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Cumulative emission scenarios using a consumption-based approach: a glimmer of hope?

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Every year, new research illustrates how the pace of global emission growth gradually reduces the chance of avoiding 'dangerous' climate change. Previous analyses that have taken a territorial emissions framing approach demonstrate how little space there is available for Annex 1 nations' emissions to continue at current levels because of the pace of growth in industrializing economies. This paper uses a cumulative emissions approach to explore whether a consumption-based framing offers new opportunities and avenues for tackling climate change. Results reveal that there is still scope for emissions to remain within a budget associated with a high probability of remaining below the 2°C temperature rise above pre-industrial levels associated with 'dangerous' climate change. However, both territorial and consumption-based approaches require a rethinking of the political orthodoxy for the highest probabilities of not exceeding 2°C. Using the consumption-based framework, mitigation policy in Annex 1 nations can address consumer-related emissions sending mitigation signals along supply chains and across national boundaries, thereby increasing their influence over global CO_2. Ultimately, allying the cumulative framing of climate change with the consumption-based approach offers additional potential for achieving a global low-carbon transition compared with policies framed solely using the conventional territorial approach. Nevertheless, cumulative budgets associated with a high probability of not exceeding the 2°C threshold between 'dangerous' and 'acceptable' climate change demand immediate and urgent emission reductions, irrespective of the accounting approach employed.

The contrasting positions of the non-Annex 1 and Annex 1 nations within global climate negotiations are underpinned by issues of historical responsibility, state of economic development and, more recently, responsibility for the production of current emissions. These positions were played out in 2009, when negotiators pushing for the Copenhagen Accord to include binding emissions reduction targets were set against a response from China quoting the historical emissions of industrialized countries where carbon was treated as a free commodity [1]. Whilst a **territorial** (or **production-based**) framework is used to account for emission within the Kyoto agreement [2], the way in which it is possible to reduce emissions by outsourcing manufacturing or, increasingly, relying on imports to meet the final demand for consumption suggests responsibility for current emissions can be more fairly illustrated using the **consumption-based** emissions framework [3], and questions the validity of a territorial accounting framework. It should be noted that there are differences between the production-based and territorial frameworks; for example, under the production-based framework, emissions produced by a UK resident traveling abroad in a car they own will be included in the UK's inventory, but excluded under Kyoto's territorial framework. It is the production-based framework that is the basis used for the UK's environmental accounts.

Issues of burden sharing and fairness have been debated considerably in relation to proposed methods for allocating permits to produce greenhouse gas (GHG) emissions in the future [4]; yet, to date, much less emphasis has been placed on the means by which baseline emissions

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Key terms

Territorial: Framework that considers emissions released within a nation's territory or borders.

Production-based: Framework that considers emissions released where they are produced. For a national production-based framework, this is normally but not exclusively within national boundaries, and therefore similar to the territorial framework.

Consumption-based: Framework that consider s emissions released by the supply chain related to goods and services consumed by national residents.

Climate change: Change in average long-term weather conditions due to natural or anthropogenic influences.

2°C: Global mean surface temperature rise above pre-industrial levels that is associated with 'dangerous' interference with the climate system.

Cumulative emissions: Emissions of long-lived greenhouse gases that accumulate in the atmosphere.

are calculated in the first instance [3]. Put simply, the territorial framework for emissions accounting allocates the emissions physically produced within a nation's territorial boundary to that nation (with obvious difficulties arising from the allocation of international aviation and shipping emissions). The consumption-based framework allocates the emissions associated with all goods and services consumed by residents of a nation irrespective of their territorial origin.

The export of emissions is frequently and unsurprisingly ignored when attempting to claim 'success' with regard to meeting Kyoto targets. Whilst there are nations successfully meeting their emission reduction targets, the Kyoto agreement was developed for the purposes of tackling **climate change** and, therefore, these nations are often unable to claim to be successfully tackling climate change. The UK is a clear example of where Kyoto emission reduction targets have been met, yet consumption-related emissions have continued to increase [5,6].

The aim of this paper is to explore the added potential of achieving the desired future of limiting global temperature rise to the **2°C** above preindustrial levels associated with 'dangerous' climate change by looking at the consumption-based approach to GHG emission accounting. 'Dangerous' climate change is defined within the Fourth Assessment report of the Intergovernmental Panel on Climate Change as causing significant adverse outcomes that are considered to be significant in terms of their ecological, social and economic implications [7,8]. It is envisaged that a consumption-based approach would shed additional light on GHG emission sources, trends and drivers. In doing so, it may uncover a more complicated story of the current and likely future direction of emissions trends as they are essentially exported to often poorer manufacturing nations. In addition, the consumption accounting approach increases the range of policy options to tackle the considerable challenge of substantial and urgent emission reduction.

Building on previous cumulative emission research, both at an aggregated global scale and focusing on Annex 1 and non-Annex 1 nations specifically [9,10], this paper explores the implications of consumption-based emission trends attributed to Annex 1 and non-Annex 1 nations in order to develop a more informed picture of the drivers of emissions than delivered using the conventional territorial approach. By bounding emissions within a **cumulative emissions** framework, the scale of emission mitigation across the full supply chain is illustrated and compared with the more conventional territorial approach to emissions accounting.

Background & framing

Despite calls from many within the academic community to address climate change as a matter of some urgency [11], there is a prevailing view, further emphasized and expressed by the behavior of society, that technology will ultimately deliver adequate mitigation solutions or that the costs (conventionally quantified in financial terms) of associated adaptation are politically and economically acceptable [12–14]. Others however, argue that the level of emissions accumulating in the atmosphere through the production of the long-lived, well-mixed GHGs are unacceptable and, coupled with the significant inertia within the global fossil fuel-focused energy system, requires concerted effort to reduce energy demand in the short-term, not only through efficiency measures, but also through behavioral change [15–20].

From within the wider sustainability literature, the 'strong sustainability' framing highlights the importance of limits on resources, planetary boundaries and the rate at which resources are being consumed in an inequitable way [21,22]. Bringing together concerns regarding resource use and consumption with the argument that addressing energy demand (and, hence, fuel resources) in the short-term is necessary to address climate change highlights complimentary opportunities for tackling GHG emissions. By comparing results using conventional national emission accounting with the arguably more insightful consumption-based framing, a particular economic approach (originally developed by the Norwegian University of Science and Technology with input from the Stockholm Environment Institute and Carnegie Mellon University [5,23]) is used in this paper to emphasize the potential for avoiding the global mean temperature rise above preindustrial levels of 2°C associated with 'dangerous' climate change that lies with the consumer end of the supply chain.

