Safe ends with just means: Charting a course to a fossil fuel free economy for Canada and beyond

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Abstract

Safe ends with just means: Charting a course to a fossil fuel free economy for Canada and beyond

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In this dissertation, I bring together a broad area of research in climate science and policy, ethics, ecological economics, political economy, and environmental sciences. I aim to cut through complexity and present clear conclusions that follow from decades of scholarship that has not yet made the impression on policymakers or the public that it deserves. This dissertation comprises three papers: 1) a critical overview of fair shares and decarbonization scenarios, and a way to reconcile what *should* be done with what experts think *can* be done (with a Canadian case study); 2) a framework for climate testing proposed fossil fuel infrastructure that can be used to evaluate an individual project's compatibility with global or domestic emissions reduction targets (with a case study of Canadian gas); and 3) an analysis of the potential for a shift towards services to mitigate GHG emissions and other environmental impacts. The results of paper 1 show that under a relatively ambitious but still insufficient decarbonization program, Canada is projected to accrue an emissions debt of 6 to 52 $GtCO_2e$ by 2050, which could be valued at \$0.8 trillion to \$6.5 trillion using the best estimate for the social cost of carbon dioxide. Paper 2 concludes current plans to extract Canadian gas are unequivocally at odds with national and global climate efforts, and that even climate action in line with an inequitable share of ~2–3°C of warming necessitates an immediate and rapid phase out of gas extraction within years. Papers 1 and 2 contribute policy tools needed for Canada and similar wealthy fossil fuel producing nations to do their fair share of a global energy transition, even when a domestic energy transition is limited by political or technological constraints. Paper 3 shows that when counting household consumption of people as part of the sectors that employ them, supposedly 'clean' sectors like services are just as harmful as 'dirty' ones. This exposes the limited potential to reduce environmental impacts by growing the service sector, refuting claims made by advocates of green growth via an explosion of the knowledge economy. These findings may be used to inform policymaking, so that appropriate emphasis is placed on behavioural, technological, and structural changes to the economy. Together, realizations from this dissertation can be used to craft fair and practical policy for a just transition for Canada, through integrated domestic and foreign policy, which also could serve as a model for other affluent nations.

Dedication

To all beings who are deprived of a decent life
by the greed, inconsiderateness or shortsightedness of others.

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Contribution of Authors

Most of this work was carried out solely by myself, under the supervision of my supervisor, H. Damon Matthews. Chapters 1 and 2 are entirely my own work, with input from Prof. Matthews. Chapter 2 is a second incarnation of analysis performed for the *Bureau d'audiences publiques sur l'environnement* (BAPE) for the *Projet de construction d'un complexe de liquéfaction de gaz naturel à Saguenay*, submitted to the BAPE in Greenpeace Canada's memorandum, and updated for the British Columbian government's environmental consultation on *Cedar LNG*. Chapter 3 was originally a team project, and was published as a coauthored study in *Environmental Research Letters* in 2020 (available at doi.org/10.1088/1748-9326/ab7f63). The project was originally devised by Tim Crownshaw and myself and its first incarnation was as a project for a course in ecological economics with Peter Victor (Professor Emeritus, York University). I performed the analysis, while TC and I co-wrote the paper, with the assistance of discussions and editing from HDM, Corey Lesk, and Konstantin Stadler. I take full responsibility for any omissions or errors found herein.

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1. Introduction

1.1 Our failure to address the climate crisis

Industrialization has brought both unprecedented wonders and dangers. The same technologies[1,i] that have allowed us to proliferate and prosper as a global organism also bring with them an escalation of risks that threaten to destroy us[2–4]. According to the Bulletin of the Atomic Scientists, humanity now stands "the closest it has ever been to civilization-ending apocalypse" since the advent of the H-bomb in 1952[ii]. Nuclear holocaust is now joined by other existential threats of our own making, most notably climate change[iii]. Humans have been altering the earth's climate for thousands of years (some say as long as 8,000 years[5]), but today's levels of anthropogenic interference with the climate are unprecedented, extremely dangerous, and have pushed us out of the stable climatic condition of the Holocene that made our planetary success possible. If left unchecked, climate disrupting greenhouse gas (GHG) emissions threaten to destabilize global organized society, as we know it.

