energy per CO_2 than coal, as the lower carbon content more than compensates for the lower EROI. The EROI of gas would have to fall dramatically to 2.3 for coal to become preferable to gas from a climate perspective. However, even greater priority should be given to eliminating the exploitation of unconventional sources of oil, which have much lower EROIs than conventional sources (Hall et al., 2014). This results in tar sands and oil shale providing only 7-8 EJ per $GtCO_2$ released. It is clear that investment in such unconventional sources is not a wise strategy from a combined net energy and climate change perspective. While CCS shows promise at considerably increasing the climate efficiency of fossil fuels, more research is required into the full energy costs associated with this technology.

2.6. Conclusions

Economic decisions are generally made from a monetary perspective. Adding a biophysical perspective as we do here is relevant for assessing the gap between needs and the actual options of society. In particular, climate externalities are currently not reflected in the cost of fossil fuel energies. One way to effectively signal biophysical differences would be imposing a carbon price (van den Bergh & Botzen, 2014), which would discourage coal use more than oil, and oil more than gas. It would thus provide appropriate incentives to realize the mentioned fuel prioritization in a transition.

Regardless of the fossil fuel strategy, our analysis suggests greatly accelerated investment in renewable energies is needed alongside dramatic improvements in energy efficiency if we are to continue supplying enough net energy to match current lifestyles. If these changes are unable to be made, or deemed impracticable, the main conclusion to draw is that the 2 °C target is in itself highly unrealistic. Incidentally, the analysis may even underestimate the challenge and speed of the energy transition needed, due to the current high level of uncertainty in estimations of both carbon budgets and of non-energy emissions. Particular obstacles in moving away from certain fossil fuels, such as petroleum use in aviation, may further require renewable energy to grow even faster than our projections. The net energy implications are complicated, and as discussed, much debate exists around EROI values. Our analysis has highlighted the importance of assessing the net energy return to carbon and what this means for a low-carbon energy transition. These implications warrant further research into net energy issues to narrow the debate.

Appendix 1.1 – Methods

Carbon energy budget

The IEA/IRENA report 'Perspectives for the Energy Transition'[5] determines a budget of 880 $GtCO_2$ from 2015 as a starting point, which falls in the middle of the range of 590–1,240 $GtCO_2$ from 2015 onwards (Rogelj et al., 2016). From this starting budget, it deducts 90 $GtCO_2$ for industrial process up until 2100. Although other studies suggest that future emissions for land use, land use change and forestry could mean a further reduction of 138 $GtCO_2$ (Peters et al., 2015), the IEA/IRENA scenario assume these to net zero over the century due to massive reforestation efforts. Despite this arguably optimistic assumption, we have chosen to use the same carbon energy budget as in the IEA/IRENA scenario of 790 $GtCO_2$ in our analysis, to allow comparability.

Energy pathway scenarios

Three scenarios of energy pathways until 2050 are considered. In the low-carbon transition (LCT) scenario, gross energy projections for all energy sources approximate values in IEA & IRENA report 'Perspectives for the Energy Transition' (2017). In the business as usual (BAU) scenario, gross energy projections for all energy sources are calculated by extrapolating trends in the ten-year period 2005-2014 from IEA 'World Energy Balances' energy production data[12]. Finally, the constant net energy (CNE) scenario aims at calculating the minimum rate of growth in solar and wind required to maintain net energy per capita at 2014 levels.

Our interest in the CNE scenario is to measure how much extra investment in renewables, above that seen in the LCT scenario, would be needed to maintain net energy per capita at 2014 levels. Hydroelectric, geothermal, nuclear and biofuels all have limits to their potential for expansion which will make significant growth beyond that already projected in the 2 ºC scenario difficult (Moriarty & Honnery, 2012). There is a limited quantity of appropriate dam sites and potential geothermal locations, while biofuels suffer from land use competition, which will become an even greater challenge as food production adapts to population growth (Foley, 2005). Nuclear energy also has technical and resource requirements that are likely to constrain its growth beyond currents plans. In the CNE scenario, we therefore treat growth in hydroelectric, biofuels, geothermal, and nuclear power to 2050 as exogenous, based on the LCT scenario, while solar and wind growth rates are endogenous to compensate for any shortages in net energy supply. Growth in solar and wind is unlikely to be constrained by technical limits, as the technology is already mature enough to be implemented quickly and on a large scale. Wind power, for instance, has an estimated potential of up to 600 EJ (Moriarty & Honnery, 2012), which is greater than current global energy production from all sources. We thus treat solar and wind as the low-carbon options for any additional growth in energy supply beyond the LCT scenario. Hence, gross production of coal, oil, gas, biofuels and waste, nuclear, hydroelectric and geothermal are identical for the CNE and LCT scenarios. For the CNE scenario, solar and wind renewables are calculated by minimising their growth rate subject to net energy per capita from 2015-2050 equalling 36 (the number of years from 2014 to 2050) times 2014 values. This optimization problem is solved employing a generalized reduced gradient algorithm.

Historical gross energy production for the period 1990-2014 is obtained from IEA (2017) world energy balances, and re-categorized into the ten energy categories seen in Table 2.2; coal, oil, gas, biofuels and waste, nuclear, hydroelectric, geothermal and solar PV, solar thermal and wind. 'Peat and peat products' and 'heat' with shares of 0.03% and 0.016%, respectively, of 2013 total energy production are discounted from the analysis due to their insignificant values.

EROI assumptions

EROI assumptions are summarised in Table 4 along with lifetime and α assumptions. The 'biofuels and waste' category is split into two subcategories; 'solids' and 'liquids and gases. This is to reflect the much higher EROI estimates of solid biomass such as wood (Pandur et al., 2015) compared to modern liquid biofuels (Hall et al., 2014). Coal, oil, natural gas, and biofuels and waste categories are split into 'thermal' and 'electricity' subcategories. EROI values for electricity production are calculated by applying power plant efficiency factors from IEA (2017) world energy balances, which are 37%, 35%, 44% and 40%, respectively. There is little research on the EROI of fossil fuels with CCS technology to date. The contribution of CCS to EROIs is therefore approximated by using the capture energy requirement in the IPCC special report on CCS (IPCC, 2005) – 16% for natural gas (NGCC plant) and 31% for coal (PC plant), which are cumulative to the electricity efficiency losses. However, as it is not clear if these percentages represent a complete depiction of the all CCS energy costs, there may be an underestimation of the CCS net energy impact in our results.

Dynamic EROI model

We generate scenarios for future energy pathways to stay within a 2°C carbon energy budget, while correcting for net vs gross energy delivered to society. Net energy is converted to per capita values to capture the effect of an increasing global population over the time period. Calculations were made using United Nations (2015) population data, gross energy from IEA (2017) energy production data. The resulting model was run for three energy forecast scenarios (TRA, BAU and CNE), each with the two sets of 'optimistic' and 'pessimistic' EROI assumptions, thus producing six model outputs in total. Historical IEA (2017) energy production data from the 'World Energy Balances' for 1971-2014 were used.

Proportions of investment and operational energy are based on data by Weißbach et al. (2013). Although the methodology for calculating EROIs has been criticised (Raugei, 2013; Raugei et al., 2015), this criticism did not pertain to these assumptions. Lifetime assumptions are calculated by taking the mean of the three data sets offered in Table 11 in Tidball et al. (2010), except for hydroelectric, as average values were not mentioned in this study. We therefore use a lifetime value of 75 years for hydroelectric, which is consistent with the IEA's range of 50-100 (IEA, 2010). One factor not explicitly considered in the model is the early retirement of fossil fuel capital, which would potentially lower the net energy returns. However, as operational and maintenance costs are the vast majority of fossil fuel energy investment, this would not be one of the key drivers of the results.

Chapter 3

Political Challenge: Normalisation of Paris Agreement NDCs to enhance transparency and ambition[2]

3.1. Introduction

The Paris Agreement (UNFCCC, 2015) takes the form of a bottom-up approach to tackling climate change, reliant on voluntary commitments in the form of Nationally Determined Contributions (NDCs), which are publicly accessible through the NDC registry (UNFCCC, 2018). The NDCs are subject to regular review and updated every five years, implying a system of 'pledge and review' with civil society holding countries to account instead of employing direct enforcement mechanisms (Jacquet & Jamieson, 2016). Under such a process, however, transparency and comparability of individual country pledges become paramount to the agreement's success. In response, online tools, such as the NDC Explorer (Pauw et al., 2016), Climate Watch (World Resources Institute, 2018), the Climate Equity Reference Calculator (Kemp-Benedict et al., 2017) and the Climate Action Tracker (Climate Action Tracker, 2018) have appeared to make pledges more comparable. Yet the main lesson from using such tools is merely how much complexity and variance exists among NDCs. It remains challenging to compare what pledges really mean in emission and temperature terms. This job has instead fallen on scientists, requiring them to spend valuable resources analysing the impact of the pledges and judging their ambition (Aldy et al., 2016; Jacoby et al., 2017).

Initial studies suggest current NDCs are insufficient at meeting the top-down goal (Höhne et al., 2017), implying a warming of 2.6-3.1°C, dependent on speculative negative emission technology (Rogelj et al., 2016a; Anderson & Peters, 2016; Schleussner et al., 2016). Here we evaluate this discrepancy by performing a bottom-up assessment of the transparency and ambition of individual pledges. We identify four main categories of NDCs, and analyse the ambition of each category of NDC. In this context, we define ambition as producing emission targets that limit emission growth or lead to emission reductions in line with the overall goal of limiting global temperature rise to 2°C. To compare the ambition of each pledge, we perform a normalisation that makes their differences comparable and quantifies their effect on global emissions. This analysis is performed by grouping countries according to geographic region and by ranking them in terms of emission intensity per capita. On the basis of the findings we detect potential counterproductive systemic effects and suggest how transparency and ambition levels of NDCs can be improved.

The Paris Agreement states that the principles of transparency, accuracy, completeness, comparability and consistency (UNFCCC, 2015) should be adhered to in accounting for emissions. We

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argue that these principles, particularly those of transparency and comparability need to be extended to the framing of NDCs themselves. Recent cooperation experiments have shown the need for greater transparency in achieving a fair climate deal (Hurlstone et al., 2017). This will have the benefit of making the pledges easier to interpret and scrutinise by external stakeholders, including civil society, alongside having the psychological effect of inducing a behavioural change to increase ambition (Thaler & Sunstein, 2008).

3.2. Methods

3.2.1. NDC differences regarding scope and gases covered

At the time of this writing, 147 parties had submitted their first NDC (including a joint submission for all 28 EU member states), the vast majority of which are unchanged from their intentions (Intended NDC or INDC) at the time the Paris Agreement was signed. A further 18 countries submitted an INDC but are yet to formalise an NDC. From here on NDCs is used to denote the combination of NDCs and INDCs, also as one may safely assume that for countries without an NDC yet it is likely that their INDC submission is representative for their future NDC submission.

Some large distinctions among the NDCs are immediately clear, such as whether targets are designated as 'conditional' or 'unconditional'. Around 80% of parties submitted conditional targets, which are subject to various stipulations, such as access to international finance, technology transfer and international cooperation. These are sometimes explicit, but often implicit or somewhat vague in their specific requirements. Meeting these conditions provides an additional challenge, but even if they are all met, a recent study indicates that emissions are unlikely to be on a substantially better trajectory for staying within the 2°C target (Rogelj et al., 2016a).

Several other significant differences between NDCs relate to emission scope and coverage. As countries can decide which Kyoto protocol gases are covered by the NDC, often we see them excluding HFCs, PFCs, SF_6 and NF_3, which is justified by their insignificant contribution to national emissions. However, some countries also exclude CH_4 and N_2O, which tend to make up a significant proportion of total national emissions. The importance of this is illustrated for China, which only includes CO_2 in its target. This means 2.5 $GtCO_2e$, or 4.9% of global greenhouse gas (GHG) emissions, is excluded from their commitment. Similarly, countries can choose which IPCC reporting sectors fall within the NDC, with perhaps the most important exclusion often being Land Use, Land Use Change and Forestry (LULUCF). Only around half of all countries fully and explicitly include LULUCF in their NDC or INDC submission. Hence, a further 1% of global emissions are not covered, and this conceivably gives license for LULUCF emissions to grow in these countries.

3.2.2. Normalisation of NDCs

More fundamentally, large differences exist among how countries express their individual targets. Based on analysing all NDCs (see Section 2) we group them into four main categories:

i) Absolute emission reduction targets

Countries submitting these pledges present absolute emission reductions for a target year in percentage terms relative to a historical base year. The base year is set by the country and ranges from 1990 to 2014, while the target year is typically 2030, and in a few cases 2025.

ii) ′Business as usual′ (BAU) reduction (covering also trajectory targets)

Countries submitting these pledges present a percentage reduction in emissions relative to a ‘business as usual’ scenario, typically to 2030. This scenario is defined by each country itself, causing a large variance to exist in emissions growth among scenarios. Also included in this category are the few countries (Bhutan, Ethiopia, Oman and South Africa – representing only around 1.5% of global emissions) which submitted a fixed emission trajectory target. This approach effectively produces the same result.

iii) Emission intensity reductions

Countries submitting these pledges present a reduction in emission intensity per GDP relative to a historical base year. Emissions targets are therefore dependent upon the historical GDP and emissions in the base year, and any future GDP growth.

iv) Projects absent of GHG-emission targets

This final category includes countries presenting NDCs that did not include an explicit greenhouse gas emission target. These submissions typically offered details about projects aiming to reduce emissions, such as investment in renewable energy. However, these are difficult to convert into actual impact on emissions and do not provide a hard limit on emissions for the countries to be held accountable against.

To analyse the ambition of each pledge type, we group countries by pledge type and perform analyses by region and rankings of emission intensity per capita. This allows for systematic comparison of countries of similar geopolitical characteristics, each covering at least 5% of global greenhouse gas emissions. The geographical groupings avoid having to report results for relatively small nations and thus assist in presenting the results in a concise way that allows for clear interpretations. Appendix 3.1 shows the resulting groups and countries within each. The PRIMAP database (Gütschow et al., 2018) was used for historical greenhouse gas emissions because it is a peer-reviewed data source that covers all countries which have submitted an NDC. Countries’ greenhouse gas emission projections to 2030 were calculated by individually assessing their NDC submissions. Where LULUCF or non-CO_2

greenhouse gas were not covered in the pledge, such emissions are forecasted using exponential smoothing methods applied to trends between 2006 to 2015. Of the seven countries submitting Category iii targets, only India presented an explicit GDP projection in their NDC. Few long-term GDP projections provide complete information available at the country level. Among these, the most reliable are those provided by the OECD (2018), which we use to calculate the expected reduction in emissions. This involves applying world average growth rates for countries without individual GDP projections. In the case of India, we calculate an additional emission projection for 2030, based on the GDP projection that was included in its NDC. When growth in a country's GHG emissions could not be interpreted from the NDC (i.e. countries falling into Category iv), growth was forecast from trends between 2006 to 2015, again using an exponential smoothing method. Finally, the Bahamas and Belize show large changes in global emissions between 2006 and 2015 in the PRIMAP database. For these two countries, forecasts were made from trends between 2011 and 2015. Furthermore, in cases of the NDC pledge holding until 2025, such as for the United States, the trend extrapolated to 2030 by applying exponential smoothing on the data from 2016 to 2025. Appendix 3.2 shows the groupings of countries by emissions per capita in 2015, used to produce the calculations reported in Table 3.2. Countries were ranked based on the absolute emissions of all greenhouse gases, and then divided into five groups based on this ranking. For the production of all tables and figures, excluding Figure 3.1, we assume that all requirements of conditional pledges have been fulfilled, thus we are working with conditional pledges rather than unconditional pledges.

3.3. Results

Table 3.1 shows the percentage of 2015 global emissions for the four groups. It also mentions weighted percentage changes of projected emissions by 2030 compared to 2015. Absolute values of the emissions in 2015 and 2030 are included in Appendix 3.3. In effect, we are normalising the emission pledges for all countries, by converting them into a format similar to category i pledges, but indicating actual emission change, whether positive or negative, compared with a consistent base year. Levels of ambition are more easily judged on the basis of such normalised pledges than for pledges in their original form.

The category i pledges generally prove to have the highest ambition in terms of tangible emission reductions. By contrast, categories ii, iii and iv tend to produce low ambitions with significant emission increases of 29-61% at global level. The effect of these changes on emissions at the regional level is illustrated in Figure 3.1. Notably, we find that Northern America and EU+ are the only regions aiming for absolute reductions in emissions, while substantial increases are expected in MENA and South Asia. Since countries in the Global North (corresponding to the Annex I countries in the Kyoto Protocol) are more likely to submit category i pledges, it may not seem surprising that they produce the targets with highest ambition.