▪ Consumption-based emissions framework

Within the Kyoto agreement, national emissions are estimated using a territorial-based framework [2]. Within this framework, a national emissions total is compromised of all GHG emissions produced within national boundaries. This framework, and the similar production-based framework, do not include those emissions associated with imported goods, nor emissions associated with international aviation and

shipping. However, they do include those emissions released during the production and manufacture of goods for export. Many have now argued that such territorial approaches do not properly account for 'national emissions' given that a significant proportion are produced by other nations for the purposes of consumption within the host nation [23–26], which arguably, is not a fair reflection of the responsibility for producing GHGs. Moreover, one of the potential consequences of this framework, since it is currently used within policy to affect emission reductions, is a drive towards exporting emission-intensive activities elsewhere, where the costs of production are lower or where they are currently without any additional carbon price imposed through the EU's Emissions Trading Scheme or similar. When the precise reason for a company shifting manufacturing is due to less stringent carbon policy, it is known as 'strong carbon leakage' [23]. However, data suggests that it is currently more likely that a growth in GHG emissions in non-Annex 1 nations will be unrelated to mitigation policy within Annex 1 nations, but rather driven by the reduced costs incurred in outsourcing ('weak carbon leakage') [23,27,28]. This may not continue to be the case if mitigation policy within Annex 1 nations strengthens to the extent that costs are either directly (through a carbon price) or indirectly (through a standard or regulation) significantly increased. Therefore, the choice of emission accounting framework plays a pivotal role in the effectiveness of mitigation policy.

Ironically, one of the sectors currently excluded from the conventional territorial-based framework, international aviation, may soon illustrate how nonterritorial-focused policies have the potential to influence emission mitigation in nations without emission targets. International aviation is not part of the national effort to mitigate emissions within Kyoto but, at an EU scale, will soon be incorporated into the EU's Emissions Trading Scheme [29]. To do this, the EU proposes that all arrivals and departures be captured by the scheme. However, there is a conflict here in attempting to drive down emissions if the departure nation is imposing a carbon-related policy while the arrival nation is not, an issue also contested by the International Civil Aviation Organization [30]. In this case, one nation, through its airlines, airports and air-traffic control (and in the wider energy system), may put measures in place to reduce any additional carbon cost arising from the need to purchase emissions rights for aviation. The other nation, without a carbon mitigation driver, may be encouraging the rapid development of new air links, without particular concern for congestion, alternative fuels or efficiency gains over and above those economically viable for the prevailing oil price. This conflict could result in the aviation emissions burden on the EU nation being higher than if the same length of flight had been between two nations with similar carbon policies in place [31,32]. On the other hand, if part of the carbon cost is passed on to the passengers, then even the nation without a carbon price will be subject to an additional cost and, with it, pressure to mitigate emissions.

Therefore, including cross-boundary emission sources within a national mitigation framework sends a signal that reaches beyond the border of that nation, offering new avenues for tackling climate change. Owing to different sectors' systematic properties, pressures or incentives for decarbonization placed on part of a sector can stimulate changes in another. This could be achieved, for example, by promoting efficiency improvements, technical innovation, and product or service substitution. The consumption-based framework could therefore be used to take advantage of the systemic nature of energy-consuming sectors. In doing so, if nations (or organizations) are to consider their full supply chain emissions, and implement policy to mitigate those emissions, the policy is likely to have global reach and could benefit the global carbon-reduction effort. A consumption-based accounting framework more directly highlights the drivers of emissions to their sources and removes low-carbon incentives that may result in a geographical shift in the production of the emissions.

There are, of course, limitations to implementing the consumption-based emissions framework, particularly at a national scale. These primarily include a further level of complexity in the calculations, difficulties in collecting data on production from nations not currently reporting their emissions to the UNFCCC, transparency in relation to the indirect nature of many emissions, and complications in overhauling an existing territorial-based system, in addition to legal impediments. However, the potential of the consumption-based framework to compliment existing territorial mitigation frameworks at both a national and organizational scale deserves attention, particularly given the challenge faced in reducing emissions to levels that avoid 'dangerous' interference with the climate system. A study by Lenzen *et al.* calculated the additional uncertainty generated by employing a consumption-based accounting framework using the UK as a case study [33]. This analysis demonstrates that the consumption-based accounting framework adds a 3% uncertainty to territorial emissions accounting.

Cumulative emissions framing

The long-lived nature of CO_2 and some of the other GHGs has resulted in some consensus regarding the importance of cumulative emissions as an appropriate approach for assessing emission pathways and developing climate policy [10,34–36]. A number of these studies

focus significantly on ensuring a scientifically credible case for such an approach by conducting analysis over up to five centuries, to fully take into account time lags in the system and the importance of the carbon cycle [34,36]. Others take a more policy-focused viewpoint by drawing attention to the nearer term century time scale, despite the potential for emissions to continue at low levels for many centuries to come [10,35]. Finally, there are those that reduce the time frame and spatial scope further to highlight the broad implications for energy policy at a national level [15,24,37]. The more abstract nature of the longer term analyses can be readily coupled with the shorter term policy-relevant studies simply because of the very high level of current annual emission output. An allowable cumulative emission budget over many centuries can be consumed in its entirety within just a few decades [10,34].

For any 'reasonable' (>50%) chance of not exceeding the 2°C threshold associated with 'dangerous' climate change, studies illustrate the need for both an early global peaking date, very rapid subsequent emission reductions [10,34] and, in some cases, deployment of untested technologies such as biomass with carbon capture and storage [38]. However, the validity of presenting global emissions pathways that peak by or before 2015 as politically feasible within the conventional economic regime is questionable, as is the danger of drawing policy conclusions based on such an optimistic assumption. In Anderson and Bows, national emissions are aggregated into their Annex 1 and non-Annex 1 groupings using a territorial framework, to illustrate the implications in relation to 'dangerous' climate change for Annex 1 nations and global peaking dates, of continued rapid growth in emissions within the industrializing nations [9]. This approach emphasizes the challenge for national governments of Annex 1 nations, given the likely continued rapid industrialization [39]. Annex 1 emissions, under a territorial framework, need to reduce immediately and at annual rates in excess of 5% within only a few years [9]. With the majority of these emissions being generated by the burning of fossil fuels, there is a danger that achieving this goal incentivizes Annex 1 nations to export production to other countries, many of which carry out manufacturing in a more carbon-intensive manner with less strict environmental control [40]. Moreover, the current trend for consumption-related emissions in Annex 1 nations being increasingly related to imports will render any effort by non-Annex 1 nations to decarbonize increasingly difficult. To take an alternative view point, the cumulative emissions scenario pathway assessment for Annex 1 and non-Annex 1 nations in Anderson and Bows is repeated in this paper using the consumption-based framework to account for emissions [9].

Data & method

▪ Cumulative emission budget

The cumulative budgets bounding the scenarios developed for this paper are chosen specifically to illustrate a reasonable-to-high probability of not exceeding the 2°C threshold. The GHG emission data generated by the Stockholm Environment Institute using national environmental accounts provides a time series in CO_2 alone, although a recent figure for total GHG emissions can be obtained [5]. Consequently, whilst it is recognized that it is the full basket of GHGs plus the impacts of more short-lived species, such as the aerosol components, that contribute to the final climate warming, the 'CO_2-plus' regime used previously by, for example, Macintosh [41] and Anderson and Bows [9] is adopted. This budgetary regime separates the CO_2 emissions and the non-CO_2 GHGs and aerosols through the application of assumptions regarding radiative forcing of the non-CO_2 elements [35], facilitating analysis with CO_2 data alone. Therefore, the cumulative CO_2-only budget is lower than the CO_2-equivalent figure would be. Although this regime does consider the warming influence of the non-CO_2 components, this approach is limited in its ability to reflect links between, for example, reduced fossil fuel combustion and associated aerosol production.