Thanks to industrialization, atmospheric carbon dioxide levels have increased more in the last 150 years than the previous 22,000. Atmospheric carbon dioxide (CO_2) in 2021 reached a record high level of 419 parts per million (ppm)[6]. The last time CO_2 levels were this high was at least 3 million years ago, possibly long before the Pliocene when our simian ancestor Australopithecus walked the earth. According to the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), 2019 was the second hottest year on record, with the global mean temperature 1.15°C above preindustrial average, and just 0.04°C cooler than the 2016 record[7]. 2020's summer was the hottest on record in the northern hemisphere[8]. The most recent record-breaking year of 2016 had the help of the 4th strongest El Niño on record, but in 2020, humans were the dominant contribution to the heat anomaly[9]. 2021 was the sixth hottest year on record, but the top ranking years differ by small amounts[10]. Industrial activity has become the dominant force altering the climate system, as well as virtually every other Earth system. Our species' planetary dominance has been marked by a new epoch, dubbed the Anthropocene, which will be indelibly recorded in Earth's geological records[11].

With the current amount of warming, we are already seeing serious harms that include increasing frequency and intensity of flooding, wildfires, droughts, heat waves, expanded impacts

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[i] This ambiguity is deliberate: I refer to technologies broadly as in all human technology (material and cultural), and also specific technologies that are primarily responsible for climate change — fossil fuel energy and the systems that rely on this kinds of energy. Industrial civilization itself is a product of highly dense energy sources (in technical terms, with high energy return on energy invested), chiefly cheap and accessible coal and oil. For a larger discussion of this aspect, see for example *Fossil Capital* by Andreas Malm (ref.[1]).

[ii] See the 'current time' and the 1953 statement from the bulletin of atomic scientists, retrieved from https://thebulletin.org.

[iii] I would just like to clarify, I am aware that the ecological crisis is broader than risks posed by climate destabilization. However, the climate crisis is the focus of this work, though I keep in mind the other existential dangers to human and other life posed by unfettered industrialization, like accelerated biodiversity loss, dangerous air and water pollution levels, and the transgression of other so-called planetary boundaries. The Bulletin of the Atomic Scientists also notes other risks to security and health of people and the planet, like a renewed nuclear arms race, the proliferation of mis- and disinformation that threatens the stability of democracies around the world, a new arms race for biological weapons, as well as for anti-satellite and hypersonic missiles, and new disease vectors like the SARS-CoV-2 virus and the related COVID-19 pandemic.

of pests and pathogens, and other effects[12]. All of these are linked to climate change, and will be exacerbated by further warming[13]. Canada is warming at twice the global average rate[14] and is already experiencing many of climate change's deleterious effects[15]. For example, last summer's catastrophic flooding in British Columbia was made at least twice as likely due to climate change, and its devastating heat wave and associated fire that destroyed the town of Lytton was made 150 times more likely[16]. Heat waves across the province killed 595 people that summer, the vast majority during the heat wave itself[17]. As noted above, the impacts of climate change are only expected to worsen, with intense heat waves, wild fires and floods becoming the new normal in BC and much of the Pacific Northwest[18]. Around the world, extreme weather events will occur with increasing frequency and intensity; for example, heat waves that occurred once every ten years during preindustrial times will be 9.4 times as likely to occur and 5.1°C hotter in a 4°C world[i].

The international scientific community has issued repeated calls for immediate and decisive climate action. Over the last few decades, consensus that industrial activity is warming the planet has strengthened. The main scientific body that brokers this consensus, the Intergovernmental Panel on Climate Change (IPCC), now states unequivocally that GHG emissions are responsible for warming the planet and destabilizing the climate[12]. Climate risks can only be adequately addressed through deep reductions in GHG emissions in the next decades, with the window for limiting warming to 1.5°C or 2°C rapidly closing (ref.[12], p. 13-14). The biggest determinant of future warming and its impacts are decisions taken today[12,19]. Most recently, the IPCC released Working Group III's contribution to the *Sixth Assessment Report*, which is responsible for reviewing the literature on emissions pathways. They found that without immediate and dramatic action, it will be impossible to limit global temperature rise to 1.5°C above pre-industrial levels; but if we act now, we can still cut emissions in half by 2030 and have a chance of avoiding the worst effects of climate change[20].

The threats to our global society posed by nuclear war and climate disruption both require unprecedented international cooperation, based on good faith and forward thinking for the collective good, however, only climate change requires transforming the energy system that has made industrialization and globalization possible – namely, the profligate use of millions of years of solar energy stored in fossil fuels over less than two centuries[ii]. This transformation will require radical changes to our economic structure that are also unprecedented, never having been required before to address any global crisis. Nations have acknowledged the problem and vowed to work together to transform our energy system and mitigate emissions, but after 30 years of negotiations, pronouncements and agreements, global GHG emissions continue to rise relatively unimpeded. Since nations first met in 1992, at the Earth Summit in Rio de Janeiro and the United Nations Framework Convention on Climate Change was first opened for signatures, annual

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[i] One in 50-year heat waves will be 39.2 times more likely to occur and be 5.3°C hotter. For a more complete list of how marginal increases in global warming will increase the frequency and intensity of weather extremes, see fig. SPM.6 in ref.[12], p.18-19.