To control for the fact that these countries tend to have higher emission intensity and thus are more likely to submit category 1 pledges, we present results with countries grouped by their 2015 emission per capita in Table 3.2. We see that category i pledges still tend to outperform the other pledge categories within the same emission intensity grouping. Additionally, it indicates that for the lowest 20% of countries in terms of emissions intensity pledge, type iv performs better in terms of emissions reduction than types i (-8 vs 64%) and ii (63%), while for the highest 20% countries, pledge type iii comes out lower than i (-49 vs -20%). Although this seems counter-intuitive, it is due to category iv pledges being based on recent trends; the more intense emitters are likely to have achieved high growth in emissions, whilst low-intensity countries are likely to have not. Overall, emission growth is lower under category iv pledges than under ii and iii. However, as the category iv pledges have been calculated by projecting recent trends in emissions, it is foreseeable that emission growth could accelerate and be higher than that seen in category ii and iii countries, given that there is no fixed target which they are pledging to limit their emission growth to.

In terms of global emissions, we see a rise of 23.8%, from 49.8 $GtCO_2$ in 2015 to 61.6 $GtCO_2$ in 2030. Rogelj et al. (2016b) calculate for a >66% chance of staying within 2°C of warming, the remaining carbon budget has a range of 590-1,240 $GtCO_2$. The cumulative emissions to 2030 from our analysis are 892 $GtCO_2$, suggesting that the 2°C budget will quite likely have already been spent by 2030. It should be noted however that our emission projections are around 10% higher than Rogelj et al., (2016a) and UNEP (2016). This is largely due to us trying to present the NDC pledges ‘as is’ rather than running them through complex modelling without making assumptions of how they translate into policies. Here we are presenting rather a maximum estimation of what the countries are actually committing to in emission terms. The effect on overall emissions, and why it may differ to other publications is also likely due to the sensitivity to the PRIMAP emission dataset and GDP assumptions used. This is particularly seen in the very high growth rate in emissions for India.

Table 3.1. | Normalised (I)NDCs by pledge type and region

Pledge type **Region**	**i. Absolute emission reduction**			**ii. BAU reduction**			**iii. Intensity reduction**			**iv. Projects absent of GHG-emission targets**			**Regional Total**
	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	% change by 2030
Asia-Pacific	8	3.7%	-20%	10	8.1%	23%	2	0.6%	61%	11	1.0%	1%	15%
China	0	0.0%	-	0	0.0%	-	1	24.9%	23%	0	0.0%	-	46%
Eastern Europe & Central Asia (EECA)	9	6.9%	17%	6	0.2%	10%	1	0.5%	52%	1	0.2%	28%	27%
Latin America & Caribbean (LAC)	6	2.9%	-10%	13	4.6%	10%	2	0.1%	386%*	11	0.8%	18%	7%
Middle East & North Africa (MENA)	0	0.0%	-	9	3.8%	68%	1	0.1%	0%	7	3.7%	47%	58%
Northern America	2	14.7%	-31%	0	0.0%	-	0	0.0%	-	0	0.0%	-	-31%
South Asia	0	0.0%	-	5	1.4%	125%	1	5.9%	219%*	2	0.2%	42%	174%
Sub Saharan Africa (SSA)	4	1.0%	-38%	32	5.0%	24%	0	0.0%	-	13	1.2%	4%	13%
EU+	34	8.1%	-14%	1	0.0%	-24%	0	0.0%	-	0	0.0%	-	-14%
GLOBAL TOTAL	**63**	**37%**	**-15.9%**	**76**	**23%**	**34.3%**	**8**	**32%**	**61.2%**	**45**	**7%**	**29.2%**	**23.8%**

2. *The 386% change in LAC intensity reduction countries is so high due to Chile having large negative emissions from LULUCF in the 2015 data, giving a very low overall emission total. This produces a very high percentage increase which is not representative of the change in emissions exclusive of LULUCF. Excluding Chile, this figure would only include the emission growth of Uruguay, which equals 104%. The 219% increase refers to that for India. In 2005, the base year for their intensity target, LULUCF emissions were much higher than in 2015. As with Chile, this large percentage increase seems largely related to LULUCF in the data used.

Table 3.2. | Normalised (I)NDCs by pledge type and emission intensity per capita

Pledge type	**i. Absolute emission reduction**			**ii. BAU reduction**			**iii. Intensity reduction**			**iv. Projects absent of GHG-emission targets**			**Total for each rank of emission intensity per capita**
Ranking by 2015 emission intensity per capita	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	Number of countries	Share of global emissions in 2015	% change by 2030	% change by 2030
Highest 20%	11	22.5%	-20%	9	5.8%	20%	1	0.2%	-49%	12	3.3%	52%	-5%
60%-80%	37	14.5%	-10%	13	7.3%	23%	4	25.9%	25%	6	1.0%	-2%	27%
40%-60%	7	0.1%	-42%	17	5.8%	36%	1	0.1%	0%	8	1.3%	16%	31%
20%-40%	4	0.1%	-19%	18	3.1%	74%	1	5.9%	219%*	10	1.0%	20%	134%
Lowest 20%	4	0.0%	64%	19	1.1%	63%	1	0.0%	2864%*	9	0.5%	-8%	56%
GLOBAL TOTAL	**63**	**37%**	**-15.9%**	**76**	**23%**	**34.3%**	**8**	**32%**	**61.2%**	**45**	**7%**	**29.2%**	**23.8%**

Deeper green shades represent greater emission reductions and deeper red colours represent greater emission growth. For definitions of ranking groups and details of calculations, see Section 2. *The 2864% change corresponds to the percentage change of Chile, the only country in the category. in intensity reduction is so high due to Chile having large negative emissions from LULUCF in the 2015 data, giving a very low overall emission total. This produces a very high percentage increase which is not representative of the change in emissions exclusive of LULUCF. The 219% increase refers to that for India. In 2005, the base year for their intensity target, LULUCF emissions were much higher than in 2015. As with Chile, this large percentage increase seems largely related to LULUCF in the data used.

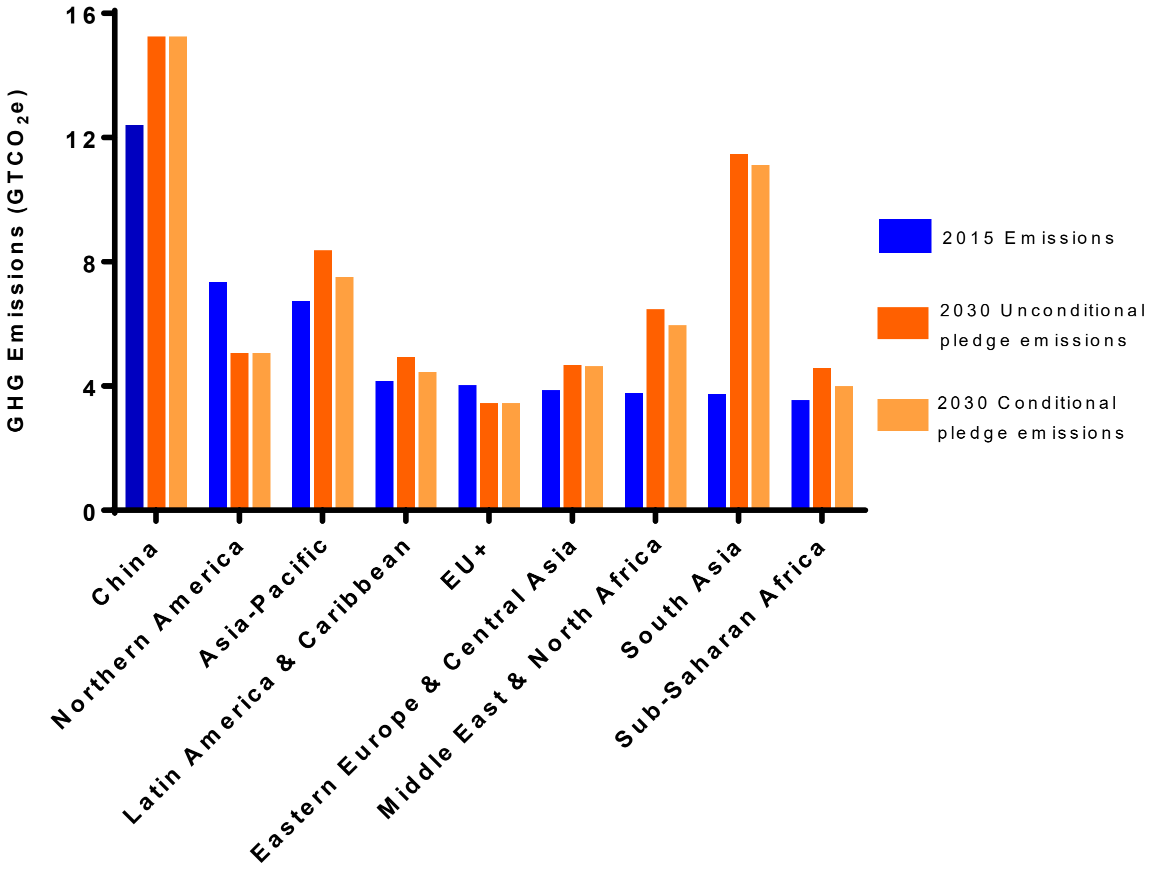

Figure 3.1. | Historical and projected GHG emissions by region. Projected 2030 GHG emissions are shown for two scenarios: only unconditional pledges are achieved; and all conditional pledges are achieved. These therefore indicate the range of effects from current commitments. In the case of India (part of South Asia), we assume the emission intensity of GDP remains unchanged from 2015 if their conditional pledges are not met.

3.4. Discussion

We now explore the variance in transparency and ambition among different pledge types. Figure 3.2 illustrates emission projections for five sample countries varying in ambition: Australia, India, Mexico, Pakistan and Russia. These countries were chosen as they provide good examples of the difficulty in comparing level of ambition amongst individual countries. Australia and Russia both submitted seemingly similar category i pledges. Although we this appears to be the most effective pledge category, due to the explicit fixed cap on future emissions, we still find much variance in ambition, suggesting a need for achieving more consistency in the future. The choice of base year is particularly relevant. For instance, Russia aims to reduce emissions by 25% relative to the base year 1990, which at face value seems comparable to Australia's 26-28% reduction relative to 2005. However, comparing both to 2015 emissions, we see Australia's emissions drop by around 9%, whereas Russia's increase by 13%, as it had considerably higher emission levels back in

1990. It is therefore clear that each country's level of ambition cannot necessarily be inferred from their NDC, even when submitting category i pledges.

Likewise, a similar issue occurs when trying to compare category ii 'BAU reduction' pledges. Mexico and Pakistan submitted Category ii, which give countries much freedom to define their business-as-usual scenarios. As a result of the scenarios being self-defined, the resulting differences amongst the emission changes for each countries are pronounced. At first sight, Pakistan's conditional BAU reduction of 20% may appear roughly comparable to Mexico's 22% unconditional GHG target. However, if we normalise both relative to 2015 emissions, we see a striking difference between how they translate into 2030 emissions. Mexico's GHG emissions decrease 11% from 2015 levels, while Pakistan´s pledge would increase emissions by 182%. Despite producing only half of Mexico's emissions in 2015, Pakistan may emit twice as much as Mexico by 2030. The key difference is in the detail of the BAU scenarios; Pakistan's BAU scenario entails a 241% increase from 2015-level emissions while Mexico´s is a more modest 38%.

Although few countries opted for category iii pledges, they include the major emitters China and India, which together account for around a third of global emissions. The outcome of these targets is more difficult to predict. Their greatest weakness is that they do not limit emissions: the more growth, the higher the emissions. These targets also suffer from needing economic data for interpretation. Using current long-term GDP growth forecasts from the OECD (OECD, 2018) India's 33% reduction in intensity will likely translate to emissions growth of 229% from 2015 levels. India include a GDP projection for 2030 in their NDC, namely a 173% increase from their 2014 GDP. The OECD projections are very similar, namely a 178% increase in GDP, resulting in a comparable result in terms of CO_2e emissions with a 213% increase from 2015. This small range is shown in Figure 3.2. However, it is important to note that the percentage increases are very high partly due to the accounting for LULUCF in the data. There was a large drop in LULUCF emissions between 2005 and 2006, the result of which can be seen clearly in Figure 3.2. This is particularly significant given that 2015 was the chosen base year for India's intensity target. However, this further illustrates the difficulties in clearly assessing countries' pledges under the current framework. Note that it is not our intention with these illustrations to question goals agreed for developing countries, but to illustrate that in their current form even a simple comparison of NDCs requires careful analysis. Detailed analysis of mitigation effort or fairness will require more informative metrics (Aldy et al., 2017).

Due to normalisation of all NDCs we are able to compare these now systematically. This results in Figure 3.3, which shows the data of emission growth and emissions per capita for all individual countries, excluding a few outliers. While there is a large degree of variance among countries, category 1 targets generally lead to more ambitious emission targets, regardless of emissions per capita. The full data on normalized pledges for each individual country is presented in Appendix 3.4. The majority of countries fall into an area between -25% and 75% emission growth, and up to 10 TCO_2e emissions per capita. However, three groups of outliers exist. Firstly, there are countries with very high emission growth; most significantly Pakistan, India, Iran and Turkey. These countries have much greater growth in emissions compared to countries of similar emission intensity. Secondly, there are category 1 countries with already very high emission intensities, including Russia, USA, Canada and Australia. These countries are generally aiming for relatively significant emission reductions with the exception of Russia. Thirdly, there are several high-emission intensity countries, such as the United Arab Emirates and Saudi Arabia, which can be expected to continue to significantly grow their emissions due to having submitted category iv targets.

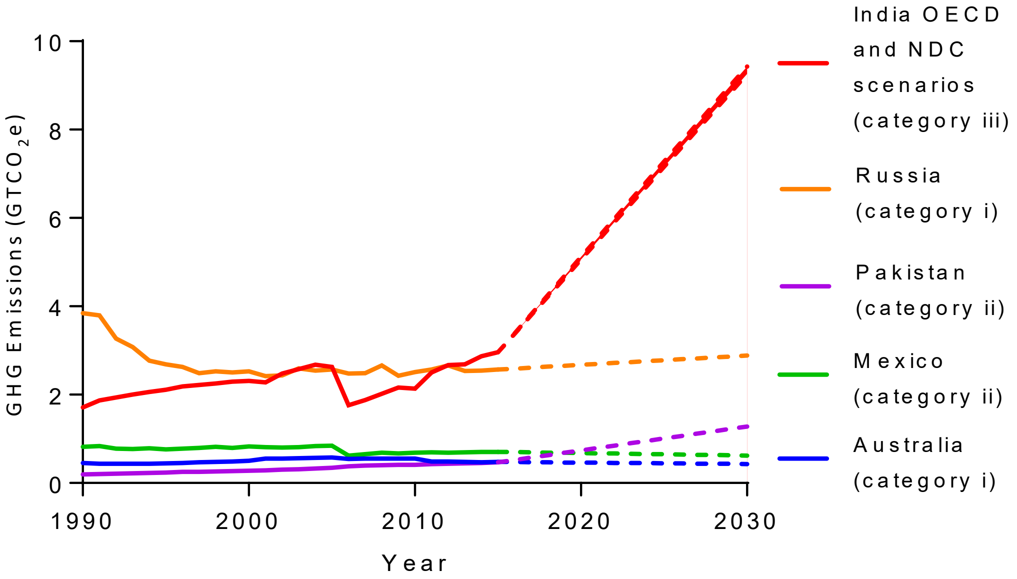

Figure 3.2. | Historical and projected emissions for referenced countries under NDC. Dashed lines indicate projections based on current NDCs for: Australia (Category i pledge, 26% reduction from 2005 base year), Russia (Category i pledge, 25% reduction from 1990 base year); Mexico (Category ii pledge, conditional 36% BAU GHG reduction pledge); Pakistan (Category ii pledge, conditional 20% BAU reduction); and India (Category iii pledge, conditional 33% intensity reduction).