Considering only the CO_2 emissions within a consumption-based framework also limits the ability of the analysis to draw conclusions with regard to consumption-related non-CO_2 GHG emissions, such as the methane emissions generated by livestock. Indeed, the emissions allocated to the Annex 1 nations would increase further if these emissions were accounted for. The implications of this limitation are discussed later in this article.

The 21st Century carbon budgets used to bound the scenarios are the middle and lower estimates presented in Macintosh [41] and subsequently used in Anderson and Bows [9] (1578 $GtCO_2$ [430 GtC] and 1321 $GtCO_2$ p[60 GtC]). These are lower than the budget proposed by Zickfield *et al.* [34] of 590 GtC for a 66% chance of not exceeding 2°C. This is in part due to the fact that within the Zickfield *et al.* analysis, the assumption is made that non-CO_2 GHGs continue to be offset by the aerosol component, which is unlikely to be the case if fossil fuel combustion is significantly reduced [38], whilst at the same time the growing population continues to increase its agricultural non-CO_2 GHG emissions associated with food. The higher of the two budgets was derived from the Garnaut Climate Change Review's 450 ppmv CO_2e mitigation scenario [42] and provides an approximate 50% chance of not exceeding 2°C [41]. The lower budget reflects the "risk that climate-carbon cycle feedbacks respond earlier and more strongly than previously believed"

and corresponds with a higher chance of not exceeding 2°C. The probability of exceeding 2°C can be calculated using the Potsdam Real-Time Integrated Model for the probabilistic Assessment of Emission Pathways (PRIMAP) tool [43] if the 2000–2049 emissions are known.

Empirical data

Consumption-based CO_2 emission data

A time series from 1992 to 2006 of consumption-based CO_2 emissions is calculated by extending the 'Multi-Regional Environmentally Extended Input Output' model developed by Peters and Hertwich [44]. Environmentally extended input–output analysis (IOA) is a method for allocating environmental pressures (e.g., emissions of GHGs) associated with production and supply chain processes to groups of final use products by means of inter-industry economic transactions. The main data sources are sectoral macroeconomic and environmental accounts.

Input–output analysis is a well-established approach widely used by analysts and researchers in the area of economic, ecological and environmental modeling [45–47]. Its main architect, Wassily Leontief, received the Nobel Prize in Economic Science in 1973. IOA has been used for many years to calculate consumption-based environmental pressures derived from nations, sub-national entities, socioeconomic groups and organizations or companies [48–51]. The strength of this approach is that it addresses production and consumption processes and their underlying technical, social and behavioral drivers simultaneously. Furthermore, it can be applied at an organizational level to inform policies aimed at emission reductions right through the supply chain, thereby providing additional levers for decarbonization to those available when implementing national mitigation policies using the conventional production-based or territorial approach.

To create the time series for CO_2 emissions between 1992 and 2006, additional assumptions were required. These mainly related to adopting the same production structure for the years for which Global Trade Analysis Project data was unavailable. This extension means that, at present, the results are not consistent with the Carbon Dioxide Information Analysis Centre data used within Anderson and Bows [9]. In order to compare consumption-based emission pathways with production-based ones, pathways (in addition to those within Anderson and Bows) are developed using the IOA data for the production-based CO_2 emissions.

Although international aviation and shipping emissions are included within this consumption-based emissions database, recent research has illustrated the likely underestimate for shipping CO_2 if based on fuel sales [17,52–54]. Consequently, it is likely that the data underestimate this element.

Deforestation & land use change

The data for deforestation and land use change is taken from the Global Carbon Project Carbon Budget Update 2009 [55]. For data up to 2005, they estimate CO_2 using deforestation statistics published by the UN FAO [56] and a bookkeeping method. Emissions from 2006 to 2008 use satellite data from the Oak Ridge National Laboratory Distributed Active Archive Center Global Fire Emissions Database in combination with a biogeochemical model [57].

Global economic downturn

It is well understood that global GHG emissions tend to mirror global economic trends. Therefore, it is of no surprise that with the economic downturn between 2007 and 2010, GHG emissions were affected. Given that the consumption-based CO_2 time series data span from 1992 to 2006, estimates for the subsequent years are necessary. Using the more recent estimates for global GHG emissions provided by the Global Carbon Project up until 2008 and estimates that were made by Anderson and Bows for 2009–2010 [9], it is assumed that between 2007 and 2010, changes in Annex 1 emissions are 0.4, -1.4, -6 and 0% in each year, respectively. Non-Annex 1 emissions are assumed to change by 6.4, 5.3, -0.5 and 2.7% in each year, respectively. Consumption-based emissions are the production-based emissions minus the emissions from exports plus those from imports. Therefore, these figures assume the recession effects emissions associated with imports and exports equally. Although world trade data suggests that both imports and exports from Annex 1 nations fell by a similar value during the economic downturn, it is not necessarily the case that the emissions associated with imports and exports would change in a similar way. For example, a shift towards carbon-intensive imports could increase the consumption-based emissions further. At present, there is insufficient data to determine how this changed; therefore, a simplified assumption that changes to the production-based emissions were similar to the consumption-based emissions was taken.

Emission pathway development

The pathways developed are simplified illustrations of emission scenarios designed to better understand the implications for Annex 1 nations of ongoing rapid growth in emissions associated with the non-Annex 1 nations. To do this, assumptions are made in relation to the fossil fuel CO_2 data split between the Annex 1 and non-Annex 1 nations in the future using the consumption-based accounting framework. The scenarios

do not specify particular fuel mixes and are not intended to be full energy scenarios, as they are in, for example, Clark *et al.* [38]. However, they explicitly do not include negative CO_2 emissions that could, in the future, result from biomass with carbon capture and storage or other geoengineering solutions. CO_2 emissions associated with deforestation are assumed to be a global overhead and, thus, removed from the constraining carbon budget through the use of an existing deforestation scenario. The deforestation scenario is taken as the average of two presented within Anderson and Bows [5] and is considered to be optimistic in terms of potential emission reductions. Therefore, excluding CO_2 from deforestation from the scenarios therefore ignores the potential opportunity to explicitly illustrate the potential for nations to count avoided deforestation, afforestation or reforestation towards their national inventories. The issue of accounting for such emissions in inventories or towards reduction targets, and the choice of appropriate baselines continues to be debated [58,59]. These scenarios are not excluding this potential, but the emission pathways presented are limited to illustrate the potential mitigation effort required for industrial and energy-related CO_2 emissions, with the additional effort relating to deforestation captured within a highly optimistic deforestation scenario [10].