[ii] To be precise, all energy is derived initially from the sun. Fossil fuels, however, are nonrenewable since they accumulate during the decomposition of organic matter under high pressures and temperatures over the course of millions of years – far longer than human or even civilizational lifespans.

carbon emissions have risen steadily by 60% and cumulative carbon emissions (since the beginning of industrialization) have doubled[i].

Developed nations have emitted the most historically, and are likewise the most culpable for, as well as the best equipped to deal with the climate crisis[21–26]. Conversely, developing nations have emitted the least historically, and still have much lower emissions per person today than richer countries, and are likewise least culpable and capable. Assuming that these countries continue to develop along traditional paths, their per capita and total emissions are also expected to grow — much more than developed countries that have already fully industrialized and reached levels of consumption of the world's most affluent. In other words, the bulk of the world's new emissions can be expected to come from the developing world as they industrialize and grow richer, producing and consuming more as they 'catch up' to our standard of living, or perhaps a more sensible lower level of consumption that we in the Global North can converge with. In other words, just because some growth is expected and indeed warranted from the Global South means that rich nations must decarbonize their economies as fast as possible in order to make room for marginal increases in emissions from developing countries — both on the basis of practicality and equity. Not only will developing nations need assistance to decarbonize, and indeed they are owed it by the affluent world to redress past inequities in emissions[27], but that perceived fairness is essential to cooperation in climate action[28].

It is also important to call attention to the responsibility of fossil fuel producers (both nations and corporations) that have played central roles in entrenching fossil fuel energy[29]. Fossil fuel corporations knew as early as the 1950s that combusting fossil fuels warms the planet, and actively sought to misinform the public and policy makers instead of adapting their business model. Their intransigence continues to this day, despite overwhelming evidence that fossil fuels must be abandoned if we are to keep warming below unacceptably dangerous levels. Instead, fossil fuel corporations and fossil fuel producing nations continue to undermine progress at the international level, heavily influencing guiding principles in negotiations by opposing the consensus of more progressive nations and non-governmental actors. Until COP26, no explicit wording around constraining fossil fuel production can be found in the text of any international climate agreements[ii]. A growing number of people within the academic, civil society and social movement communities have called for fossil fuel corporations to be excluded from climate negotiations, since they have proven year after year to use their presence only to impede or delay the energy transition as much as possible. Despite their vested interest in obstructing the transition and their hindering influence, they are continually allowed to participate in international proceedings.

1.2 A brief history of international climate negotiations

Governments first met together in 1992 to discuss the problem formally under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) at the first Conference of the Parties (COP). The UNFCCC became the world's international treaty to address climate

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[i] Carbon emissions are from fossil fuel and cement only. Annual emissions grew from approximately 22.5 to 36.5 Gt CO_2 (or 6.1 to 10.0 in units of Gt C, using a ratio of 3.67 for molar mass of CO_2 to C of 44 to 12 g/mol). Data on historical carbon and carbon dioxide emissions is taken from CDIAC and the Global Carbon Atlas.

[ii] Some wryly refer to fossil fuels as the 'f-word', given how taboo its mention is. On the difficulty of getting fossil fuels explicitly mentioned in climate treaties, see, for example, ref.[30]

change when ratified in Rio de Janeiro at the Earth Summit shortly thereafter. Since then, nations participating in the UNFCCC process, known as 'the Parties', have met 26 times at COP summits, most recently hosted by the United Kingdom in Glasgow, Scotland.

The asymmetry in responsibility to act on climate change was formalized from the outset of international climate governance in the principle of "Common But Differentiated Responsibilities" (CBDR) at the 1992 Earth Summit in Rio de Janeiro, Brazil. The principle is outlined as follows, and recognizes the inherent differences in responsibilities for and capabilities to act on climate change:

> The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof.[i]

It was in this spirit that countries who joined the UNFCCC committed to global cooperation to act on climate change[ii]. Since the Parties agreed that equity is central to the energy transition, research into ways to operationalize equity has become increasingly popular. Although sharing emissions is necessarily a subjective question, approaches have been developed by researchers from both the scientific community[31] and social science community[32,33], each with their own flavour and emphasis on technique or outcome priorities, as well as inherent biases or technical limitations[iii].