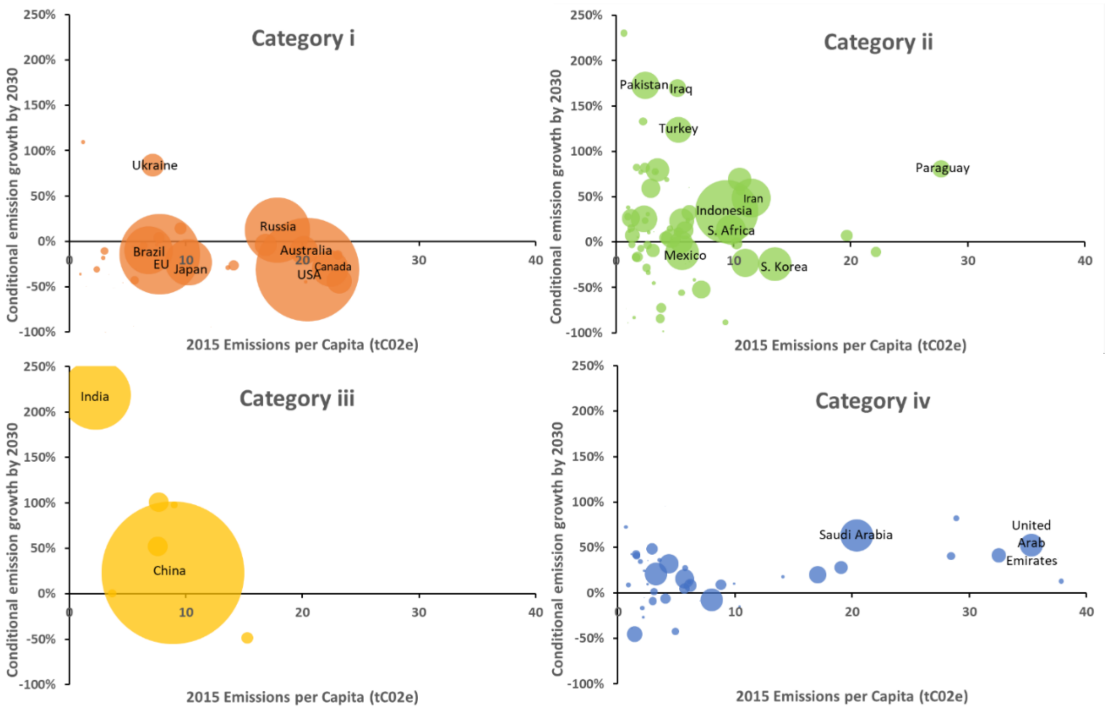

Figure 3.3. | Normalised conditional NDC pledges for all countries. The size of each sphere represents total greenhouse gas emissions for each country in 2015. The top 15 emitters and some of the more significant outliers are explicitly mentioned (the centre of a country name coincides with the centre of the respective sphere). Extreme outliers in terms of conditional emission growth and emissions per capita, and those with negative emissions have been excluded from the graph to avoid that discernibility would be compromised. These are Bhutan, Burundi, Chile, Gabon, Fiji, Trinidad & Tobago and Qatar.

The calculations underlying the tables and figures assume that nations stick to, and successfully meet their stated pledge. There is a lot of potential for countries to meet or exceed their targets, particularly if economic growth turns out to be below current projections. However, one may expect the targets to be difficult to achieve due to systemic effects, such as carbon rebound (Antal & van den Bergh, 2014; Druckman et al., 2011), carbon leakage (Babiker, 2005) and the green paradox (Sinn, 2012). Of these, carbon leakage is of particular interest to our discussion as it is influenced by differences in national policy stringency, which can be connected to differences in NDCs. Carbon leakage arises when companies move production to countries with weaker climate policies or when imports from such countries increase due to products being cheaper than ones from other countries or produced domestically. This merely transfers emissions from one country to another. As we have seen, countries fall into four tiers of pledge ambition, which creates the problem of carbon leakage from countries with relatively ambitious NDCs to those with relatively non-ambitious NDCs. Although category iv NDCs theoretically lead to less emission growth than category ii and iii pledges in our analysis, one should expect considerable carbon leakage to these countries as they lack a target for emissions. This will make compliance of the latter countries with their NDCs more difficult, leading to higher cost of compliance – as more emissions have to be reduced than foreseen – which in turn may lead to efforts by such countries to reduce their NDC or to increase it less in the future than originally intended.

The current format of pledges presents two problems. Firstly, it is difficult to accurately assess and compare what the pledges will mean in actual emission terms. Russia, India and Pakistan all frame their NDCs in terms of percentage reductions; Russia relative to a base year, India relative to emissions per GDP and Pakistan relative to a BAU scenario. Not only does this make the associated pledges difficult to interpret and compare to other pledges without detailed analysis, but may produce a psychological effect of reducing ambition level. Psychology shows us that the framing of information is important in the decision-making process (Thaler & Sunstein, 2008). Russia, for instance, might have been more ambitious in its pledge if it was unable to frame its actual 13% increase in emissions as a 25% decrease against a base year of choice. The same applies for all pledges in categories 1-3: here pledges are being framed as percentage reductions, although the actual effect of the reduction rarely corresponds to the actual effect on emissions. In view of this, our advice would be to prevent countries from presenting their pledges in a frame which appears more ambitious than its true effect. This is in line with experiments demonstrating how aversion from shame is a powerful motivator in public contribution (Samek & Sheremeta, 2014). This would likely be challenging to achieve politically, as one of the factors that brought countries into the agreement was the freedom to be able to able to set their own targets in a format of their choosing. However, what we are proposing is not a radical change. For the majority of countries (those not in category iv), this would involve a simple conversion based on already available data, as we have done so in this analysis, so would not prove to be an undue burden on parties. Instead, it will be important achieving the goal of the Paris Agreement through the ratcheting mechanism. Alternatively, the countries could submit in a flexible format but their "ratcheted pledges" would be immediately normalized by the UNFCCC. If known before, this would create healthy pressure on delivering ambitious updates.

3.5. Conclusions

The Paris Climate Agreement was undoubtedly a giant step in the right direction for international climate policy. However, studies have shown that, in its current form, it is at best inadequate and at worst grossly ineffective. Civil society has the right to be able to clearly understand and compare climate change commitments by countries, including whether they are fair, ambitious and add up to international climate goals. Moreover, providing consistent and easily comparable information about national climate goals has been found to contribute to their public acceptance (Gütschow et al., 2018). The current lack of transparency and consistency, which requires compensation by tools and models supplied by academic research, will hinder the NDC process. To move forward, we propose that the Principles of Transparency and Consistency from the TACCC framework are extended to the framing of the NDCs themselves. This would be easy to achieve, by having countries convert their pledges into clear emission targets relative to the most recent available year in the data, inclusive of all significant gases and sectors. Alternatively, countries could deliver pledges in a flexible format which then would be normalized by the UNFCCC. An important detail is that the base year should be consistent across all countries' NDCs. In effect, countries' NDCs would then be normalized as we have done in our analysis (Table 3.1), according to a category i style target. In our analysis we accomplished this normalisation comparing emissions to a consistent base year of 2015, the most recently available base year in the PRIMAP dataset. Going forward, as countries update their NDCs this base year should be updated, to keep pledges relevant for the next period. Not only can this help produce targets of greater ambition that are more open to external scrutiny, but it also will assist in improving effectiveness through minimising counterproductive systemic effects. Normalization of pledges will also put pressure on delivering ambitious updates of pledges every five years under the Paris Agreement's ratcheting mechanism.

Appendix 3.1. Definition of regions

Region	Countries	% of 2015 global emissions
Asia-Pacific	Australia, Brunei, Cambodia, Cook Island, Fiji, Indonesia, Japan, Kiribati, Korea (Democratic Republic), Korea (Republic), Laos, Malaysia, Marshall Islands, Micronesia, Mongolia, Myanmar, Nauru, New Zealand, Niue, Palau, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Thailand, Timor-Leste, Tonga, Vanuatu, Vietnam	13.5%
China	China	24.9%
Eastern Europe & Central Asia	Albania, Armenia, Azerbaijan, Belarus, Bosnia & Herzegovina, Georgia, Kazakhstan, Kyrgyzstan, Macedonia, Moldova, Montenegro, Russian Federation, Serbia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan	7.8%
Latin America & Caribbean	Antigua & Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Panama, Paraguay, Peru, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & Grenadines, Suriname, Trinidad & Tobago, Uruguay, Venezuela	8.4%
Middle East & North Africa	Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, United Arab Emirates, Yemen	7.6%
Northern America	Canada, United States	14.7%
South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka	7.5%
Sub Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo (DRC), Congo (Republic), Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Namibia, Niger, Nigeria, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe	7.2%
EU+	European Union (28), Switzerland, Iceland, Norway, Liechtenstein, Monaco	8.1%
No INDC submission	Libya, Nicaragua, Syria,	0.4%

Appendix 3.2. Definition of groups ranked by emission intensity per capita

Ranking Group of 2015 emission intensity per capita	**Countries**	**% of 2015 global emissions**
Highest 20%	Qatar, Trinidad & Tobago, Brunei, Niue, United Arab Emirates, Kuwait, Guyana, Bahrain, Paraguay, Zambia, Botswana, Canada, Mongolia, United States, Saudi Arabia, Iceland, Australia, Oman, Turkmenistan, Russian Federation, Bolivia, Kazakhstan, Singapore, New Zealand, Suriname, Equatorial Guinea, Korea, Rep. (South), Palau, Iran, Argentina, Central African Republic, Venezuela, Belize	31.7%
60%-80%	Israel, Japan, The Bahamas, South Africa, Belarus, Indonesia, Namibia, Uruguay, China, Papua New Guinea, Bosnia & Herzegovina, Sudan, European Union (28), Serbia, Malaysia, Uzbekistan, Montenegro, Angola, Ukraine, Antigua & Barbuda, Brazil, San Marino, Mauritius, Norway, Seychelles, Cameroon, Saint Kitts & Nevis, Ecuador, Azerbaijan, FYR of Macedonia, Timor-Leste, Andorra, Peru	48.7%
40%-60%	Panama, Algeria, Liechtenstein, South Sudan, Mexico, Switzerland, Republic of Congo, Thailand, Tanzania, Cook Islands, Barbados, Turkey, Honduras, Iraq, Laos, Colombia, Dominica, Lebanon, Myanmar, Georgia, North Korea, Nauru, Zimbabwe, Solomon Islands, Cambodia, Marshall Islands, Chad, Tunisia, Jamaica, Vietnam, Saint Vincent & Grenadines, Maldives, Monaco	7.3%
20%-40%	Jordan, Egypt, Saint Lucia, Armenia, Morocco, Grenada, Cuba, Guinea, Somalia, Democratic Republic of Congo, Moldova, Morocco, Albania, Kyrgyzstan, Mauritania, Guatemala, Mali, Vanuatu, Swaziland, Pakistan, Benin, Madagascar, Nigeria, Dominican Republic, Tonga, Burkina Faso, India, Guinea-Bissau, Samoa, Lesotho, Togo, Senegal, El Salvador	10.2%
Lowest 20%	Sierra Leone, Djibouti, Tuvalu, Uganda, Niger, Yemen, Sri Lanka, Nepal, Eritrea, Micronesia, Philippines, Ethiopia, Cote d'Ivoire, Ghana, Bangladesh, Tajikistan, Cape Verde, Gambia, Liberia, Haiti, Afghanistan, Sao Tome & Principe, Comoros, Costa Rica, Malawi, Kiribati, Burundi, Rwanda, Kenya, Chile, Fiji, Bhutan, Gabon	1.7%

Countries are ranked by 2015 total greenhouse gas emissions per capita (United Nations 2017).

Appendix 3.3. Absolute emission values for region and pledge type groupings

Pledge type	**i. Absolute emission reduction**		**ii. BAU reduction**		**iii. Intensity reduction**		**iv. Projects absent of GHG-emission targets**	
Region	2015 emissions (MtCO$_2$e)	Conditional 2030 emissions (MtCO$_2$e)	2015 emissions (MtCO$_2$e)	Conditional 2030 emissions (MtCO$_2$e	2015 emissions (MtCO$_2$e)	Conditional 2030 emissions (MtCO$_2$e	2015 emissions (MtCO$_2$e)	Conditional 2030 emissions (MtCO$_2$e
Asia-Pacific	1,855	1,486	4,060	5,012	321	517	499	502
China	0	0	0	0	12,400	15,255	0	0
Eastern Europe & Central Asia (EECA)	3,433	4,026	93	102	235	358	106	136
Latin America & Caribbean (LAC)	1,432	1,287	2,299	2,522	35	168	402	475
Middle East & North Africa (MENA)	0	0	1,893	3,183	41	42	1,851	2,726
Northern America	7,345	5,066	0	0	0	0	0	0
South Asia	0	0	703	1,579	2,960	9,433	78	110
Sub Saharan Africa (SSA)	476	298	2,502	3,112	0	0	615	639
EU+	4,017	3,440	0	0	0	0	0	0
Global Total	**18,558**	**15,603**	**11,552**	**15,512**	**15,991**	**25,772**	**3,551**	**4,588**

Appendix 3.4. normalised conditional (I)NDCs for all countries

Country	Submission	NDC category	2015 greenhouse gas emissions (GtCO2e)	2030 conditional greenhouse gas emissions (GtCO2e)	% change 2015 to 2030
Afghanistan	NDC	ii	33.3	42.7	28.2%
Albania	NDC	ii	8.1	9.0	10.8%
Algeria	NDC	iv	227.0	262.2	15.5%
Andorra	NDC	ii	0.5	0.4	-24.0%
Angola	INDC	ii	202.0	96.6	-52.2%
Antigua & Barbuda	NDC	iv	0.7	0.6	-8.5%
Argentina	NDC	ii	478.0	369.0	-22.8%
Armenia	NDC	ii	9.3	5.1	-44.9%
Australia	NDC	i	479.0	430.7	-10.1%
Azerbaijan	NDC	i	58.8	51.5	-12.3%
Bahamas, The	NDC	iv	3.8	4.2	10.4%
Bahrain	NDC	iv	39.0	54.9	40.7%
Bangladesh	NDC	ii	200.0	252.9	26.4%
Barbados	NDC	i	1.6	1.5	-5.6%
Belarus	NDC	i	90.6	103.7	14.4%
Belize	NDC	iv	3.7	3.2	-15.0%
Benin	NDC	ii	25.9	32.0	23.6%
Bhutan	NDC	ii	-1.3	-1.3	-6.7%
Bolivia	NDC	iv	183.0	219.7	20.1%
Bosnia & Herzegovina	NDC	ii	30.3	33.3	9.8%
Botswana	NDC	i	50.9	43.3	-14.9%
Brazil	NDC	i	1400.0	1,265.6	-9.6%
Brunei	INDC	iv	15.8	17.9	13.0%
Burkina Faso	NDC	ii	41.5	96.7	133.1%
Burundi	NDC	ii	8.2	60.3	633.8%
Cambodia	NDC	ii	59.7	16.3	-72.7%
Cameroon	NDC	ii	142.0	188.1	32.5%
Canada	NDC	i	805.0	565.6	-29.7%
Cape Verde	NDC	iv	0.6	0.4	-38.9%
Central African Republic	NDC	ii	48.2	75.7	57.1%
Chad	NDC	ii	52.4	8.2	-84.3%
Chile	NDC	iii	3.6	135.0	7468.5%
China	NDC	iii	12,400.0	18,086.4	24.0%
Colombia	INDC	ii	225.0	234.5	4.2%
Comoros	NDC	ii	0.8	0.1	-89.1%
Congo, DRC	NDC	ii	224.0	356.9	59.3%
Congo, Republic	NDC	ii	27.8	12.3	-55.7%
Cook Islands	NDC	i	0.1	0.0	-93.2%
Cote d'Ivoire	NDC	ii	30.8	30.0	-2.6%
Cuba	NDC	iv	35.3	35.8	1.5%
Djibouti	NDC	ii	1.7	1.8	5.3%
Dominica	NDC	i	0.3	0.2	-45.5%