All of the illustrative scenarios focus on the initial development of the non-Annex 1 emissions profile, given that it is growing much more rapidly than emissions associated with the Annex 1 nations. The consequence for the Annex 1 emissions profile is then derived from the remaining carbon budget. The first three scenarios (Con1, Con2 and Con3) are constrained by a 21st Century carbon budget of 1321 $GtCO_2$, while the second three (Con4, Con5 and Con6) are constrained by a 21st Century carbon budget of 1578 $GtCO_2$. Discrepancies between the fossil fuel CO_2 data used within the Anderson and Bows analysis [9] and this analysis, due to their differing sources, results in a slightly greater available budget under the consumption-based framing than this territorial analysis. Additional production-based pathways using the same IOA dataset are therefore developed for comparative purposes; these are denoted 'Con1 variation,' 'Con3 variation' and 'Con4 variation', as the rates of growth and cumulative budgets for these scenarios mimic those associated with Con1, Con3 and Con4, respectively.

Con1 (Figure 1) assumes that the rate of increase in non-Annex 1 nations experienced between 1992 and 2006 (4% p.a.) resumes from 2011 until 2015, peaks by 2020 and subsequently begins to fall at a constant rate of 6% by the early 2030s. To remain within the set budget, Annex 1 nations do not resume growth following the economic downturn, and reduce by a constant rate of 11% p.a. by the early 2020s.

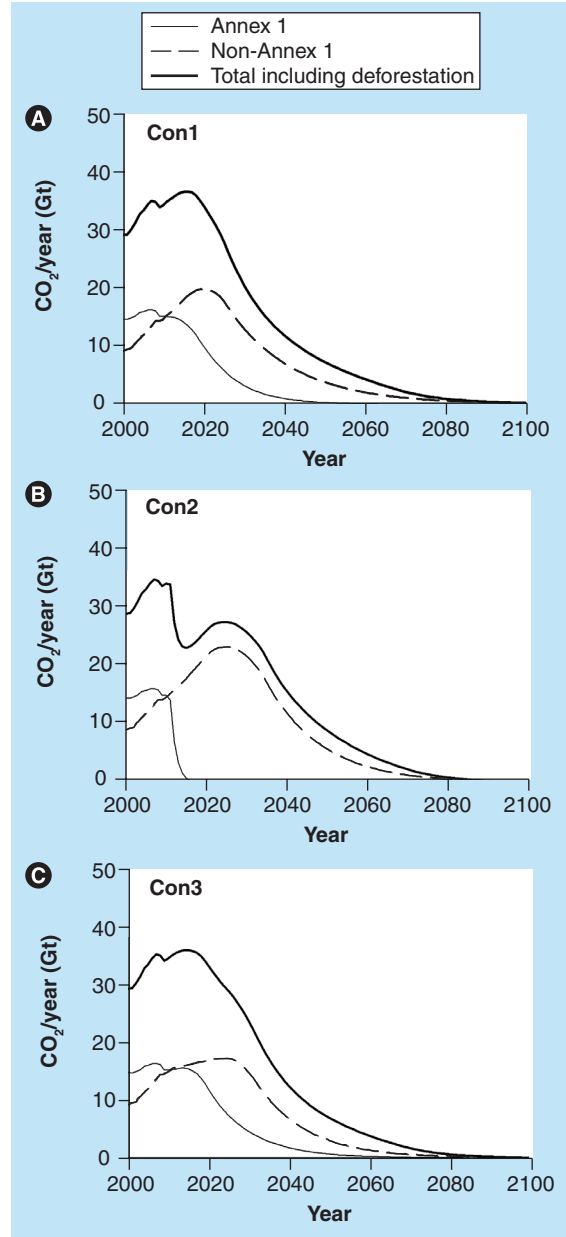

Figure 1. Three sets of scenario pathways constrained by a cumulative budget providing an approximate 36% probability of not exceeding the 2°C threshold.

Con2 (Figure 1) assumes the same rate of non-Annex 1 emissions growth rate as in Con1 but, on this occasion, emissions continue to grow at this rate until 2020, at which point they begin to slow and peak in 2025. As a result of the later peaking date for non-Annex 1 nations, there is no space available for CO_2 emissions from Annex 1 nations and, as such, this scenario is not viable.

Con3 (Figure 1) takes a significantly reduced growth rate for the non-Annex 1 nations of 1% per year, peaking in 2025. Emission reductions reach 8% per year

by the mid 2030s for both Annex 1 and non-Annex 1 nations. Therefore, Annex 1 nations are able to reduce emissions by 3% less per year than under the Con1 constraints. Using the PRIMAP tool [35,43], scenarios Con1 to Con3 have a 'best estimate' of between 35 and 36% chance of exceeding the 2°C threshold.

Con4 (Figure 2) is the first of three scenarios bounded by the higher of the two carbon budgets. To illustrate the difference that the higher budget makes, Con4 assumes the same growth and peaking date for the non-Annex 1 nations as Con1, although emission reductions following peak are somewhat less stringent, reaching 4% p.a. by the early 2030s. With no growth in emissions for Annex 1 nations from 2011 onwards, emission reductions are again less stringent than Con1, reaching 7.5% by 2020.

Con5 (Figure 2), as with Con2, assumes continued 4% growth for non-Annex 1 nations until 2020, with a peak in 2025, and constant emission reductions of 7.5% by the early 2040s. The consequence of the larger budget for the Annex 1 nations allows for the historical annual growth rate until 2015, then a decline towards a constant rate of reduction of 7% per year by the early 2020s. Therefore, owing to the additional budget available, this scenario is viable, unlike Con2.

Finally, Con6 (Figure 3) assumes the historical rate of growth of 4% for non-Annex 1 nations until 2020, after which emissions growth starts to slow and peaks by 2025, with constant emission reductions of 4–5% p.a. from 2030. This lower emission reduction rate for the non-Annex 1 nations constrains the remaining budget for Annex 1 forcing an immediate decline at a constant rate of 10% by the mid-2030s. Using the PRIMAP tool, scenarios Con4 to Con6 have a 'best estimate' of between 43 and 50% chance of exceeding the 2°C threshold [35,43].

A selection of production-based emission scenario pathways using the identical dataset to that used for the Con scenarios were developed to illustrate the difference for Annex 1 and non-Annex 1 under alternative accounting frameworks. Con1 variation (Figure 3) includes three variants: A, B and C. Variant A assumes identical growth rates for non-Annex 1 emissions as assumed within Con1. As a result of the higher starting point for non-Annex 1 nations, Annex 1 emissions must decline sooner than they would under the consumption-based alternative. However, variant B illustrates that with emission reduction rates 4% higher than in variant A, Annex 1 emissions can still have a post-recession peak in emissions identical to the consumption-based equivalent. Finally, variant C delays the non-Annex 1 emission peak by 5 years but, by increasing reduction rates to 11% per year, Annex 1 emissions can again peak at the same date as the consumption-based alternative.

Con3 variation (Figure 4) considers production-based pathways that have a much slower growth rate within the non-Annex 1 nations in early years. The first variant (A) assumes that non-Annex 1 emissions grow at the same rate as in Con3. As a result, Annex 1 emissions must decline earlier than with the same assumptions under a consumption-based framework. If, on the other hand, Annex 1 emission growth mimics the consumption-based alternative, then emissions in non-Annex 1 nations peak by 2020 instead of 2025.