However, high-level framing of action is of course not action in and of itself. Within the cadre of international diplomacy, operationalizing climate policy (or any international effort on a global scale) requires international treaties. The Parties have tried two fundamentally different approaches. First, Parties agreed to try a top–down legally binding international treaty. More recently, Parties opted instead to try a bottom-up voluntary pledge-based system paired with an iterative process to continuously increase the ambition of national pledges until they are collectively sufficient to meet agreed-upon warming targets.

The first attempt at codifying climate action was the Kyoto Protocol, modeled after the successful international treaty to phase out CFCs, the Montreal Protocol[iv]. Following the first

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[i] See Article 3, Paragraph 1 of the "United Nations Convention on Climate Change". *UNFCCC*. 1992. p. 4. Retrieved November 2, 2018 from https://unfccc.int/resource/docs/convkp/conveng.pdf

[ii] *ibid*. See Article 4, Paragraph 1.

[iii] One early method, Contraction and Convergence (C&C), was proposed by the British think tank GCI. Documentation on the approach can be found at their website: http://www.gci.org.uk/SDa.html. Since then, many new ways of sharing emissions have been put forward. Emissions sharing will be explored in greater depth in Chapter 1.

[iv] The Montreal Protocol's ease of success can be attributed to the fact that CFCs had a ready-made alternative, hydrofluorocarbons (HFCs), which could be produced by the same actors who already were manufacturing CFCs. It was a relatively trivial matter to switch from CFCs to HFCs as refrigerants, and there was little resistance from the chemical industry since the technology to produce either was the same and the recipes and patents had already been procured. Phasing out fossil fuels, on the other hand, requires shifting the entire energy paradigm of industrial civilization, where the most profitable industrial industry, fossil fuel extraction, will be rendered obsolete. Corporate interest and their fierce opposition aside, the question remains whether humanity at this scale of consumption can even be supported in the same economic paradigm without energy sources of such high energy returns for energy invested. For these reasons and more, it should not come as a surprise to any astute observer that modeling a climate

approach, it was an ambitious piece of international diplomacy that took the form of a legally binding agreement between the world's most developed nations to reduce their greenhouse gas pollution levels, with financial penalties for failing to meet agreed upon targets. Developing nations[i] — having emitted the least historically and having lower per capita emissions than affluent nations — were not obligated to participate, at least in the first incarnation of the protocol, though it was acknowledged that developing nations would have to eventually curtail their emissions as well.

Some developed nations, like the United States, argued that developing or rapidly industrializing nations like China and India should not be excluded since they are the fastest growing sources of emissions and are destined to make up a larger proportion of global GHG emissions than developed nations in the near future. It was on this basis that the United States, under George W. Bush's Republican administration, refused to ratify the treaty. Almost ten years later, Stephen Harper's Conservative government withdrew Canada from the Kyoto Protocol when it became clear that national emissions would not decline to meet the national target of 6% reduction by 2012 relative to 1990 levels. Emissions instead rose 19% from 1990 levels by 2012[ii]. Globally, emissions continued to rise, and many affluent nations who did report reductions in line with their targets (like many in the European Union) were due to the dislocation of manufacturing to developing nations[34]. Others could attribute their emissions reductions to a combination of reductions in fossil fuel intensity of their economies and economic downturn, most notably Russia's economic decline following the collapse of the Soviet Union, whose emissions have only recently started to rebound[35,iii].

Following the failure of the Kyoto Protocol, the Parties abandoned the top-down governance model in favour of an opt-in approach — bottom-up voluntary pledges. This form of international climate governance has been most recently codified in the Paris Agreement, where Parties have renewed and reaffirmed their vows to work collectively to avoid unacceptably dangerous levels of climate change, but this time allowing each other to pledge whatever they feel is reasonable at the time, while also revising the current temperature limit downwards from 2°C to 1.5°C. While this has shown a strengthening of resolve, the Paris Agreement's language leaves some ambiguity, countries have agreed to strive towards holding warming to 1.5°C, but have committed to keeping warming to 'well below' 2°C[iv] above preindustrial times.[v] This increase in ambition, even with its inherent ambiguity, does acknowledge the most recent scientific consensus that any warming in excess of 1.5°C will likely prove deleterious to human

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agreement that necessitates a strong phase down of emissions would conflict with fossil fuel interests and the incumbent economic paradigm, and that its success would be doubtful.

[i] Developing nations were referred to in the Kyoto Protocol as 'non-Annex countries', while those who were obliged to make emissions reduction commitments were called 'Annex 1' countries.