Dominican Republic	NDC	i	24.8	17.2	-30.7%
Ecuador	INDC	iv	99.7	107.8	8.2%
Egypt	NDC	iv	305.0	368.8	20.9%
El Salvador	NDC	iv	13.1	10.9	-16.6%
Equatorial Guinea	INDC	i	16.0	11.4	-29.0%
Eritrea	INDC	ii	7.3	1.2	-83.3%
Ethiopia	NDC	ii	135.0	145.0	7.4%
European Union (28)	NDC	i	3,930.0	3,378.0	-14.0%
Fiji	NDC	iv	-0.6	-1.2	84.5%
Gabon	NDC	ii	-85.2	65.0	-176.3%
Gambia	NDC	iv	2.3	3.3	42.6%
Georgia	NDC	ii	17.0	28.7	68.9%
Ghana	NDC	ii	35.2	40.7	15.5%
Grenada	NDC	i	0.3	0.0	-100.3%
Guatemala	NDC	ii	43.1	41.7	-3.3%
Guinea	NDC	i	36.5	32.6	-10.6%
Guinea-Bissau	INDC	iv	4.0	5.0	24.6%
Guyana	NDC	iv	22.2	40.4	82.1%
Haiti	NDC	ii	10.7	14.8	38.3%
Honduras	NDC	ii	47.2	52.6	11.5%
Iceland	NDC	i	6.7	3.7	-44.7%
India	NDC	iii	2,960.0	8,545.4	228.7%
Indonesia	NDC	ii	2430.0	3,245.2	33.5%
Iran	INDC	ii	913.0	1,355.2	48.4%
Iraq	INDC	ii	188.0	507.1	169.7%
Israel	NDC	ii	82.7	81.4	-1.6%
Jamaica	NDC	iv	10.2	13.9	36.1%
Japan	NDC	i	1310.0	1,007.1	-23.1%
Jordan	NDC	ii	30.3	53.9	77.8%
Kazakhstan	NDC	i	299.0	288.0	-3.7%
Kenya	NDC	ii	30.3	100.1	230.4%
Kiribati	NDC	ii	0.1	0.0	-73.0%
Korea, Dem. Rep. (North)	NDC	ii	107.0	112.2	4.8%
Korea, Rep. (South)	NDC	ii	684.0	518.1	-24.3%
Kuwait	INDC	iv	128.0	181.1	41.5%
Kyrgyzstan	INDC	ii	16.0	10.7	-33.4%
Laos	NDC	iv	32.7	18.9	-42.3%
Lebanon	INDC	ii	26.8	30.8	14.9%
Lesotho	NDC	iv	4.7	3.5	-26.6%
Liberia	INDC	ii	5.1	5.7	11.8%
Libya	No submission	N/A	87.6	95.9	9.5%
Liechtenstein	NDC	i	0.2	0.1	-30.4%
Macedonia, FYR	INDC	ii	12.7	15.7	23.6%
Madagascar	NDC	ii	58.6	106.8	82.3%
Malawi	NDC	iv	15.5	16.9	8.8%
Malaysia	NDC	iii	236.0	661.2	107.0%
Maldives	NDC	ii	1.4	2.5	76.6%

Mali	NDC	ii	45.0	32.3	-28.3%
Marshall Islands	NDC	i	0.2	0.1	-51.3%
Mauritania	NDC	ii	11.2	14.6	30.7%
Mauritius	NDC	ii	8.4	4.9	-41.6%
Mexico	NDC	ii	707.0	622.7	-11.9%
Micronesia	NDC	i	0.2	0.1	-49.3%
Moldova	INDC	i	11.9	9.7	-18.1%
Monaco	NDC	i	0.1	0.1	-36.0%
Mongolia	NDC	ii	65.9	58.9	-10.6%
Montenegro	NDC	i	4.7	4.5	-3.7%
Morocco	NDC	ii	109.0	98.9	-9.3%
Mozambique	INDC	iv	81.1	120.6	48.7%
Myanmar	NDC	iv	228.0	301.0	32.0%
Namibia	NDC	ii	22.6	2.6	-88.6%
Nauru	NDC	iv	0.0	0.1	96.0%
Nepal	NDC	iv	44.3	63.2	42.6%
New Zealand	NDC	i	65.1	47.8	-26.6%
Nicaragua	No submission	N/A	16.7	19.4	16.4%
Niger	NDC	Ii	34.6	63.1	82.3%
Nigeria	NDC	Ii	430.0	540.0	25.6%
Niue	NDC	iv	0.1	0.1	38.3%
Norway	NDC	i	33.1	31.6	-4.7%
Oman	INDC	ii	82.6	88.7	7.4%
Pakistan	NDC	ii	470.0	1,282.4	172.9%
Palau	NDC	i	0.3	0.0	-94.2%
Panama	NDC	iv	22.8	29.1	27.6%
Papua New Guinea	NDC	iv	69.6	76.0	9.1%
Paraguay	NDC	ii	184.0	332.8	80.9%
Peru	NDC	ii	184.0	208.8	13.5%
Philippines	INDC	iv	145.0	79.3	-45.3%
Qatar	NDC	iv	186.0	314.7	69.2%
Russian Federation	INDC	i	2,570.0	2,887.5	12.4%
Rwanda	NDC	iv	8.0	13.7	72.6%
Saint Kitts & Nevis	NDC	ii	0.3	0.5	60.2%
Saint Lucia	NDC	ii	0.6	0.6	11.4%
Saint Vincent & Grenadines	NDC	ii	0.4	0.5	24.8%
Samoa	NDC	iv	0.4	0.4	-5.3%
San Marino	NDC	i	0.2	0.2	0.3%
Sao Tome & Principe	NDC	ii	0.2	0.2	-6.5%
Saudi Arabia	NDC	iv	643.0	1,050.8	63.4%
Senegal	INDC	ii	31.4	29.2	-6.9%
Serbia	NDC	i	68.1	70.8	4.0%
Seychelles	NDC	ii	0.6	0.5	-21.5%
Sierra Leone	NDC	iv	13.8	18.6	34.5%
Singapore	NDC	iii	84.5	50.5	-45.7%
Solomon Islands	NDC	ii	2.4	0.0	-98.4%
Somalia	NDC	iv	41.3	37.6	-8.8%

South Africa	NDC	ii	540.0	614.0	13.7%
South Sudan	INDC	iv	67.2	70.5	4.9%
Sri Lanka	NDC	iv	33.3	47.0	41.1%
Sudan	NDC	iv	309.0	285.6	-7.6%
Suriname	INDC	iv	7.8	9.2	17.9%
Swaziland	NDC	iv	3.3	3.6	9.7%
Switzerland	NDC	i	46.6	26.7	-42.8%
Syria	No submission	N/A	78.5	23.5	-70.0%
Tajikistan	NDC	i	10.2	21.4	109.6%
Tanzania	INDC	ii	299.0	299.7	0.2%
Thailand	NDC	ii	382.0	471.0	23.3%
Timor-Leste	NDC	iv	7.6	8.5	11.9%
Togo	NDC	ii	15.6	27.6	77.1%
Tonga	NDC	ii	0.2	0.2	-21.6%
Trinidad & Tobago	NDC	ii	91.1	87.6	-3.9%
Tunisia	NDC	iii	41.4	56.4	1.9%
Turkey	INDC	ii	415.0	929.0	123.9%
Turkmenistan	NDC	iv	106.0	135.8	28.1%
Tuvalu	NDC	i	0.0	0.0	-79.8%
Uganda	NDC	ii	72.0	60.3	-16.3%
Ukraine	NDC	i	320.0	588.6	83.9%
United Arab Emirates	NDC	iv	323.0	493.4	52.8%
United States	NDC	i	6,540.0	4,497.8	-31.2%
Uruguay	NDC	iii	30.9	47.3	104.0%
Uzbekistan	INDC	iii	235.0	637.2	54.8%
Vanuatu	NDC	iv	0.7	0.9	35.8%
Venezuela	NDC	ii	328.0	556.0	69.5%
Vietnam	NDC	ii	329.0	590.6	79.5%
Yemen	INDC	ii	45.3	37.7	-16.8%
Zambia	NDC	i	373.0	210.4	-43.6%
Zimbabwe	NDC	iv	63.9	60.0	-6.0%

NDC Categories: i) Absolute emission reduction target, ii) ‘business as usual’ reduction iii) reduction of emission intensity of GDP, and iv) projects absent of greenhouse gas emission targets. The percentage growth in emissions appear very high in some countries such as Burundi, Chile and Kenya (634%, 7469% and 230%, respectively) due to inconsistencies in the accounting of 2015 emissions in the PRIMAP dataset used and country’s own accounting in the NDC. In particular, there seem to be irregularities in the accounting for emissions associated with land use, land use change and forestry (LULUCF) in the PRIMAP database.

Chapter 4

Economic Challenge: Potential Carbon Leakage under the Paris Agreement[3]

4.1. Introduction

Climate change has become one of the most pressing environmental concerns on the public agenda. Unlike some environmental challenges that are local in nature, climate is a problem on a global scale and thus requires global co-operation for effective solutions. One issue in achieving effective mitigation is that of the 'free-rider' problem. Countries have an incentive to abstain from climate mitigation strategies in the pursuit of individual economic growth and development while benefiting from the mitigation of others. For this reason, a globally inclusive climate agreement is necessary to successfully tackle climate change.

The first multi-national agreement to combat climate change was the Kyoto Protocol, which came into effect in 1997. It required most industrialised nations to reduce their greenhouse gas emissions relative to 1990 levels. However, the overall success of the protocol at reducing global emissions has been questioned. One limitation was the exclusion of developing countries, which therefore had no restraint on growing their emissions. Indeed, emissions saw sharp increases occurred in countries such as China during the period the Kyoto Protocol was active.

One particular systemic issue that affected the Kyoto Protocol was carbon leakage. This occurs when emissions rise in one country as a result of strict climate change policies in another. Emissions are then merely transferred from one country to another through changes in trade patterns and relocation of industries. Estimates of the magnitude of carbon leakage from the Kyoto Protocol, expressed as a percentage of the emission reductions in the abating country, range from around 10% (Palstev, 2001) to as high as 130% (Babiker, 2005).

The successor to the Kyoto Protocol, the Paris Agreement was adopted in 2015. It had a clear aim to limit the increase of the global average temperature to 2°C relative to pre-industrial levels. Importantly, and unlike Kyoto, the Paris Agreement includes almost all countries, and could therefore be seen as the first truly global agreement on climate change. Here we analyse the potential effectiveness of the Paris Agreement at reducing emissions on the global scale by assessing its carbon leakage. We do this by building on a previous study (King & van den Berg,h 2019) that categorises the pledges of individual countries based on their potential ambition and effectiveness. This is accomplished through normalising the pledges to indicate the actual change in emissions relative to a recent base year, which makes them directly comparable. Next, we use

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[3] Under review at *Climatic Change*

a computable general equilibrium model of the world economy, GTAP-E, to analyse the potential leakage under several scenarios consistent with the normalised pledges. As much can be learned from the Kyoto Protocol, we will start by examining assessments of its carbon leakage.

4.2. The Kyoto Protocol

4.2.1. Background

The Kyoto Protocol was signed on 11 December 1997. It marked the first legally binding limits on greenhouse gas emissions for industrialised countries. These nations were designated as Annex I countries, and accounted for over 55% of total greenhouse gas emissions in 1990 (Breidenich et al., 1998). It was the general view that the main responsibility for tackling climate change belonged to the industrialised Annex I countries as they had through their historical development become by far the largest greenhouse gas emitters. Imposing comparable greenhouse gas emission targets for developing countries was considered as a serious risk for their economic development.

Legally binding emission targets were set for the first commitment period of 2008-2012 for the Annex I counties, covering six greenhouse gases; carbon dioxide (CO_2), methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur hexafluoride (SF_6). The commitments were based on emission targets against a base year, which was set as 1990 for most parties. In addition, it also allowed for using a number of flexibility mechanism allowing Annex I countries to meet their treaty targets by reducing emissions in other Annex I countries (known as Joint Implementation) or in developing countries (Clean Development Mechanism), while at the same time helping these countries to implement cleaner technologies and achieve a more sustainable development.

A key debate amongst the parties was whether the industrialised nations should have a uniform target, or individual, differentiated targets based upon the natural resources and consumption profiles of the countries. The parties were unable to agree a uniform target, so individual targets were set, with the average commitment at 5% below 1990 levels.

The Kyoto Protocol had several other important features. Firstly, the Protocol considered emissions and sequestration from the land use change and forestry sector (LUCF). This created some problems due to inconsistencies in accounting and whether there were net emissions in the countries' base year.

A compromise was reached with a new accounting system that rewarded countries increasing their forestry sinks by human-induced activities that began after 1990. Also, Annex I countries were able to offset some of their emission increases through 'joint implementation', which was seen as a cost-effective solution to reduce global emissions. CDM was controversial, however, as it was seen by some as a way for developed countries to avoid taking domestic action and removing cheap opportunities for developing countries to invest themselves in once being subject to limits. Finally, an enforcement mechanism was established. If a country did not comply with their targets over the first commitment period, they would have to make up the difference in the second commitment period, plus an additional 30%. They would also be suspended from making transfers under the emissions trading programme.

4.2.2. Effectiveness at reducing emissions

The Kyoto Protocol however ran into several difficulties. Firstly, although it was signed by the United States in 1998, it was never ratified by the Senate and thus never became legally binding. This was out of concern that an international climate agreement excluding developing countries would seriously harm the economy of the United States. As the United States accounted for 36% of emissions in 1990, this was a serious blow to the Kyoto Protocol. In 2011, Canada, Japan and Russia decided they would not make any further Kyoto targets after the first commitment period. Canada then decided to withdraw from the Protocol effective from December 2012.

Despite these issues, the remaining countries surpassed their average commitment by 2.4GtCO$_2$e per year (Shishlov et al., 2016). Nine of the 36 countries that fully participated in the commitment period failed to meet their individual targets and had to resort to flexibility mechanisms. However, this was more than made up for by the countries that overachieved their targets. This however, principally came from the countries of the former Soviet Union. Due to the rapid collapse of their economies, emissions fell dramatically compared to their base year, which was generally 1990. However, even ignoring this effect (estimated at 2.2GtCO$_2$e per year), the targets still slightly overachieved. However, this would not have been realised if the United States and Canada had been included in the first commitment period.

The effect on emissions at the global scale is a little more complicated. From 1998, just after the Kyoto Protocol was signed, to 2015, global emissions rose 30% from 38.4 GtCO$_2$e to 49.8 GtCO$_2$e, according to data from the PRIMAP database (Gütschow et al., 2018). However, these emission increases were not evenly distributed across countries. The Annex I countries reduced their emissions by 6%, while the non-Annex I countries saw a 61% increase in emissions, negating the small reduction in Annex I countries and leading to the overall rising trend in global emissions. This shows that the Kyoto Protocol was ineffective at reducing emissions at the global scale. One factor involved in this trend of emissions rising in non-Annex I countries while falling in Annex I countries is carbon leakage.

4.2.3. Carbon leakage under Kyoto

Carbon leakage denotes the phenomenon of emissions rising in countries with relatively weak climate policies as a result of stronger climate policies in other countries. The mechanisms through which this operates is changes in patterns in the trade of products and relocation of energy- or carbon-intensive industries to other countries. The relative stringency of climate policies among countries is therefore important. In the context of the Kyoto Protocol, there was a more extreme case of policy differences between a group of abating countries (Annex I) and non-abating countries, with effectively absence of climate policy in the latter. Carbon leakage under the Kyoto Protocol therefore mainly took the form of a rise in emissions in non-Annex I countries resulting from the emission reductions in Annex I countries.

A common measurement of carbon leakage is the ratio of the increase in emissions in non-abating countries to the reduced emissions in abating countries. A hypothetical carbon leakage rate of 100% would then imply that all emission reductions leak away causing the climate policy in the abating country to be completely ineffective at reducing emissions globally. According to Görlach (2018), carbon leakage occurs through three main channels:

(i) Operational leakage

Operational leakage occurs when climate policies increase the costs of production in carbon-intensive industries in a country. This results in a decline in exports of the good from the country, and in increase in imports from countries with less strict climate policies (Alexeeva-Talebi et al., 2012; Dröge et al., 2009; Marcu et al., 2013). There is in effect a change in the global trade flows of the carbon-intensive goods from countries with strict to less strict climate policies.

(ii) Investment leakage

Investment leakage is more a longer-term effect than production leakage. Companies will start up production plants or invest more in countries with less stringent climate change policies as it is relatively more attractive to do so (Marcu et al., 2013). In effect, over time there will a relocation or 'capital flight' of carbon-intensive industries to the countries with less stringent climate policies. How quickly this will happen will depend on the particular industry and the size of the investment required to move the infrastructure to a different country.

(iii) Leakage through resource markets

The third type of carbon leakage occurs due to interaction of resource markets, particularly fossil fuel markets. If one country with a large enough share of the fossil fuel market introduces policies that reduce demand for fossil fuels, the result will be a reduction in the price of those fossil fuels. This will provide an incentive for other countries to consume more of the fossil fuels due to the lower costs. The effect of this can be substantial (Böhringer et al., 2010), and involves a net increase in emissions, this is known as the Green Paradox (Sinn, 2012).