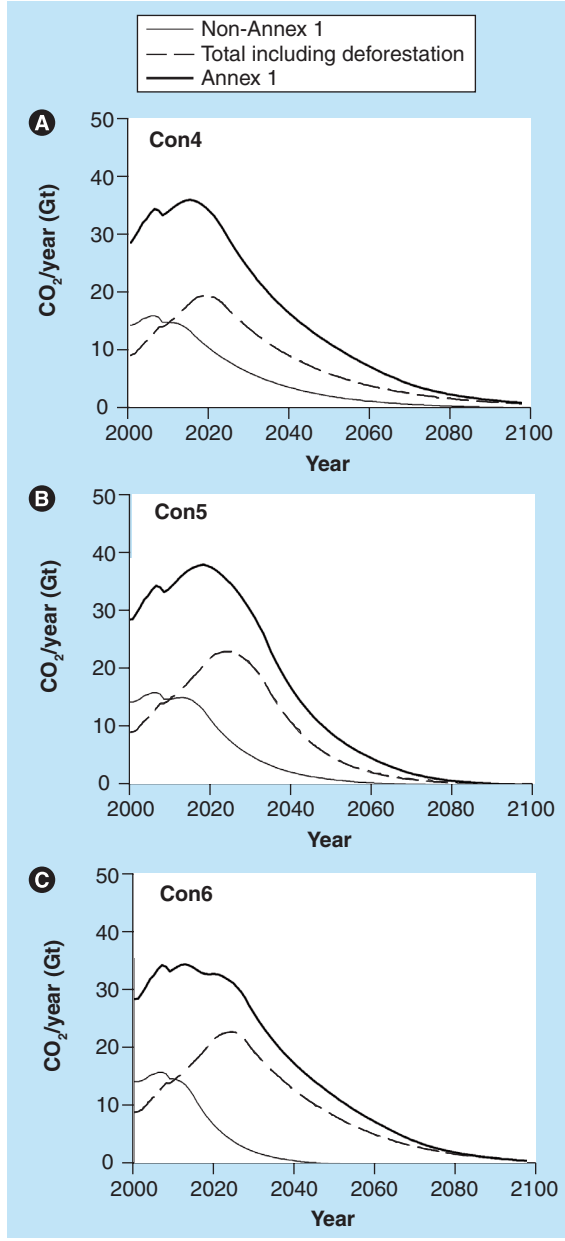

Figure 2. Three sets of scenario pathways constrained by a cumulative budget providing an approximate 45% probability of not exceeding the 2°C threshold.

Therefore, in this instance, the consumption-based framework requires later peaking dates than the production-based equivalent.

Finally, the Con4 variation (Figure 4) presents scenario pathways for the higher of the two cumulative budgets for two production-based variations of Con4. These pathways illustrate how small changes in the reduction rates for the non-Annex 1 nations under the production-based framework dictate peaking dates and rates of reduction in the Annex 1 nations.

Discussion

Taking the territorial approach, CO_2 emissions growth associated with Annex 1 nations has stalled in recent years, while non-Annex 1 nations have demonstrated average growth rates of over 4% per year since the 1990s (excluding recent recession years). The picture changes when taking a consumption-based approach; instead of CO_2 emissions remaining stable in Annex 1 nations, there is a growth in emissions of approximately 10% between 1992 and 2006. The significance of using a consumption-based approach highlights that the stalling in emissions for Annex 1 nations relates to outsourcing, or an increase in final demand being met by imports, as opposed to domestic production (carbon leakage). Thus, suites of policies addressing both Annex 1 energy-related CO_2 emissions and CO_2 linked to imports through domestic consumption can reduce the rate of growth in territorial emissions in the non-Annex 1 nations and, as a consequence, the growth in global CO_2. However, whilst quantitatively coupling this alternative framework with a cumulative budgeting approach highlights how Annex 1 nations can take responsibility for an additional portion of global CO_2 emissions, thus broadening the scope of the Annex 1 reach in terms of mitigation, it also serves to reinforce the challenge of decarbonization for Annex 1 nations given the likely development paths in non-Annex 1 nations. There is a range of options available to Annex 1 nations to influence their consumer emissions that occur from imports and these would have to form part of a successful policy response to climate change mitigation. These include a combination of technology transfer and funds for the installation of low carbon technologies. In addition, there is the possibility to change the composition of consumption.

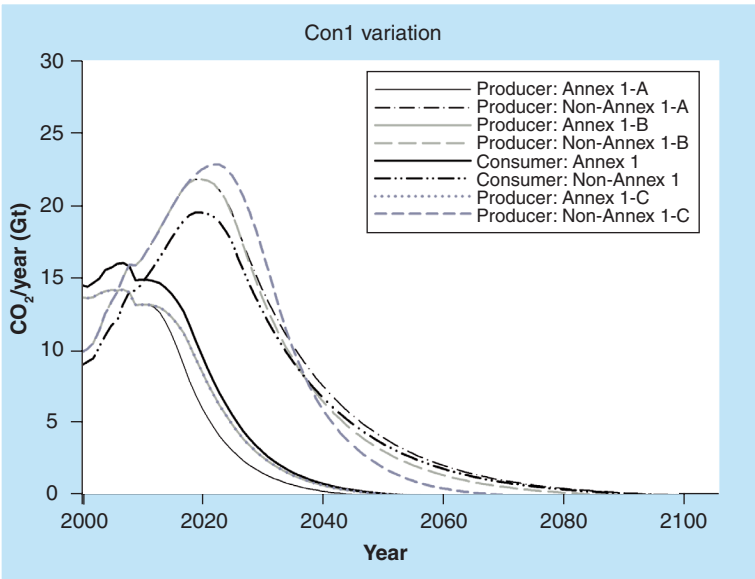

Figure 3. Four sets of scenario pathways constrained by a cumulative budget providing an approximate 36% probability of not exceeding the 2°C threshold. Thick black lines denote the Con1 consumption-based scenario pathways, where all other profiles represent production-based alternatives.

Table 1 presents the rate of CO_2 emission reductions for each of the consumption-based emission pathways following the peaking date. By contrast, Table 2 summarizes a series of scenarios developed within the Anderson and Bows paper under the territorial framework [9], and Table 3 presents parameters resulting from three scenario pathways developed for this paper using the identical dataset as the consumption-based scenarios, but analyzed from the production-based perspective (Figures 3–5). The results show that for the same cumulative budget, and notwithstanding very small differences between the databases in terms of the CO_2 emissions released per year, emission reductions in excess of 5% per year for Annex 1 nations are required under both the territorial and consumption-based frameworks within the scenarios presented, in order to allow for emission growth within non-Annex 1 nations.

The main quantitative difference between the consumption and production pathways is illustrated by the increasing viability of scenarios under the consumption-based framework for the most limited budgets. By redirecting some of the responsibility for CO_2 from non-Annex 1 nations to Annex 1 nations under the consumption-based approach, emissions peak a few years later in Annex 1 nations, and/or Annex 1 rates of reduction are marginally lower. This is also illustrated by non-Annex 1 CO_2 emissions being higher than Annex 1 nations later than would be the case using the production-based approach.

This pattern occurs in all six scenarios when comparing a consumption and production perspective. This can be seen most clearly by looking at the percentage reduction in all the scenarios; for example, in Con1, from the production perspective, non-Annex 1 countries are required to reduce emissions by 54% on 1992 levels by 2050. For the same scenario, this requirement is reduced to 48%, from a consumption-based perspective. This percentage variation in responsibility remains similar across all the scenarios, rising to 8% in Con5.

Table 1. Scenario data under the consumption-based framework.

Scenario	Global 21st Century CO_2 or greenhouse gas budget in $GtCO_2$ or [$GtCO_2e$]	Annex 1 peak date	Non-Annex 1 peak date	Global peak date	Annex 1 reduction on 1992 levels by 2020 (2050) (%)	Non-Annex 1 reduction on 1992 levels by 2020 (2050) (%)	Post-peak Annex 1 rate of reduction (%)	Post-peak non-Annex 1 rate of reduction (%)	Post-peak global rate of reduction (%)	Approximate percentage of exceeding 2°C (based on 2000–2049 emissions using Meinshausen PRIMAP [43])
Con1	1321	2007	2020	2016	33 (98)	+174 (48)	11	6	6	35
Con2	1321	2007	2020	2007	100 (100)	+204 (19)	50	6	7	X
Con3	1321	2007	2025	2015	21 (95)	+133 (59)	8	8	8	36
Con4	1578	2007	2020	2016	25 (84)	+174 (11)	5	4	4	43
Con5	1578	2007	2025	2019	17 (92)	+204 (24)	8	7	7	50
Con6	1578	2007	2025	2013	+51 (96)	+204 (24)	10	5	5	44

Table 2. Subset of scenario data using the territorial approach from Anderson and Bows.

Scenario	Global 21st Century CO_2 or greenhouse gas budget in $GtCO_2$ or [$GtCO_2e$]	Annex 1 peak date	Non-Annex 1 peak date	Global peak date	Annex 1 reduction on 1990 levels by 2020 (2050) (%)	Non-Annex 1 reduction on 1990 levels by 2020 (2050) (%)	Post-peak Annex 1 rate of reduction (%)	Post-peak non-Annex 1 rate of reduction (%)	Post-peak global rate of reduction (%)	Approximate percentage of exceeding 2°C (based on 2000–2049 emissions using Meinshausen PRIMAP [43])
C+ 1	1321	2007	2020	2012	56 (98)	+171 (54)	10–11	6–7	6–7	36
C+ 2	1321	2007	2025	2007	100 (100)	+193 (27)	X	6–7	6–7	X
C+ 3	1321	2007	2025	2007	56 (98)	+143 (54)	10–11	7–8	7–8	37
C+ 4	1578	2007	2020	2019	6 (84)	+186 (45)	5–6	5–6	5–6	50
C+ 5	1578	2007	2025	2020	44 (95)	+220 (32)	8	7–8	7–8	52
C+ 6	1578	2007	2025	2024	100 (100)	+220 (+38)	X	4–5	4–5	X

Data from [9].

Table 3. Scenario output from production-based analysis.

Production-based scenario	Global 21st Century CO_2 or greenhouse gas budget in $GtCO_2$ or [$GtCO_2e$]	Annex 1 peak date	Non-Annex 1 peak date	Global peak date	Annex 1 reduction on 1990 levels by 2020 (2050) (%)	Non-Annex 1 reduction on 1990 levels by 2020 (2050) (%)	Post-peak Annex 1 rate of reduction (%)	Post-peak non-Annex 1 rate of reduction (%)	Post-peak global rate of reduction (%)	Approximate percentage of exceeding 2°C (based on 2000–2049 emissions using Meinshausen PRIMAP [43])
Con1 variation										
A	1321	2007	2020	2014	55 (99)	+174 (48)	12	6	6	35
B	1321	2007	2020	2017	37 (98)	+174 (59)	11	7	7	36
C	1321	2007	2025	2012	37 (98)	+183 (73)	11	11	8	37
Con3 variation										
A	1321	2007	2025	2024	43 (95)	+134 (59)	8	8	8	36
B	1321	2007	2023	2018	26 (96)	+127 (52)	8	6	6	35
Con4 variation										
A	1578	2007	2020	2017	23 (93)	+174 (11)	8	4	5	44
B	1578	2007	2020	2017	30 (85)	+174 (21)	5	4	5	44

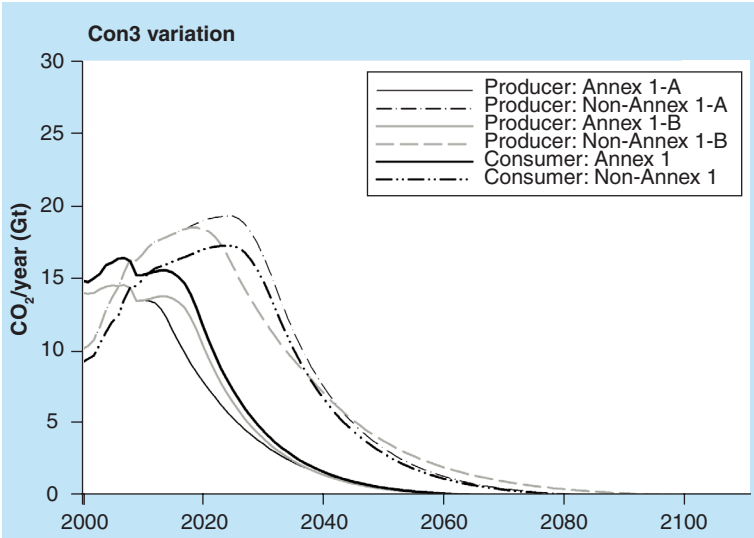

Figure 4. Three sets of scenario pathways constrained by a cumulative budget providing an approximate 43–50% probability of not exceeding the 2°C threshold. Thick black lines denote the Con3 consumption-based scenario pathways; all other profiles represent production-based alternatives.