One method of assessing the extent of carbon leakage under a climate change policy is through a computable general equilibrium (CGE) model, which use economic data to estimate how an economy might react to policy changes. This typically divides the global economy into different regions and sectors and runs policy scenarios to see the effect on the economic sectors in each region and change in trade flows between them. Models of this type are particularly useful for assessing carbon leakage, as their central mechanisms evolve around relative costs and prices and how these are affected by national climate policies.

Peters et al. (2011) used the Global Trade Analysis Project (GTAP) database CGE model to analyse emission transfers via international trade from 1990 to 2008. They found that emissions from the production of traded goods increased from 20% of global emissions in 1990 to 26% illustrating the importance in monitoring emission transfers in international trade. Other studies have attempted to directly assess the leakage rate under the Kyoto Protocol using a similar approach. Paltsev (2001) calculated this rate to be between 5% and 15%, depending upon assumptions in the GTAP-EG model, specifically the fossil fuel supply elasticity and the Armington elasticity of substitution between domestic and imported goods. Other models have produced similar ranges: 8% to 20% (Bernstein et al., 1999) and 2% to 21% (Burniaux & Martins, 2000). However, another study found much higher levels of leakage, up to 130%, when modelling relocation effects (Babiker, 2005). These studies suggest that carbon leakage was a non-trivial issue that significantly reduced the effectiveness of the Kyoto Protocol.

4.3. The Paris Agreement

4.3.1. Background and comparison with the Kyoto Protocol

On 12 December 2015, during the 21st Conference of Parties (COP21), the Paris Agreement was adopted by 196 states parties within the United Nations Framework Convention on Climate Change (UNFCCC). It became fully effective on 4 November 2016 after it was ratified by countries accounting for over 55% of global emissions. The primary goal of the agreement is "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCCC, 2015). This was arguably the first truly global agreement on mitigating climate change, as unlike Kyoto there is no distinction made between developed and developing countries, and covers almost all global emissions. There is, however, still a principle of "common but differentiated responsibility and respective capabilities", which may put greater expectations on developed countries to reduce their emissions. As of May 2020, eight parties had still not ratified the agreement, including the significant emitters Iran and Turkey.

The Paris Agreement takes a 'bottom-up approach' to reducing emissions, through countries making voluntary commitments in the form of Nationally Determined Contributions (NDCs). This contrasts with the Kyoto Protocol's 'top-down approach' of setting emission reduction targets, such as the target of cutting emissions 5% below 1990 levels during the first commitment period. The NDCs are subject to regular review and updated every five years, with the first round of NDCs typically setting emission targets until 2030. Unlike Kyoto, the commitments are not legally binding and there is no direct enforcement mechanism. The Agreement instead relies on a system of 'pledge and review' to hold countries to accountable for their promises (Jacquet & Jamieson, 2016). The initial round of NDC commitments has already come under strong criticism for being insufficient at meeting the overall goals of the Agreement, with studies suggesting they would result in a temperature rise of 2.6-3.1°C (Rogelj et al., 2016; Höhne et al., 2017; Schleussner et al., 2016). There has also been criticism that countries may fail to meet the pledges they have made, with all major industrialised currently falling short of their targets (Victor et al., 2017). On top of this, the potential withdrawal of the US from the Agreement could further undermine its efficacy (Zhang et al., 2017).

4.3.2. Potential for carbon leakage

The potential for carbon leakage in the Kyoto Protocol was clear. Countries were divided into abating and non-abating countries, making emission transfers across the borders very likely. In the Paris Agreement process, 165 Intended Nationally Determined Contributions (INDCs) were submitted, covering 192 countries as the EU submitted a joint INDC for its 28 member countries. Many countries submitted both unconditional and conditional commitments. The conditional pledges are more ambitious than the unconditional pledges, but dependent on certain external stipulations, such as the access to international finance. The majority of the INDCs have now been converted to NDCs by the countries formally joining the Paris Agreement by submitting an instrument of ratification, acceptance, approval or accession. The INDCs cover 96.4% of global emissions (World Resources Institute, 2019), and include major emitters such as China and India, which did not have emission targets in the Kyoto Protocol. Being inclusive of almost all nations, carbon leakage conceivably seems less of an issue under Paris than with Kyoto. However, there are several challenges which give high potential for carbon leakage under Paris.

Firstly, absent of any direct enforcement mechanism, countries are not legally bound to meet the emission targets set out in their NDCs. Other goals, such as economic growth and development, may have greater priority for some countries than reducing carbon emissions. Through the carbon leakage mechanisms, there may be opportunities for economic growth in carbon-intensive production in some, particularly developing countries if others do successfully reduce emissions. Some countries may go for carbon-intensive growth regardless of their promises, as there is very little in the way of punishment for not meeting targets. If the US do go through with the intention of withdrawing from the Paris Agreement in 2020, countries may be more reluctant to meet their targets at the detriment of economic growth opportunities. The US itself could likely become a country where the carbon leakage flows to.

Secondly, the NDC targets presented by countries varied considerably, with some countries producing much weaker targets than others. In an earlier study we grouped the pledges into four categories (King & van den Bergh, 2019):

i) Absolute emission reduction targets relative to a historic base year,

ii) 'Business as usual' (BAU) reduction targets,

iii) Emission intensity per GDP reductions,

iv) Projects absent of GHG-emission targets

Of these, category ii, iii and iv pledges are more susceptible to carbon leakage. Category iii pledges include the big emitters China and India, and in total cover 32% of global emissions, are also susceptible to leakage. Although they may meet their target of reducing the intensity per GDP of emissions, having no fixed target on emissions may result in GDP growth at a greater rate than projected as carbon leakage opportunities arise. The 45 countries submitting category iv pledges, covering 7% of global emissions in 2015, are also highly susceptible to leakage. These countries did not present an explicit emission target, but instead listed intentions for various projects such as investment in renewable electricity. As they are not stating an emission target, there is little to prevent these countries from increasing emissions at any rate, as they are not easily held accountable under the system of pledge and review.

Lastly, only 28% of all unconditional NDC pledges, resulted in emission reductions by 2030 relative to 2015 levels. Many developing countries submitted BAU reduction targets, where some level of abatement takes place compared to no policies. However, these pledges this still often convert into substantial growth in emissions by 2030. We can therefore assume that the countries projecting increases in emissions by 2030 will have far weaker climate policies than those aiming at absolute reductions in their emissions. The marginal abatement costs between countries also vary by two orders of magnitude (Aldy et al., 2016). This is significant as the relative strength of policies is an important factor in the carbon leakage mechanisms. It is therefore likely that the countries projecting emission growth will overshoot their targets through the carbon leakage mechanisms, and they were unlikely to have been factored in when producing their pledges.

Carbon leakage therefore has the potential to be a significant concern in the Paris Agreement, despite overcoming a key weakness of the Kyoto Protocol by including almost all nations, due to the relative differences in policy strength amongst countries and the lack of enforcement mechanisms. Hereon we quantitatively analyse the potential for the Paris Agreement to produce carbon leakage under various scenarios using the GTAP-E general equilibrium model.

4.4. Methodology

4.4.1 Scenarios

To create a range of scenarios to analyse the potential for carbon leakage we take the previous study by King & van den Bergh (2019), which normalised the NDCs for all countries to show expected emission changes by 2030, as a starting point. It calculated countries' emission changes for both the conditional and unconditional pledges relative to 2015 emission levels. For the purpose of this analysis, we assume that all the conditions will be met, and thus use the expected emission changes of the conditional pledges. We re-perform the normalisation to change the base year to 2014, to be consistent with the data year we use for our analysis in the GTAP-E model. The results are supplied in Appendix 4.1. Countries can be divided into two groups; a 'leakage from' region that is using serious climate policy to reduce emissions, and a 'leakage to' region, with weaker policies, in which will see a rise in emissions as a result of those policies in the first group. To account for how much the Paris Agreement reduces leakage potential through being a collective agreement, we also include two scenarios of regions implementing climate policy in isolation to the rest of the World. Using this framework, we have developed the following six scenarios:

Scenario 1: Net abating countries (NAB)

In the previous study by King & van den Bergh (2019), 74 of the 168 conditional pledges result in net emission reductions by 2030. The remaining countries have climate change policies that are inadequate at producing a net abatement of emissions. These countries are therefore more likely to be susceptible to inwards emission transfers as they are already willing to accept growth in emissions. We therefore divide the countries into two regions: abating and non-abating countries. Both the abating and non-abating regions comprise of a mixture of the four different NDC categories, so the NDC category itself is not directly relevant in defining the regions under this scenario. The 'leakage from' region for this scenario instead consists of the net abaters in our normalisation provided in Appendix 4.1. This produces a 'leakage from' region that accounts for 37.7% of global emission in 2014.

Scenario 2: Net abating countries minus the US (NAB-US)

In this scenario we explore the potential impact on carbon leakage rates of the US withdrawing from the Paris Agreement. The US therefore moves from the abating to the non-abating region while all other countries remain the same. This reduces the share of global 2014 emissions for the 'leakage from' region to 24.2%.

Scenario 3: Category i abating countries (CIAB)

In this scenario we take a stricter variation of the NAB by assuming that only category i countries in King & van den Bergh (2019), targeting a net reduction in emissions by 2030, will be in the 'leakage from' group. All category ii, iii and iv countries, and those category i countries such as Russia which are not targeting a net reduction in emissions, will therefore be susceptible to receiving carbon leakage. In effect, the 'leakage from group' is very similar to the Kyoto Annex i countries, with the notable inclusion of Brazil and Kazakhstan, but exclusion of Russia and Ukraine. This adapted category i accounted for 31.6% of global emissions in 2014.

Scenario 4: Category i abating countries minus the US (CIAB-US)

As with scenarios NAB-US, in this scenario we explore the impact of the US withdrawal from the Paris Agreement. The US is moved to the 'leakage to' category in this scenario to explore the impact of the US withdrawing from the Paris Agreement. This reduces the emissions in the 'leakage from' group to 18% of global emissions in 2014.

Scenario 5: EU only abating (EUAB)

The previous scenarios look to analyse the effect of the Paris Agreement as a global, cohesive agreement. To assess the benefit of this collective action, we also want to analyse the carbon leakage effects of regions acting independently. This could also be interpreted as a situation where these regions have much more stringent policy than the rest of the World. Given its high ambition level and size, in this scenario we consider the case of only the European Union reducing emissions, which accounted for 7.9% of emissions in 2014.

Scenario 6: Japan only abating (JAPAB)

Here, we take an even more extreme example of the EUAB scenario above, with a single country attempting climate policy independently. We have chosen Japan here as the single abater, due to its significant 2.6% share of 2014 global emissions, and its high level of ambition in their NDC pledge.

4.4.2 Calculation of abatement rates

The level of abatement of carbon emissions for each scenario is calculated by comparing the NDC pledges to a base year of 2014, following the same methodology in King & van den Bergh (2019). The base year of 2014 is used to be consistent with the most recent year of data in the GTAP version 10 database. This abatement rate is derived using a separate method for each of the four NDC categories. The dataset used for historical greenhouse gas emissions is The PRIMAP database (Gütschow et al., 2018). Category i abatement levels are calculated by projecting the emissions to 2030, and re-normalising the percentage reduction to a consistent base year of 2014. Similarly, for category ii pledges we take the projected 2030 emissions, calculated from the reduction against the 2030 BAU submissions. We then compute the percentage change relative to actual 2014 emission levels. Category iii abatement rates are combined with OECD (2018) long-term GDP forecasts to calculate the expected 2030 emissions. Category iv 2030 emissions are assessed by extrapolating the trends of emissions between 2005 and 2014. This involves applying an exponential smoothing method, as for this category no particular level of 2014 emissions were defined in their NDCs. Libya, Nicaragua and Syria did not submit NDCs, so the same methodology as category iv is applied to the these countries.

The anticipated abatement rates, or increase in emissions, relative to 2014 levels for all countries are detailed in Appendix 4.1. As previously mentioned, we assume that all conditions of the NDCs are fulfilled and thus use the conditional NDC targets rather than the unconditional targets. In the cases that Land Use Land Use Change and Forestry (LULUCF) were excluded from the NDCs, the projected emissions associated with these were added using an exponential smoothing method

To run the analysis through the GTAP software, we need to aggregate individual countries into broader regions. In order to use the GTAP model to assess the carbon leakage it requires as an input the specific abatement rate for the 'leakage from' region. To calculate this, we divide a weighted average of the 2030 NDC emissions by a weighted average of the 2014 emissions. This is illustrated in Equation 4.1:

$$A_r = \frac{\sum_{i=1}^{n} w_i^{NDC} s_i^{NDC}}{\sum_{i=1}^{n} w_i^{t} s_i^{t}} \tag{4.1}$$

Where A_r = abatement rate of region *r,* w_i = emissions of country *i, and* s_i = share of emissions of country *i* in region *r* under the projections *NDC* (King and van den Bergh 2019) and at base year *t* (2014 in our analysis).

Using these abatement rates for the 'leakage from' regions as an input, the GTAP-E model will calculate the emissions for the 'leakage to' regions. In other words, these emission levels are endogenous variables in the model. How this translates into carbon leakage is discussed in the next section.

Table 4.1 presents the calculated overall abatement rates for the 'leakage from' region under the four scenarios. The abatement rates range from 13.6% in scenario EUAB to 25.4% in scenario JAPAB. The differences in rates between scenarios are due to there being different combinations of countries forming the 'leakage from' region. The abatement rates are significantly lower in scenarios NAB-US and CIAB-US, compared to scenarios NAB and CIAB, as the US has a high abatement rate and a large weight in the share of emissions. The rate for the CIAB scenario is smaller than that for NAB, as it is a more selective set of countries, namely those that are amongst the most ambitious ones in terms of percentage reduction in emissions.

Table 4.1 | Abatement rates for the four scenarios

Scenario	2014 emissions ($GTCO_2e$)	% global 2014 emissions	Conditional NDC 2030 emissions ($GTCO_2e$)	Potential abatement by 2030 ($GTCO_2e$)	Abatement rate
	'Leakage from' region				
NAB	18.2	37.7%	14.0	4.2	22.8%
NAB-US	11.5	24.2%	9.6	2.0	17.0%
CIAB	15.6	31.6%	11.9	3.7	23.9%
CIAB-US	8.9	18.0%	7.4	1.5	17.3%
EUAB	3.9	7.9%	3.4	0.5	13.6%
JAPAB	1.4	2.6%	1.0	0.3	25.4%

4.4.3. GTAP-E Model

Computable general equilibrium (CGE) models are a popular tool for analysing national climate change mitigation policy in the context of global social-economic and policy issues (Babatunde et al., 2017). The reason is that they are well suited to analyse the impact of policy-induced price changes on emissions. CGE models take real world data to build a multi-sector model of the global economy in a state of general equilibrium. A policy shock, such as a carbon tax or emissions quota, is then applied to one of more of the regions, which generates a new equilibrium state based on the global impact of that shock by adjusting prices and quantities. In the context of this study, a CGE model is a useful tool as it can model changes in supply of and demand for commodities, both domestically and through trade, from the policies or policy targets at national levels. Hence, we are able to analyse the effect on emissions of the 'leakage to' region as a result of the climate policy shock in the abating or 'leakage from' region.

The four scenarios outlined in Section 4.1 are analysed using the GTAP-E CGE model, which is a multi-region, multi-sector model of the global economy using the latest GTAP 10 database depicting the global economy in 2014. The GTAP-E model is a modified version of the standard GTAP model, to incorporate inter-fuel and energy-capital substitution in production, carbon emissions from the combustion of fossil fuels, carbon taxation and emissions trading (Truong & Burniaux, 2007). This provides a more complete representation of energy-environmental-economy linkages than the standard GTAP model. Although the GTAP-E model allows for emission trading between countries, we decided to deactivate this mechanism, as the Paris Agreement does not specify any emission trading instruments in its current form. The EU Emission Trading Scheme is the only active multi-national greenhouse gas emission trading system, but since the EU is treated as a single unit in our analysis we are unable to model intra-region trading[4].