Therefore, policies directed at consumption or final household demand within Annex 1 nations, in addition to more conventional climate policy, will influence a larger portion of emissions than is the case using only the territorial approach underpinning Kyoto targets. These polices could be implemented at a national scale to address levels and types of consumption, or equally could be adopted by organizations with global reach

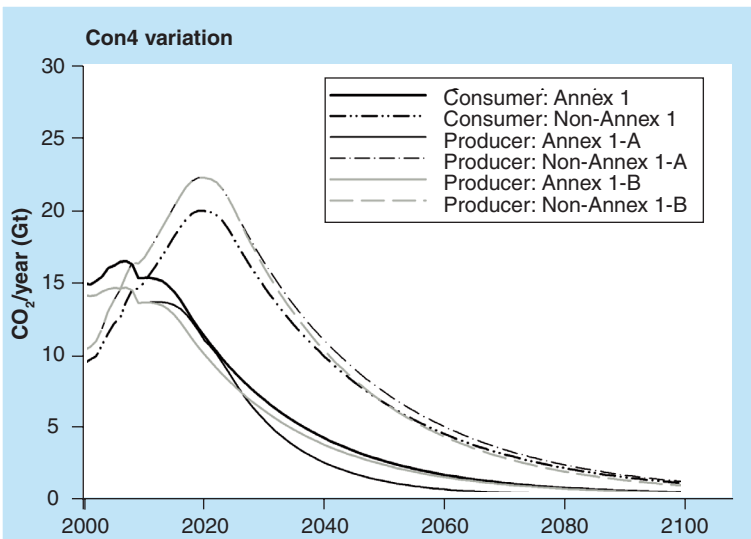

Figure 5. Three sets of scenario pathways constrained by a cumulative budget providing an approximate 36% probability of not exceeding the 2°C threshold. Thick black lines denote the Con4 consumption-based scenario pathway; all other profiles represent production-based alternatives.

who can influence both their domestic and international consumers in addition to technology transfer down supply chains beyond national boundaries [60]. As is the case with policies aiming to address energy demand, as opposed to energy supply, such measures have the potential to immediately influence global CO_2 emissions irrespective of any overarching global or multination agreement. Owing to their direct effect on emissions, they may also be less susceptible to some of the complications regarding leakage associated with instruments such as the Clean Development Mechanism. However, as **Figure 6** illustrates, it is the overarching cumulative budget used that has as much, if not more, impact on peaking dates and emission reduction rates than the chosen accounting framework. This is most pronounced for non-Annex 1 nations, given their higher cumulative share of emissions. Nevertheless, developing policies and measures that tackle a greater share of global emissions are essential if a reasonable chance of avoiding 'dangerous' climate change is to be maintained.

Whilst the consumption-based approach reduces the urgency of peaking dates and rates of emission reduction, the absolute quantity of carbon reductions necessary is increased for Annex 1 nations. However, what this analysis also highlights is that it is the overarching cumulative emission budgets that dictate the scale of change required. Irrespective of the emissions framework governing the scenarios, a growing population and rapid pace of economic growth, coupled with broader development within the non-Annex 1 nations, are defining factors for Annex 1 nations in meeting their climate change objectives. Only by recognizing the implications of a return to historical or even slightly below historical emission growth rates following the economic downturn for non-Annex 1 nations [39], can Annex 1 countries develop appropriate mitigation policy. Framing the problem around the feasibility of global emission reductions ignores how non-Annex 1 emissions growth will shape future global mitigation (and adaptation) policy [37,61]. Whether including or excluding the emissions from imports, the conclusion for Annex 1 nations is the same – to avoid a 'reasonable' probability of exceeding the 2°C characterization of climate change, emission reductions in excess of 5% per year are required as a matter of some urgency.

With regards to limitations of this analysis, the non-CO_2 GHGs were not explicitly incorporated into the emission pathways, although the cumulative budgets available for CO_2 were derived from modeling studies incorporating all emissions [41]. However, if they had been explicitly incorporated in the development of the consumption-based emission pathways, the conclusions

would probably be reinforced. Emissions associated with, for example, livestock would be allocated to the consumers of the meat, increasing the emissions allocated to Annex 1 nations. A further limitation is in relation to the explicit omission of emissions associated with land use change. However, since there is considerable uncertainty as to the scale of these emissions, in addition to debate regarding appropriate baselines, including them was beyond the scope of this study. Finally, the study does not include a global emission forecast based on future economic growth patterns coupled with the future composition of final demand by country. Additional research on the role of changing household composition required to deliver these emission pathways would be a valuable next stage in the work.

One final advantage of addressing consumption-related emissions is that it redirects the focus from the more technically-oriented discussion and debate surrounding energy systems. Pinning aspirations on the roll out of existing state-of-the-art technologies, or the development and deployment of new technologies is a 'dangerous' strategy given the timeframe necessary to avoid 2°C of warming. Although it is clearly not a straightforward task to either decarbonize supply chains, or influence consumer behavior towards lower-carbon lifestyles [60], tackling complementary avenues that have the potential to deliver in the short-term is essential for any reasonable chance of avoiding 'dangerous' climate change. Therefore, only by additionally tackling the consumption-related emissions can Annex 1 nations retain any hope of making a fair contribution to the climate change challenge.

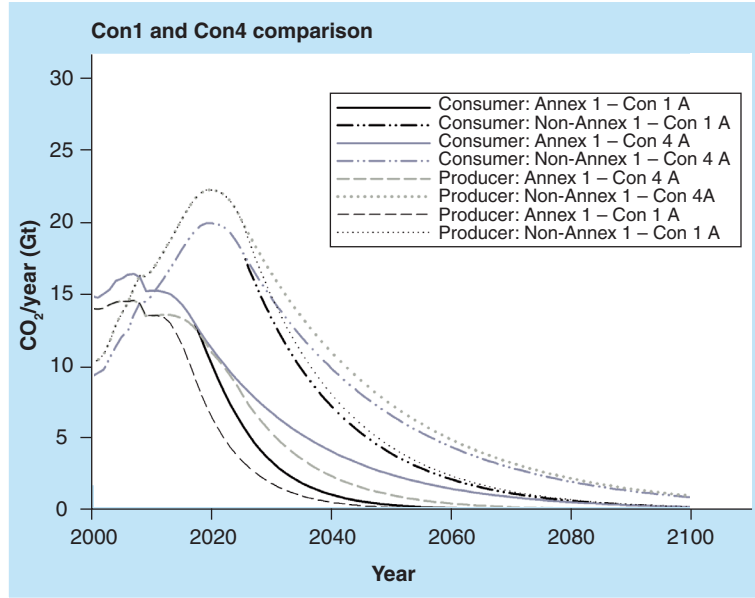

Figure 6. Comparison of consumer and producer-related emissions. Four sets of scenario pathways constrained by two different cumulative budgets to illustrate the difference between **(A)** consumer and producer-related emissions for similar growth assumptions and **(B)** the difference between those scenarios when meeting a larger or a smaller cumulative budget. Con1 has the smaller of the two budgets.

Conclusion

Emissions must reduce as a matter of urgency if the 2°C characterization of 'dangerous' climate change is to be avoided. The traditional territorial approach to emissions accounting within a cumulative emissions framing presents a stark picture for Annex 1 nations for what this means – urgent and radical emission reductions in the short term. Taking the alternative consumption-based approach delivers slightly less stark emission scenarios, since, at present, Annex 1 nations emit marginally more CO_2 than non-Annex 1 nations. However, this situation will not remain as such and, within just a few years, non-Annex 1 CO_2 emissions will exceed those within Annex 1 nations using the consumption-based framework for national emission accounting. The implications for Annex 1 nations are that there will be little room to increase emissions further if a reasonable probability of not exceeding the 2°C characterization of 'dangerous' climate change is to be maintained. This will necessitate a broadening of the policy focus from decarbonizing Annex 1 energy systems, to decarbonizing consumption through addressing how and what citizens consume. As illustrated with the example of the aviation sector, implementing mitigation policy aimed at reducing consumption-related emissions can reduce emissions throughout the supply chain. The gain in influence over emissions generated by international supply chains gives Annex 1 nations control over a greater proportion of global CO_2. This could, in turn, assist non-Annex 1 nations in their own decarbonization programs in promoting low-carbon development, given that many of the major exporting nations have the most carbon intensive industries. Although there are clearly implications in implementing such a framework at a national scale in relation to data gathering, particularly within non-Annex 1 nations, this does not preclude organizations from applying consumption-based mitigation measures immediately in order to compliment the existing territorial emission targets.