The GTAP-E model modifies the standard GTAP production structure to incorporate a capital-energy composite, which comprises 'electricity' and 'non-electricity' groups. The 'non-electricity' group covers Coal, Gas, Oil and Petroleum Products. On the consumption side, the GTAP model assumes a separation of government and private consumption. For both types of consumption, energy commodities are separated from non-energy commodities, to allow for different substitution elasticities within, and between, the two sub-groups. Goods are aggregated into eight sectors: agriculture, coal, oil, gas, oil products, electricity, energy intensive industries and other industry and services. Appendix 4.2 provides the disaggregation of these sectors.

The model is adapted to group countries into two regions; namely the 'leakage from' and 'leakage to' region. The composition of countries in each region for the four scenarios was already explained in Section 4.1. To analyse the scenarios, the model is run with a percentage reduction shock to CO_2 emissions equivalent to the abatement in Table 4.1.

4.4.4. Regions

The GTAP 10 database which is used in the analysis divides the data into 141 regions. Of these, 121 are individual countries comprising 98% of global GDP, with the other countries falling into a further 20 aggregate regions. For this analysis we use the eight countries/regions with 2014 emissions above $1GtCO_2e$ (China, USA, EU, India, Indonesia, Russia, Brazil and Japan) as individual regions, with two more regions aggregating the remaining 'leakage from' and 'leakage to' countries. Table 4.2 shows the regional aggregation within each of the four scenarios.

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[4] As of 1 January 2020 the Emission Trading Scheme also incudes Switzerland, but this is not included in the analysis as Switzerland is not treated as an individual region. The impact would anyway not be large enough to significantly influence the results.

Table 4.2 | Regional aggregation of six scenarios

Scenario	'Leakage from' regions	'Leakage to' regions
NAB	USA, EU, Brazil, Japan, 'Other Abaters'	China, India, Indonesia, Russia, 'Other Non-Abaters'
NAB-US	EU, Brazil, Japan, 'Other Abaters'	China, USA, India, Indonesia, Russia, 'Other Non-Abaters'
CIAB	USA, EU, Brazil, Japan, 'Other Category i Abaters'	China, India, Indonesia, Russia, 'Other non-Abaters'
CIAB-US	EU, Brazil, Japan, 'Other Category i Abaters'	China, USA, India, Indonesia, Russia, 'Other Non-Abaters'
EUAB	EU	China, USA, India, Indonesia, Russia, Brazil, Japan, 'Other Non-Abaters'
JAPAB	Japan	China, USA, EU, India, Indonesia, Russia, Brazil 'Other non-Abaters'

One complication when making this aggregation is that some of the 20 aggregate regions in the GTAP 10 database contain countries that split across the 'leakage from' and 'leakage to' regions for the purposes of our analysis. For example, the "South Central Africa" region comprises of Angola (in the 'abater' category) and Democratic Republic of the Congo (in the 'non-abater' category). In these cases, we calculate the total 2014 emissions which fall into each category, and then allocate the aggregate region to which category has the greater emissions. For example, the "South Central Africa" region is allocated to our "Other Non-Abaters" region as the emissions of Democratic Republic of Congo (241 $MtCO_2e$) were greater than Angola's (52 $MtCO_2e$). Although this reallocation of countries is not desirable, it is a way of working around the limitations of the database. This should have an insignificant impact on the results since the countries reallocated in scenario NAB, for example, amount to less than 1% of 2014 global emissions. The breakdown of all regional allocations for the NAB and CIAB scenarios is detailed in Appendices 4.3 and 4.4.

4.4.5. Scenario shocks

Using equation 1 in Section 4.2, we first calculate the abatement rates for the regions in the different scenarios. This is a weighted average of the abatement rates for countries as shown in Appendix 4.1. We then take these abatement rates for the 'leakage from' regions and run them as a scenario shock through the GTAP-E model for the six scenarios, as specified in Table 4.3. The GTAP-E model then generates a new equilibrium of the world economy including energy substitution effects. Each of the abating regions will have an individual carbon price corresponding to the level of abatement they are trying to achieve. Along with this, the GTAP model generates the CO_2 emissions for the 'leakage to' regions.

Table 4.3 | Scenario shocks in GTAP

Region	**% reduction in emissions from 2014**					
	NAB	NAB-US	CIAB	CIAB-US	EUAB	JAPAB
US	32.8	0	32.8	0	0	0
EU	13.6	13.6	13.6	13.6	13.6	0
Brazil	8.3	8.3	8.3	8.3	0	0
Japan	25.4	25.4	25.4	25.4	0	25.4
Other abaters	19.9	19.9	24.2	24.2	N/A	N/A
China	0	0	0	0	0	0
India	0	0	0	0	0	0
Russia	0	0	0	0	0	0
Indonesia	0	0	0	0	0	0
Other non-abaters	0	0	0	0	0	0

4.4.6. Sensitivity analysis

General equilibrium models are imperfect approximations of the global economy, among others, as the results are dependent on the parameters underlying the models. It is therefore important to perform a sensitivity analysis around key parameters to see how my they influence the results. Paltsev (2001) found that the Armington elasticity, which specifies the degree of substitution in demand between countries, was an important factor in determining the level of leakage from the Kyoto Protocol. Leakage rates ranged between 6.9% and 15.4% depending on the Armington elasticities used. The Armington elasticity is a key parameter in trade economics analysis, however its size remains an area of much debate (Feenstra et al., 2018, McDaniel et al., 2003).

There are also other elasticities in the GTAP-E which are likely to significantly influence the results. Appendix 4.5, taken from Burniaux & Troung (2002), shows the GTAP-E Production function and Capital-Energy composite structure, which is what differentiates it from the standard GTAP model. There are four important elasticities of substitution in the structure; between capital and energy, between electricity and non-electricity energy, between coal and non-coal energy, and between gas, oil and petroleum products. In view of this, we perform a sensitivity analysis of the results by adjusting both elasticities of substitution and the Armington elasticities to establish a range of leakage rates. This produces three sets of results with default, low and high GTAP-E parameter values; involving reducing the default parameters by 50% and increasing them by 100%. Full details about the parameter values used for distinct sectors are available in Appendix 4.6.

4.5. Results

The model output using default parameters for scenarios NAB and NAB-US is provided in Appendix 4.7, for scenarios CIAB and CIAB-US in Appendix 4.8, and for scenarios EUAB and JAPAB in Appendix 4.9. From these we have been able to calculate the carbon leakage rate, which is the total emission increase in the 'leakage to' regions divided by the total emission reduction in the 'leakage from' regions. These are shown in Figure 4.1. It should be noted that the emission increases given in Appendices 4.7, 4.8 and 4.9 do not represent the total expected increase in emissions as a result of the NDC pledges, but merely the potential carbon leakage effect. These increases are in addition to any increases in emissions already expected from the NDC, and hence would provide an additional challenge to staying within the 2°C above those commonly identified (Rogelj et al., 2016).

In all our scenarios, carbon leakage effects are observed, and follow patterns that we might expect. Scenarios EUAB and JAPAB, where we are analysing isolated climate policy, have high leakage rates of 13.6% and 17.0% respectively. The higher leakage rate of the JAPAB scenario is expected as it is one country in isolation rather than a region of countries as with the EU. We see a much lower rate of leakage with the co-ordinated Paris Agreement scenarios of

NAB and CIAB, 3.8% and 3.1% respectively. These levels are comparable to the lower range of values analysed in previous studies of the Kyoto Protocol. The lower leakage rate of the CIAB scenario is perhaps counter-intuitive given the smaller number of countries in the 'leakage to' region compared to NAB, but may reflect the differences in geographic location and economic development between the scenarios. However, the leakage rates between CIAB and NAB are broadly similar. The main difference between the two scenarios concerns the less developed countries that are planning emission reductions but are instead allocated to the 'leakage to' region. This suggests that the more developed, primarily Annex I countries, are still the most influential when it comes to potential for leakage.

However, we see quite a dramatic effect on leakage rates as a result of the US withdrawal from its Paris Agreement obligations. In these scenarios the rate of leakage roughly doubles; to 6.61% in Scenario NAB-US and 7.62% in Scenario CIA-US. This clearly illustrates the importance that a major player in the global economy and source of greenhouse gas emissions, such as the US, can have on the effectiveness of climate policy in other countries.

Table 4.4 shows the results of the sensitivity analysis for the rates of climate leakage. It indicates that the rates of leakage are very sensitive to changes in the Armington and substitution elasticities. The rates of leakage roughly half using the "low leakage" parameters and roughly double using the "high leakage" parameters. The expected rate of leakage most likely falls within this range generated. However, as the magnitude of these elasticity parameters is debatable, there is quite a degree of uncertainty as to the extent of leakage we may see in the real-life implementation of the Paris Agreement.

Table 4.4: Sensitivity analysis results

Scenario	**Leakage rates**		
	Low parameter values	Default parameter values	High parameter values
NAB	1.4%	3.8%	8.7%
NAB-US	2.9%	6.7%	14.7%
CIAB	1.2%	3.1%	7.6%
CIAB-US	3.5%	7.6%	16.0%
EUAB	5.4%	13.3%	25.7%
JAPAB	8.1%	16.1%	31.3%

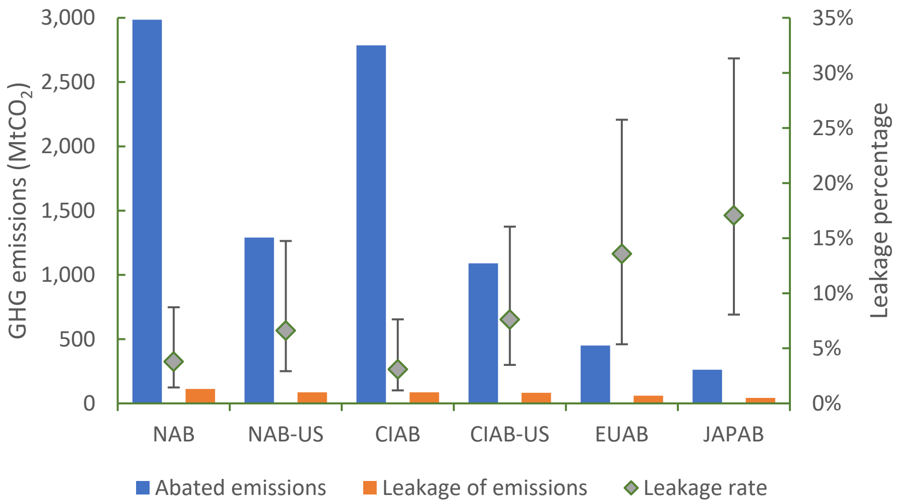


Figure 4.1. | Scenario leakage rates. The range on the leakage rate values shows the distribution of results from the sensitivity analysis. The bars with leakage of emissions pertain to default parameters.

4.6. Discussion

Considering the very globalised economy that has developed over the past few decades, a change in domestic policy can have far-reaching effects across the global economy. Exports as a percentage of global GDP have risen from 23% in 1997, when the Kyoto Protocol came into effect, to 30% in 2018 (World Bank, 2020). This suggests that carbon leakage could be an even greater problem under Paris, as there is clearly a lot of potential for trade flows to shift and companies to relocate to countries that are more competitive due to less stringent climate policy. Table 4.5 illustrates how these two effects appear as a result of our analysis of scenario NAB.

We generally see trade moving from the abating countries to the non-abating, particularly for the US, with a $6bn reduction in their trade balance. However, Russia and India have a negative change in their trade balances due to reduced exports of fossil fuels. There is also a significant relocation of energy-intensive industry such as metal and chemical manufacture (explained fully in Appendix 4.2), from the abating to non-abating countries. For example, Japan's output from these industries reduces by 8.3% while Russia's increase by 4.6%. There is also a relocation of other industries and services, but at much lower rate than the energy-intensive industry.

Table 4.5 | Change in trade, industry output and carbon prices for scenario NAB

Region	**Change in trade balance** (million USD)	**% change in industry output** Energy-intensive industry	Other industry and services	**Nominal carbon price** (USD per tonne of CO_2)
US	-5985.7	-0.6	-0.22	60.2
EU	405.6	-1.2	-0.24	52.5
Brazil	-484.5	-0.80	-0.19	41.5
Japan	-163.8	-8.32	-0.86	141.8
Other Abaters	680.1	-1.77	0.07	45.3
China	4325.9	0.69	-0.05	0
India	-813.9	1.50	0.06	0
Russia	-975.0	4.60	0.11	0
Indonesia	127.6	1.93	0.19	0
Other Non-Abaters	2883.6	2.88	0.17	0

Our analysis demonstrates that there is potential for significant carbon leakage effects, in line with the rates produced from studies on the Kyoto Protocol. This highlights several failures of the Paris Agreement that could likely lead it to be even less effective than envisioned. Firstly, we see the problem arising from a lack of enforcement mechanisms. Only six of the G20 members (den Elzen et al., 2019) are currently on track to meet their NDC pledge, and will face little in the way of repercussion if they fail to do so. Even if all countries do successfully implement the required policies to meet their goals, our analysis suggests that some countries will overshoot their goals and between 1.4% and 16.0% of abatement could be lost to leakage.

The scenarios we ran where the US withdrew from the Paris Agreement demonstrate the vulnerability of current framework. Under these scenarios, the rate of leakage roughly doubled as the US took advantage of the economic opportunities arising from policies in the abating countries. The non-compliance of such a significant party as the US could also cause other countries to relax their commitment to their NDC targets, particularly if they see the US outcompeting them economically as a result of the carbon policies.

Another way of looking at the challenge of carbon leakage is by examining the nominal carbon price produced by the model simulation in GTAP, which are shown in Table 4.5 for scenario NAB. These represent nominal carbon tax rates that the model computes as being equivalent to the emission reductions we inserted as a shock. There are notable differences between regions, ranging from \$41.5 per tonne of CO_2 in Brazil to \$141.8 in Japan, with the non-abating countries having zero carbon price. This is consistent with patterns found by other studies (Aldy et al., 2016; Fujimori et al., 2016). As with any tax, a difference between countries will create economic opportunities in the lower tax regime and make their goods more internationally competitive. This highlights another failure of the Paris Agreement. Although it was able to get almost all countries onboard, it failed to get them to move towards a global carbon price, i.e. consistent among all countries. This would effectively limit carbon leakage effects and related systemic issues, such as carbon rebound and the Green Paradox, which undercut policy effectiveness (Baranzini et al., 2017).

4.7. Conclusions

The Paris Agreement was undoubtedly a step in the right direction regarding global efforts to limit the extent of climate change. It improved on the Kyoto Protocol by getting almost all nations into an agreement on reducing or curbing emissions. However, it has some inherit weaknesses which ultimately challenge its effectiveness. Other studies have already shown that current pledges are insufficient to stay within the 2°C target, and need a significant increase in future ambition to achieve this. Asymmetries have been created through the freedom given to countries to design pledges in the format and to the level of their choosing. On top of this there are no enforcement mechanisms to make countries stick to their pledges. And arguably the most important deficiency is that the Paris agreement was unable to coordinate policies.

To analyse the degree to which not having fully co-ordinated policies could produce carbon leakage in the Paris Agreement, we used the GTAP-E general equilibrium model to assess the impact of climate policy on the global economy. Six scenarios were analysed: two baseline scenarios of regions implementing policy in isolation (JAPAB and EUAB), two scenarios representing collective but unharmonized Paris Agreement policies (NAB and CIAB), and two further scenarios showing the impact of the US withdrawal from the agreement (NAB-US and CIAB-US). A sensitivity analysis was performed on key parameters to produce a range of potential leakage rates for each scenario.

The results of our analysis were very sensitive to the adjustments in parameters, creating a wide range of results for the rate of leakage. Our baseline scenarios of regions implementing policy in isolation produced high levels of leakage. For the JAPAB scenario the leakage was between 8.1% to 31.3% (16.1% with default parameters). The NAB and CIAB scenarios produced significantly lower levels of leakage between 1.4% and 8.7% (respectively 3.8% and 3.1% with default parameters), showing the benefit of some degree of global policy co-ordination. However, leakage still remains a potential issue, and if the US withdraws from the agreement, this would roughly double its rate to between 2.9% and 16.0% depending on parameters used. This would be a doubly-bad scenario as we would suffer from both missing out on the planned emission reductions of the US, and increased levels of leakage.

Our conclusions support a call to revisit aspects of the Paris Agreement to produce a more homogenous treaty with stronger policy coordination and enforcement, notably through a global carbon price, if we want to increase the chance of controlling climate change. Having a globally co-ordinated climate policy rather than mere national targets has the potential to significantly reduce rates of carbon leakage.