The global consumption-based emission scenario pathways developed suggest that Annex 1 countries have marginally more emissions space to use compared with a similar analysis taking the territorial approach. By taking responsibility for a proportion of the emissions currently associated with non-Annex 1 nations, Annex 1 nations can increase the chance of avoiding 'dangerous' climate change through their influence over supply chains. Moreover, given the growing number of 'consumers' residing in non-Annex 1 nations, there remain

few opportunities for meeting any global agreement to mitigate emissions to the extent necessary to avoid a 2°C temperatures rise.

Since non-Annex 1 nations are increasingly dominant in shaping both future climate change and the available emissions space for Annex 1 emissions (depending on the climate change target), Annex 1 nations have an additional incentive, under the consumption-based framework, to tackle consumption-related GHG emissions in order to have greater influence over global emission growth rates.

Ultimately, allying the cumulative framing of climate change with the consumption-based approach sheds light on new potential for a global low-carbon transition in line with avoiding a 2°C temperature rise than the conventional territorial approach. Nevertheless, cumulative budgets associated with a high probability of not exceeding the 2°C threshold between 'dangerous' and 'acceptable' climate change demand immediate and urgent emission reductions, irrespective of the accounting approach employed.

Future perspective

The conventional territorial framework governing emissions accounting nationally and internationally hides the growing influence of the consumer on the emissions burden. Goods consumed in one nation but manufactured in another are not conventionally quantitatively captured within the existing emission reporting mechanisms. Non-Annex 1 nations have increasingly manufactured goods for consumers within Annex 1 nations, yet the emissions associated with manufacture, if a Kyoto-like framework were to be implemented globally, would be allocated to them. Not surprisingly, this framework is not currently popular with non-Annex 1 nations but, as the threat and impacts of climate change grow, the need for meaningful and concerted global action becomes ever more pressing.

Following the failure of recent negotiations in Copenhagen to reach a global climate deal, academics are increasingly searching for new ways to tackle and frame the climate change challenge. The consumption-based

Executive summary

- Emissions must reduce as a matter of urgency if the 2°C characterization of 'dangerous' climate change is to be avoided.
- Following the failure of the Copenhagen negotiations of 2009 to deliver a global agreement on climate change, areas of impasse between non-Annex 1 and Annex 1 nations require further research.
- The consumption-based framework for emission accounting allocates responsibility for emissions associated with imports to the 'final demand' of nations, thereby potentially redressing elements of perceived inequity inherent within the conventional territorial emissions accounting framing underpinning the Kyoto agreement.
- Moreover, the scope for nations or organizations with global reach to influence emissions elsewhere in the world through effective climate policies outside of the inevitably drawn-out process of global negotiations must be explored.
- To determine the climate change mitigation effort required under the alternative consumption-based accounting framework, emission scenarios bounded by a cumulative emission budget over the 21st Century are developed and compared with a similar analysis that used the conventional territorial approach.
- Despite using this alternative framing, if emissions continue to grow at similar to historical rates in non-Annex 1 nations, Annex 1 nations are still required to mitigate their emissions at rates in excess of 5% per year within the decade.
- The most significant quantitative difference between scenarios developed using the consumption-based approach compared with those developed using the territorial approach is that mitigation pathways are slightly less stringent under a 2°C budget, even if non-Annex 1 nations' emissions continue to grow rapidly or peak as late as 2025.
- However, despite redirecting responsibility for a proportion of the emissions from non-Annex 1 to Annex 1 using the consumption-based framework, emissions growth in non-Annex 1 nations, driven by their own final demand for energy, goods and services, will be a defining factor in the emissions space available for Annex 1 nations.
- The consumption-based framework allows mitigation signals to cross-boundaries and, thus, opens up potential for internationally decarbonizing supply chains without any global agreement and increasing Annex 1 influence over global CO_2.
- As the high rates of growth in emissions in non-Annex 1 nations dictate the emissions space for Annex 1 nations, the Annex 1 nations have an additional incentive to tackle consumer-related greenhouse gas emissions.
- The implications for Annex 1 nations are that there will be little room to increase emissions further, requiring a broadening of the policy focus from national energy demand and supply, to how and what citizens consume.
- By taking responsibility for a proportion of the emissions currently associated with non-Annex 1 nations, Annex 1 nations can lever a greater chance of avoiding 'dangerous' climate change through their influence over domestic consumption and, hence, supply chain emissions.
- Without taking on this responsibility, and given the growing number of 'consumers' residing in non-Annex 1 nations, there remain few opportunities for meeting any global agreement to mitigate emissions to the extent necessary to avoid a high probability of exceeding a 2°C temperature rise.
- Ultimately, allying the cumulative framing of climate change with the consumption-based approach offers some additional potential for a global low-carbon transition in line with avoiding a 2°C temperature rise than the conventional territorial approach. Nevertheless, cumulative budgets associated with a high probability of not exceeding the 2°C threshold between 'dangerous' and 'acceptable' climate change demand immediate and urgent emission reductions, irrespective of the accounting approach employed.

framework is one way to address the issue that will likely increase in importance as negotiations with non-Annex 1 nations gather pace. The priority for a considerable proportion of non-Annex 1 countries is development and any climate change regime that significantly compromises this in a globally inequitable manner will remain unfeasible. The need to facilitate rapid and necessary development in many countries combined with adaptation and mitigation pressures due to climate change sets the challenge. Therefore, it will probably be difficult for large exporting and poorer nations to accept any binding target that does not remove, at least in some part, those emissions associated with their exports, adding them to the 'final demand' measure within industrialized nations.

On the other hand, these nations benefit economically from exporting to Annex 1 countries. If a balance between the two is to be sought, then it is likely that the academic community will increasingly explore more complicated but representative burden-sharing options to reach a global deal. Alternatively, some academics consider that a global deal is not an appropriate route forward at all. As such, academic research may also pay more attention to more nuanced and subtle measures implemented at a local scale that can influence emission mitigation further afield; for example, adding the emissions associated with EU imports into the EU Emission Trading Scheme, thereby extending the scope of influence of Europe. Whilst it is essential that this type of academic research continues, in this particular field every year is important, with the danger that if, in 5 or even 10 years time, a constructive route forwards has not been demonstrated, the emphasis for climate scientists will likely be on dealing with the impacts and adaptation strains put on the system.

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