Appendix 4.1. Projections to 2030 for all countries

Country	NDC category	2014 emissions ($MTCO_2e$)	2030 conditional emissions ($MTCO_2e$)	Projected % change from 2014 to 2030
Afghanistan	B	35.4	40.2	13.5%
Albania	B	8.0	8.7	8.6%
Algeria	D	200	253	26.4%
Andorra	B	0.5	0.4	-18.5%
Angola	B	184.0	124.7	-32.2%
Antigua & Barbuda	D	1	1	-1.3%
Argentina	B	457.0	398.1	-12.9%
Armenia	B	9.9	6.2	-36.9%
Australia	A	486.0	443.6	-8.7%
Azerbaijan	A	50.6	53.5	5.7%
Bahamas, The	D	3	4	29.2%
Bahrain	D	34	51	50.7%
Bangladesh	B	180.0	238.8	32.7%
Barbados	A	1.7	1.5	-12.6%
Belarus	A	94.3	100.2	6.2%
Belize	D	3	3	7.1%
Benin	B	24.3	30.4	25.0%
Bhutan	B	-1.4	-1.3	N/A
Bolivia	D	171	210	22.8%
Bosnia & Herzegovina	B	31.9	32.5	1.8%
Botswana	A	41.9	45.3	8.2%
Brazil	A	1360.0	1301.4	-4.3%
Brunei	D	16	17	5.5%
Burkina Faso	B	38.4	82.0	113.5%
Burundi	B	7.8	46.4	498.3%
Cambodia	B	57.3	27.9	-51.4%
Cameroon	B	139.0	175.8	26.5%
Canada	A	790.0	629.4	-20.3%
Cape Verde	D	1	0	-23.0%
Central African Republic	B	44.5	68.4	53.6%
Chad	B	53.3	20.0	-62.5%
Chile	C	2	79.2	4701.1%
China	C	12000	14,493.64	20.8%
Colombia	B	210.0	232.0	10.5%
Comoros	B	0.7	0.3	-63.5%
Congo, DRC	B	214.0	321.5	50.2%

Congo, Republic	B	29.2	16.5	-43.7%
Cook Islands	A	0.1	0.0	-64.6%
Costa Rica	A	3.9	3.3	-13.8%
Cote d'Ivoire	B	28.6	30.2	5.6%
Cuba	D	35	36	2.0%
Djibouti	B	1.6	1.8	12.5%
Dominica	A	0.3	0.2	-32.2%
Dominican Republic	A	23.8	19.2	-19.3%
Ecuador	D	95	106	11.5%
Egypt	D	309	352	13.8%
El Salvador	D	13	12	-11.5%
Equitorial Guinea	A	15.3	12.6	-17.7%
Eritrea	B	7.2	2.9	-60.1%
Ethiopia	B	126.0	142.3	13.0%
European Union (28)	A	4180.0	3525.2	-15.7%
Fiji	D	-1	-1	N/A
Gabon	B	-84.9	24.9	N/A
Gambia	D	2	3	55.1%
Georgia	B	18.2	25.6	40.6%
Ghana	B	31.5	39.2	24.5%
Grenada	A	0.3	0.1	-74.7%
Guatemala	B	35.3	42.0	19.1%
Guinea	A	35.8	33.7	-6.0%
Guinea-Bissau	D	4	5	18.4%
Guyana	D	23	36	56.0%
Haiti	B	9.8	13.7	39.4%
Honduras	B	45.6	51.2	12.2%
Iceland	A	6.6	4.5	-31.9%
India	C	2670	7,706.9	188.6%
Indonesia	B	2500.0	3027.8	21.1%
Iran	B	861.0	1237.3	43.7%
Iraq	B	190.0	422.0	122.1%
Israel	B	87.2	81.7	-6.3%
Jamaica	D	10	13	27.7%
Japan	A	1380.0	1087.9	-21.2%
Jordan	B	28.4	47.6	67.5%
Kazakhstan	A	303.0	290.9	-4.0%
Kenya	B	25.2	81.5	223.4%
Kiribati	B	0.1	0.0	-48.7%
Korea, Dem. Rep. (North)	B	89.4	110.8	23.9%

Korea, Rep. (South)	B	668.0	562.4	-15.8%
Kuwait	D	124	167	34.7%
Kyrgyzstan	B	17.7	12.1	-31.8%
Laos	D	32	23	-28.6%
Lebanon	B	26.9	29.7	10.5%
Lesotho	D	5	4	-15.9%
Liberia	B	5.0	5.5	9.3%
Libya	-	80	94	17.2%
Liechtenstein	A	0.2	0.2	-31.1%
Macedonia, FYR	B	12.6	14.9	18.3%
Madagascar	B	55.3	94.0	69.9%
Malawi	D	15	16	11.5%
Malaysia	C	186	410.5	120.7%
Maldives	B	1.2	2.2	84.8%
Mali	B	41.5	35.7	-14.1%
Marshall Islands	A	0.2	0.1	-31.5%
Mauritania	B	10.9	13.7	25.9%
Mauritius	B	7.5	5.8	-21.7%
Mexico	B	690.0	645.2	-6.5%
Micronesia	A	0.2	0.1	-43.9%
Moldova	A	12.8	10.3	-19.4%
Monaco	A	0.1	0.1	-29.7%
Mongolia	B	73.3	60.8	-17.1%
Montenegro	A	5.1	4.6	-10.1%
Morocco	B	96.0	101.6	5.8%
Morocco	D	73	110	51.2%
Myanmar	D	212	282	32.8%
Namibia	B	25.6	7.9	-69.1%
Nauru	D	0	0	84.9%
Nepal	D	44	58	33.4%
New Zealand	A	64.9	52.4	-19.2%
Nicaragua	-	16	19	17.7%
Niger	B	31.3	55.5	77.3%
Nigeria	B	428.0	510.7	19.3%
Niue	D	0	0	30.5%
Norway	A	32.9	32.0	-2.8%
Oman	B	83.3	87.1	4.5%
Pakistan	B	434.0	1065.8	145.6%
Palau	A	0.3	0.1	-68.7%
Panama	D	24	27	16.1%

Papua New Guinea	D	65	74	15.1%
Paraguay	B	181.0	293.1	61.9%
Peru	B	174.0	202.2	16.2%
Philippines	D	120	97	-19.3%
Qatar	D	143	280	96.1%
Russian Federation	A	2660.0	2802.8	5.4%
Rwanda	D	7	12	66.8%
Saint Kitts & Nevis	B	0.3	0.5	49.0%
Saint Lucia	B	0.6	0.6	11.3%
Saint Vincent & Grenadines	B	0.4	0.4	8.6%
Samoa	D	0	0	-0.2%
San Marino	A	0.2	0.2	-2.0%
Sao Tome & Principe	B	0.2	0.2	-0.6%
Saudi Arabia	D	585	942	61.0%
Senegal	B	28.8	29.8	3.5%
Serbia	A	64.7	70.1	8.3%
Seychelles	B	0.5	0.5	-3.7%
Sierra Leone	D	14	17	27.2%
Singapore	C	54	54.4	1.3%
Solomon Islands	B	2.3	0.7	-71.9%
Somalia	D	41	39	-6.7%
South Africa	B	536.0	594.3	10.9%
South Sudan	D	69	70	0.7%
Sri Lanka	D	33	43	30.5%
Sudan	D	355	292	-17.8%
Suriname	D	9	9	2.5%
Swaziland	D	3	4	10.1%
Switzerland	A	50.2	32.0	-36.3%
Syria	-	63	38	-39.1%
Tajikistan	A	9.5	18.4	93.6%
Tanzania	B	295.0	299.5	1.5%
Thailand	B	360.0	447.2	24.2%
Timor-Leste	D	7	8	10.3%
Togo	B	14.8	24.4	65.0%
Tonga	B	0.2	0.2	-9.2%
Trinidad & Tobago	B	84.1	88.5	5.2%
Tunisia	C	39	41.5	7.0%
Turkey	B	389.0	791.9	103.6%
Turkmenistan	D	93	128	37.2%

Tuvalu	A	0.0	0.0	-80.6%
Uganda	B	67.2	63.4	-5.6%
Ukraine	A	420.0	517.0	23.1%
United Arab Emirates	D	256	448	75.0%
United States	A	6500.0	5044.0	-22.4%
Uruguay	C	31	53.0	68.9%
Uzbekistan	C	212	324.9	53.3%
Vanuatu	D	1	1	37.2%
Venezuela	B	345.0	495.2	43.5%
Vietnam	B	269.0	520.8	93.6%
Yemen	B	36.7	39.7	8.2%
Zambia	A	360.0	253.8	-29.5%
Zimbabwe	D	59	61	3.2%

Percentages not calculated for Bhutan, Fiji and Gabon as 2014 emissions in the GTAP database were negative. Percentage changes for some countries such as Chile are very high due to large LULUCF adjustments in the 2014 data.

Appendix 4.2. Sector disaggregation in GTAP-E

Sector code	**Sector description**	**GTAP sectors covered**
Agriculture	Primary agriculture, forestry and fishing	Paddy rice; wheat cereal grains n.e.c*; vegetables, fruit, nuts; oil seeds; sugar cane, sugar beet; plant-based fibers; crops n.e.c.; bovine cattle, sheep and goats; animal products n.e.c.; rat milk; wool, silk-worm cocoons; forestry; Fishing
Coal	Coal mining	Coal
Oil	Crude oil	Oil
Gas	Natural gas extraction	Gas; gas manufacture, distribution
Oil_Pcts	Refined oil products	Petroleum, coal products
Electricity	Electricity	Electricity
En_Int_Ind	Energy-intensive industry	Minerals n.e.c.; chemical, rubber, plastic prod; mineral products n.e.c.; ferrous metals; metals n.e.c.
Oth_Ind_Ser	Other services and industry	Bovine cattle, sheep and goat; meat products; vegetable oils and fats; dairy products; processed rice; sugar; food products n.e.c.; beverages and tobacco products; textiles; wearing apparel; leather products; wood products; paper products, publishing; metal products; motor vehicles and parts; transport equipment n.e.c.; electronic equipment; machinery and equipment n.e.c.; manufactures n.e.c.; water; construction; trade; transport n.e.c.; water transport; air transport; communication; financial services n.e.c.; insurance; business services n.e.c.; recreational and other services; public admin. And defense, edu; ownership of dwellings

*n.e.c. abbreviation for ‘not elsewhere covered’.

Appendix 4.3. Scenario NAB

Region name	Countries
Abating countries (37.7% share of 2014 emissions)	Argentina, Armenia, Australia, Azerbaijan, Belize, Bhutan, Botswana, Brazil, Cambodia, Canada, Central African Republic*, Chad, Congo (Republic), Costa Rica, Cote d'Ivoire, Dominican Republic, El Salvador, Equatorial Guinea, European Union (28), Gabon*, Guatemala, Guinea, Iceland, Israel, Japan, Kazakhstan, Korea, Rep. (South), Kyrgyzstan, Laos, Lesotho, Liechtenstein, Mauritius, Mexico, Moldova, Mongolia, Morocco, Namibia, New Zealand, Norway, Philippines, Sao Tome & Principe, Senegal, Singapore, Sudan, Switzerland, Trinidad & Tobago, Uganda, United States, Zambia, Zimbabwe
Non-abating countries (62.3% share of 2014 emissions)	Andorra*, Angola*, Afghanistan, Albania, Algeria, Antigua & Barbuda*, Bahamas, Bahrain, Bangladesh, Barbados*, Belarus, Benin, Bolivia, Bosnia & Herzegovina, Brunei, Burkina Faso, Burundi, Cameroon, Cape Verde*, Chile, China, Colombia, Comoros*, Congo (DRC), Cook Islands*, Cuba, Dominica*, Djibouti*, Ecuador, Egypt, Eritrea*,Ethiopia, Fiji, Gambia, Georgia, Ghana, Guinea-Bissau, Grenada*, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kenya, Kiribati*, Korea (North), Kuwait, Lebanon, Liberia, Libya, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Mali*, Marshall Islands*,Mauritania, Micronesia*, Monaco*, Montenegro*, Morocco, Myanmar, Nauru, Nepal, Nicaragua, Niger, Nigeria, Niue, Oman, Pakistan, Palau*, Panama, Papua New Guinea, Paraguay, Peru, Qatar, Russian Federation, Rwanda, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & Grenadines, Samoa*, San Marino, Saudi Arabia, Serbia, Seychelles*, Sierra Leone, Solomon Islands*, Somalia*, South Africa, South Sudan, Sri Lanka, Suriname, Swaziland, Syria*, Tajikistan, Tanzania, Thailand, Timor-Leste, Tonga*, Togo, Tunisia, Turkey, Tuvalu*, Turkmenistan, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen*

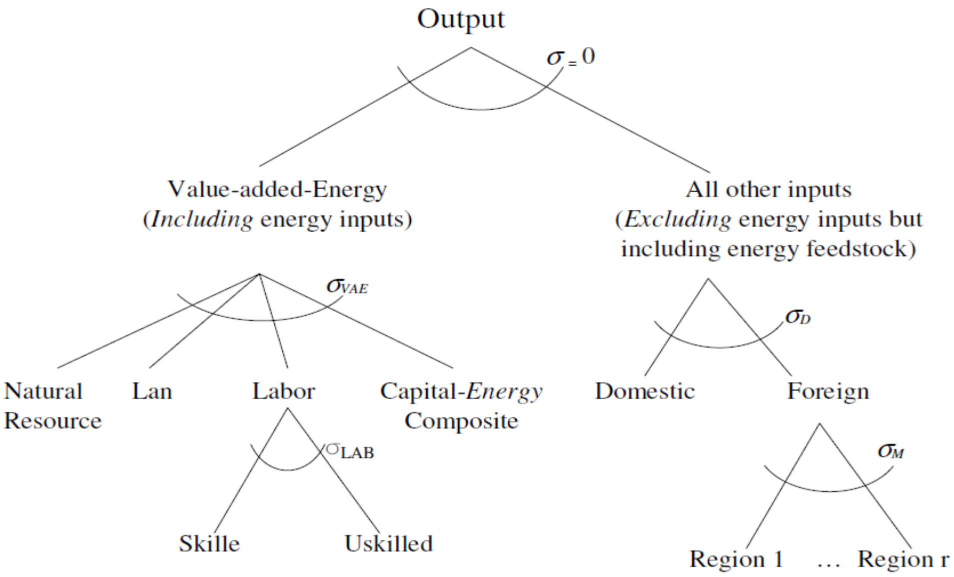
*These countries have been moved to the alternate category due to being in an aggregated region in the GTAP10 database

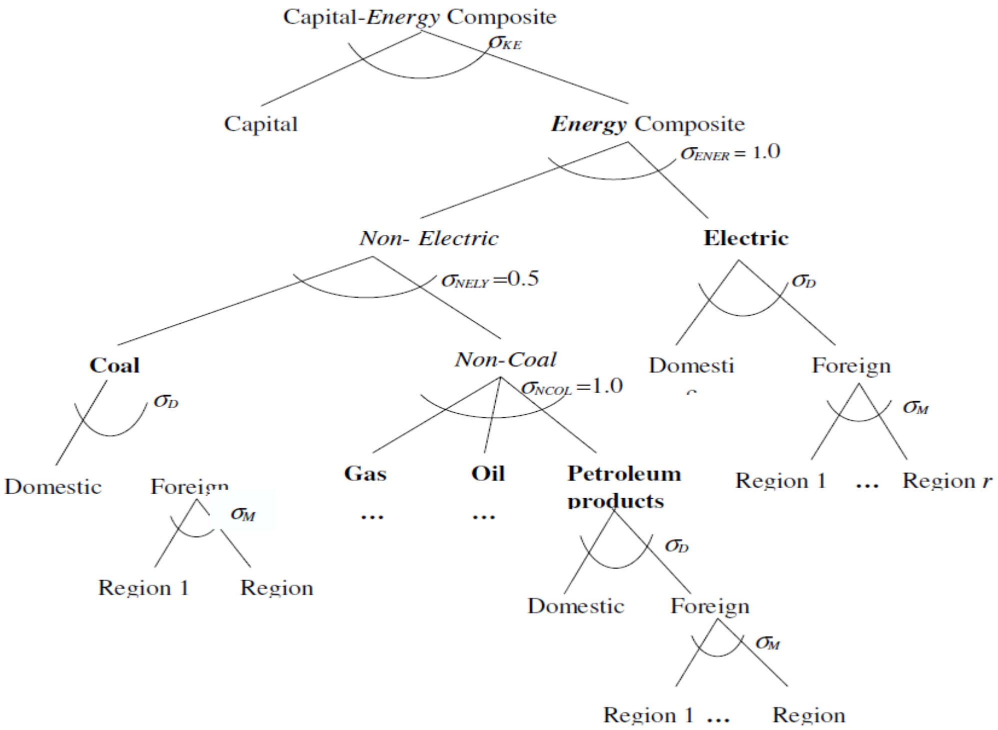
Appendix 4.4. Scenario CIAB

Region name	**Countries**
NDC Category i abating countries (31.6% share of 2014 emissions)	Australia, Azerbaijan, Bangladesh, Brazil, Canada, Costa Rica, Dominican Republic, European Union (28), Guinea, Iceland, Japan, Kazakhstan, Liechtenstein, Moldova, New Zealand, Norway, Switzerland, United States, Zambia
NDC category i non-abating countries, and all category ii, iii and iv countries (69.4% share of 2014 emissions)	Afghanistan, Albania, Algeria, Andorra, Angola, Argentina, Armenia, , Antigua & Barbuda, Bahamas, Barbados*, Bahrain, Belarus, Belize, Benin, Bhutan, Bosnia & Herzegovina, Botswana, Bolivia, Brunei, Burkina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo (DRC), Congo (Republic), Cook Islands*, Cote d'Ivoire, Cuba, Dominica*, Djibouti, Ecuador, Egypt, El Salvador, Equatorial Guinea*, Eritrea, Ethiopia, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada*, Guatemala, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran, Iraq, Israel, Jamaica, Jordan, Kenya, Korea (North), Korea (South), Kyrgyzstan, Kiribati, Kuwait, Laos, Lebanon, Lesotho, Liberia, Libya, Macedonia, Madagascar, Malawi, Malaysia, Maldives, Mali, Marshall Islands*, Mauritania, Mauritius, Mexico, Micronesia*, Monaco*, Mongolia, Montenegro*, Namibia, Morocco, Myanmar, Nauru, Nepal, Nicaragua, Niger, Nigeria, Niue, Panama, Oman, Pakistan, Palau*, Papua New Guinea, Paraguay, Peru, Philippines, Qatar, Russian Federation, Rwanda, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & Grenadines, Samoa, San Marino, Sao Tome & Principe, Saudi Arabia, Senegal, Serbia, Seychelles, Sierra Leone, Singapore, Solomon Islands, Somalia, South Africa, South Sudan, Sri Lanka, Sudan, Suriname, Swaziland, Syria, Tajikistan, Tanzania, Thailand, Timor-Leste, Tonga, Togo, Trinidad & Tobago, Tunisia, Turkmenistan, Turkey, Tuvalu*,Uganda, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Vietnam, Yemen, Zimbabwe

*These countries have been moved to the alternate category due to being in an aggregated region in the GTAP10 database

Appendix 4.5. Production Function and Capital-energy composite structure in GTAP-E.





Source: Figures 16 17 in Burniaux and Troung (2002).

Appendix 4.6. Elasticity Parameters

Parameter		Agriculture	Coal	Oil	Gas	Oil products	Electricity	Energy intensive industry	Other industry & services
Armington elasticity between domestic and imported goods	High	4.83	6.10	10.40	25.94	4.20	5.60	6.40	6.48
	Default	2.42	3.05	5.20	12.97	2.10	2.80	3.13	2.36
	Low	1.21	1.53	2.60	6.48	1.05	1.40	1.56	1.18
Armington elasticity between imported goods from different regions	High	9.61	12.20	20.80	64.78	8.40	11.20	12.81	12.95
	Default	4.81	6.10	10.40	32.39	4.20	5.60	6.40	6.48
	Low	2.40	3.05	5.20	16.19	2.10	2.80	3.20	3.24
Elasticity of substitution between capital and energy (ELFKEN)	High	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
	Default	0.50	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	Low	0.250	0.00	0.00	0.00	0.00	0.25	0.25	0.25
Elasticity of substitution between electricity and non-electricity energy (ELFENY)	High	0.50	0.00	0.00	0.00	0.00	0.00	0.50	0.50
	Default	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00
	Low	2.00	0.00	0.00	0.00	0.00	0.00	2.00	2.00
Elasticity of substitution between coal and non-coal energy (ELFNELY)	High	0.25	0.00	0.00	0.00	0.00	0.25	0.25	0.25
	Default	0.50	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	Low	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
Elasticity of substitution between oil, gas and petroleum products (ELFNCOAL)	High	0.50	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	Default	1.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00
	Low	2.00	0.00	0.00	0.00	0.00	2.00	2.00	2.00

Appendix 4.7. NAB and NAB-US GTAP-E model output

Scenario	Region	2014 emissions ($MtCO_2$)	Emissions after shock ($MtCO_2$)	Percentage change in emissions
NAB	US	5,168.81	3,473.4	-32.80
	EU	3,309.11	2,859.1	-13.60
	Brazil	450.94	413.5	-8.30
	Japan	1,034.16	771.5	-25.40
	Other Abaters	2,712.76	2,172.9	-19.90
	Total Abaters	**12,675.78**	**9,690.43**	**-23.6**
	China	8,322.69	8,347.0	0.29
	India	1,912.44	1,923.3	0.57
	Indonesia	1,412.09	1,423.4	0.99
	Russia	512.11	517.2	0.80
	Other Non-abaters	5,184.20	5245.6	1.18
	Total Non-Abaters	**17,343.52**	**17,456.54**	**0.65**
NAB-US	EU	3,309.11	2,859.1	-13.60
	Brazil	450.94	413.5	-8.30
	Japan	1,034.16	771.5	-25.40
	Other Abaters	2,712.76	2,172.9	-19.90
	Total Abaters	**7,507.0**	**6,217.0**	**-17.2**
	China	8,322.69	8,340.5	0.21
	US	5,168.8	5,171.3	0.05
	India	1912.44	1920.8	0.44
	Indonesia	1412.09	1421.5	0.73
	Russia	512.11	515.9	0.66
	Other Non-abaters	5184.20	5228.7	0.86
	Total Non-Abaters	**22512.3**	**22,598.7**	**0.38**

Appendix 4.8. CIAB and CIAB-US GTAP-E model output

Scenario	Region	2014 emissions (MtCO_2)	Emissions after shock (MtCO_2)	Percentage change in emissions
CIAB	US	5,168.81	3,473.4	-32.80
	EU	3,309.11	2,859.1	-13.60
	Brazil	450.94	413.5	-8.30
	Japan	1,034.16	771.5	-25.40
	Other Category i Abaters	1,404.7	1,064.8	-24.20
	Total Category i Abaters	**11,367.8**	**8,582.3**	**-24.5%**
	China	8,322.7	8,343.9	0.25
	India	1,912.4	1,921.8	0.49
	Indonesia	512.1	516.8	0.92
	Russia	1,412.1	1,421.7	0.68
	Other non-abaters	6,492.2	6,533.4	0.63
	Total Non-category i Abaters	**18,651.5**	**18,737.7**	**0.46%**
CIAB-US	EU	3,309.1	2,859.1	-32.80
	Brazil	450.9	413.5	-13.60
	Japan	1,034.2	7,71.5	-8.30
	Other Category i Abaters	1,404.7	1,064.8	-25.40
	Total Category i Abaters	**6,198.9**	**5,108.9**	**-17.59%**
	China	8,322.7	8,337.0	0.17
	US	5,168.8	5,169.7	0.02
	India	1,912.4	1,919.4	0.37
	Indonesia	512.1	515.7	0.70
	Russia	1412.1	1,420.0	0.56
	Other Non-Abaters	6,492.2	6,541.6	0.76
	Total Non-category i Abaters	**23,820.4**	**23,903.4**	**0.35%**

Appendix 4.9. EUAB and JAPAB GTAP-E model output

Scenario	Region	2014 emissions ($MtCO_2$)	Emissions after shock ($MtCO_2$)	Percentage change in emissions
EUAB	**EU**	3,309.1	2,859.1	-13.60%
	China	8,322.7	8,329.0	0.08%
	US	5,168.8	5,176.2	0.14%
	India	1,912.4	1,915.2	0.15%
	Russia	1,412.1	1,416.8	0.33%
	Indonesia	512.1	513.2	0.22%
	Brazil	450.9	452.0	0.23%
	Japan	1,034.2	1,036.8	0.25%
	Other non-abaters	7,897.0	7,930.9	0.43%
	Total Non-abaters	26,710.2	26,770.2	-0.22%
JAPAB	**Japan**	**1,034.2**	**771.5**	**-25.40**
	China	8,322.7	8,326.7	0.05%
	US	5,168.8	5,174.1	0.10%
	EU	3,309.1	3,316.0	0.21%
	India	1,912.4	1,915.1	0.14%
	Russia	1,412.1	1,414.4	0.16%
	Indonesia	512.1	514.0	0.37%
	Brazil	450.9	451.8	0.19%
	Other Non-Abaters	7,897.0	7,915.3	0.23%
	Total Non-abaters	**28,985.1**	**29,027.4**	**-0.15%**

Chapter 5

Conclusions

The Paris Agreement was seen as a landmark moment and potential turning point in the global effort to combat climate change (Kinley, 2016). Almost all nations came together to sign what could be considered as the first truly global agreement, with a clear central goal of keeping the rise in temperatures this century well below 2°C. Although it was initially greeted with enthusiasm, criticism of the Agreement soon appeared (Clémençon, 2016). Studies suggest that countries are failing to meet their pledges (Victor et al., 2017), and even if they do meet them, they are of insufficient ambition to stay within the overall goal of 2°C (Höhne et al., 2017; Schleussner et al., 2016; Rogelj et al., 2016). The intention of the US, the largest cumulative emitter of greenhouse gases, to withdraw from the agreement has further highlighted its fragility. Although it is too early to evaluate if the Paris Agreement will be a success or failure, it is undoubtedly running into challenges that mean it will not be a panacea for tackling climate change.

Paris was not the first time the World had united to solve an environmental issue. The Montreal Protocol, agreed in 1987, was designed to protect the ozone layer by phasing out emissions in ozone depleting substances. The goal was similar in nature to that of Paris; agree globally to reduce emissions of a global pollutant to protect the long-term environmental balance of the planet. However, the Montreal Protocol is almost universally regarded as a success (Mckenzie et al., 2019, Morgenstern et al., 2008). This was due to depletion of the ozone layer being perceived as a serious health risk, it being caused by a relatively small industry, and easy substitutes being available, altogether contributing to a quick and effective solution. The first climate treaty, the Kyoto Protocol, however, was ineffective at reducing global emissions, and signs suggest the Paris Agreement will not perform very differently. Climate change evidently has unique features among environmental problems that makes solving it far more challenging. Whereas ozone depleting substances were easily replaced with alternative chemicals with no ozone-depleting potential, greenhouse gases are less easy to replace. The main sources of greenhouse gases are energy production, industrial processes, agriculture and land use change, which are all primary drivers behind economic growth and development. Reducing greenhouse gases without harming economic growth and development is therefore a more fundamental issue, which is difficult to overcome. In this thesis I explored how this fundamental challenge can be more clearly understood by separating it into three separate aspects: biophysical, political and economic. Each of these is analysed in a separate chapter.

In Chapter 2 I analysed the biophysical challenge of net energy in the context of a low-carbon energy transition. To stay within a carbon budget that would limit climate change to 2 °C, in line with the goal of Paris, a rapid growth in renewable energy sources alongside improved energy efficiency and carbon capture and storage would be needed. However, current scenarios of such a low-carbon energy carbon transitions tend to overlook the concept of net energy, which factors in the energy input in the process of energy production. Through the concept of EROI, I corrected from gross to net energy, to show that a low-carbon transition would likely lead to a 24–31% decline in net energy per capita by 2050. This implies a strong reversal of the recent rising trends of 0.5% per annum. The challenge comes from renewable sources typically having lower EROI values than historical fossil fuels, an expected decline in the EROI of oil and gas, and fossil fuels being necessary to produce the renewable sources. Unless vast end-use efficiency savings can be achieved in the coming decades, current lifestyles might be impaired. I also analysed a scenario which had the goal of maintaining the present net energy returns, which suggested that solar and wind renewable power sources should grow two to three times faster than in other proposals. I suggested a new indicator, 'energy return on carbon' (EROC), which combines the concept of EROI and the carbon intensity of an energy source. Optimising energy policy through the EROC would assist in maximizing the net energy from the remaining carbon budget.

In Chapter 3, I explored the political aspect of the challenge. The Paris Agreement takes a bottom-up approach to tackling climate change with parties submitting pledges in the form of nationally determined contributions (NDCs). Although the Agreement was successful at getting almost all countries to agree to signing it and its central goal, studies show that the sum of these national pledges falls short of meeting the agreement's 2°C target. This suggests that the current process is not sufficient at eliminating the political challenges of climate change policy. To explore this discrepancy, I analysed individual pledges and classified them into four categories. By doing so, a lack of consistency and transparency between individual countries' pledges became apparent. To make the pledges directly comparable, I performed a normalisation which involved calculating changes in emissions by 2030, using data for the most recent base year of 2015. I found that pledges framed in terms of absolute emission reductions against historical base years generally produce the greatest ambition, with average emission reductions of 16% by 2030. Pledges defined as GDP intensity targets performed the worst with average emission increases of 61% by 2030. I propose that a normalisation procedure of the type developed in this chapter becomes part of the NDC process. It will allow not only to increase the transparency of pledges for policymakers and wider society, but also promote more effective NDCs upon revision as is foreseen to happen every 5 years under the 'ratcheting mechanism' of the agreement.

In Chapter 4 I analysed the economic challenge of carbon leakage, which is the effect of emissions increasing in certain countries due others having a stricter climate policy. Effectively emissions are transferred to those countries that have weaker climate policy. This phenomenon is shown to have undercut the effectiveness of the Kyoto Protocol. Considering the increasingly globalised nature of the world economy, carbon leakage may have an even greater potential under the Paris Agreement some fifteen years later. Although a more global approach to combatting climate change, the Paris Agreement is susceptible to leakage because of its lack of policy harmonization and enforcement mechanisms. I performed a normalisation of countries’ Paris pledges to create abatement rates to 2030, which I then entered in the GTAP-E general equilibrium model of the world economy, with energy and carbon emissions, to analyse leakage effects under six scenarios. Two of these scenarios analysed regions implementing climate policy in isolation. A further two scenarios analysed the global Paris Agreement policy with greater participation, but still not harmonized policy. A final two scenarios analysed the effect of US withdrawal from the agreement. Depending on model elasticities, I found medium carbon leakage in the range of 1-9% (with a central estimate of 3-4%) under co-ordinated Paris Agreement policy across countries, compared to high leakage of 8-31% when countries operate in isolation. However, scenarios where the US withdraws from the agreement result in roughly doubling of leakage rates, in the range of 3-16% (central estimate 7%), which demonstrates the vulnerability of the Paris Agreement in its current form. To limit leakage effects greater policy co-ordination to achieve consistent implicit carbon prices is needed across countries.

The ultimate success of the Paris Agreement can only be judged in the future, namely by how effective it will have proven to be at reducing greenhouse gas emissions by 2050. However, it is important to analyse its potential effectiveness now, and a method to do so is critically assessing how it is able to overcome the biophysical, political and economic obstacles which have contributed to the failure of reducing emissions in the past. The political challenges have resulted in a set of pledges which are not aligned with the central goal of the Paris Agreement, and instead would lead to a warming of around 3°C. My analysis has shown how even limiting warming to this level can be seen as optimistic, as it is also not taking into account the biophysical and economic challenges. The biophysical challenge of net energy may make the planned energy transitions unrealistic if countries’ want to maintain, or grow, their energy-driven economic activities. Instead more fossil fuels are likely to be consumed in order to achieve this, meaning the carbon budget will be overshot. One aspect of the systemic economic challenge, carbon leakage, is also likely to negate emission reductions by around 10%. Other economic challenges, such as the Green Paradox and carbon rebound, not analysed in this thesis, would have cumulative effects, further limiting any overall emission reductions. Arguably the greatest failure of the Paris Agreement was its inability to agree on a serious, global carbon price (van den Bergh et al., 2020). This would have had multiple effects that limit the challenges discussed in this thesis. A carbon price would reduce the biophysical challenge by correcting the energy return on carbon to guide energy policy to maximise the net energy from the carbon budget. It would further limit the political challenge of reducing the ‘free-rider’ problem and promote policy harmonisation across countries. This would weaken economic challenges such as carbon leakage because having a consistent carbon price would prevent some countries from out-competing others in carbon-intensive production.

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