[ii] Emissions rose from 590 to 700 Megatonnes (Mt) carbon dioxide equivalents (CO_2e) excluding emissions from Land Use, Land Use Change and Forestry (LULUCF). Source: https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2014

[iii] It is worth noting the 2008 global financial crisis only caused a brief downturn in economic growth and likewise a temporary decline in global emissions, which quickly rebounded.

[iv] 'Well below 2°C' has been left open to interpretation (i.e. it has not been uniquely defined nor explicitly quantified), and in practice most research quantifies it as 1.75°C or 1.8°C.

[v] See Article 2, Paragraph 1.a. of the "Paris Agreement". *UNFCCC*. 1992. p. 3 Retrieved November 2, 2018 from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

society, and other earth systems our species rely upon, and that the impacts from an additional 0.5°C of warming are substantial enough to warrant avoiding.

Despite these recent insights and reaffirmations, global GHG emissions continue to rise. Global emissions reached a record high rate of 35 Gt CO_2 in 2019 (ref.[36]), before the start of the COVID-19 pandemic. While emissions growth did decline briefly during the COVID-19 pandemic, this trend has since reversed, with 2021's global emissions rebounding to only 1% shy of 2019's record high[37,38]..

The implications for fossil fuel use are clearer than ever. The 2018 Special Report on 1.5°C put numbers to what we have known for decades — that the vast majority of fossil fuel reserves cannot be combusted under 1.5°C or 2°C scenarios, and that drastic reductions in our consumption of fossil fuels must be achieved by midcentury, with reductions of 87% of oil, 74% of gas, and 97% of coal combustion by 2050 (relative to 2010 levels) to keep global temperatures under 1.5°C warming[39].

1.3 Policy options under the Paris Agreement

So what can be done about rising emissions? Most policy to date has focused on ways to decrease carbon emissions by targeting the consumption of fossil fuels, for example by introducing carbon prices or caps on emissions, spurring innovation and the proliferation of renewable energy technologies, or improving the energy efficiency of utilities, buildings or transport. Comparatively little attention has been paid to the converse of these approaches, that is to constraining fossil fuel supply, rather than demand for fuels. Mitigation policies that target the supply of fossil fuels would complement demand-side measures, greatly enhancing their effectiveness, and are likely needed to conduct an energy transition at the scale and pace needed, while safeguarding the global economy from undesirable shocks that may surprise nations and cause severe social harms[40–44,i]. Under the Paris Agreement, Parties have pledged domestic emissions reduction targets via a mechanism called 'Nationally Determined Contributions' (NDC). The vast majority of these NDCs express demand-side mitigation measures, like phasing out the use of coal-fired plants for electricity production (called the 'Powering Past Coal Alliance', of which Canada is a member) or improving energy efficiency. Moving beyond demand-side policies alone to a holistic framework that also employs supply-side measures is a promising next step[41]. A select few NDCs already address fossil fuel supply directly[45]. Extreme

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[i] Demand-side and supply-side measures can be formalized as follows: 'Demand-side climate policy' focuses on reducing emissions from the consumption of fossil fuels. These policies may target any actor in the economy, including individuals, businesses, public sector operations, or utilities. Examples of demand-side policy include programs that encourage the uptake of low-carbon energy technology (e.g. renewable energy), carbon pricing (e.g. carbon tax or cap-and-trade markets), efficiency measures (e.g. better insulation in buildings, lower carbon intensity of fossil fuel production), and so on. Most policies today fall in this category. In contrast, 'Supply-side climate policy' is aimed constraining the production of fossil fuels themselves. This includes limiting extraction directly, as well as upstream investments in extraction (existing and future projects), exploration for new reserves, and transportation of fuels. Examples of supply-side policy include removal of financial incentives for fossil fuel production (e.g. fossil fuel subsidy phase outs), moratoriums on new extraction projects, and so on. Much fewer supply-side measures exist at present, with certain countries with modest reserves opting to constrain production, but the practice of constraining fossil fuel production has not been made an explicit requirement of any international climate governance treaty or agreement thus far.

policies include placing moratoriums on new oil and gas extraction, while less ambitious measures could involve removing subsidies to the fossil fuel industry or awarding more to their low carbon or carbon free alternatives like renewable energy utilities.

1.4 The need for an orderly phase out of fossil fuels

Every decision to invest in new fossil fuel production or infrastructure carries with it a commitment to future emissions[46–49]. Globally, committed emissions from existing fossil fuel infrastructure have grown from 496 Gt CO_2 in 2010 (ref.[48]) to 658 Gt CO_2 in 2018 (ref.[49]), which undermine our ability to curtail emissions sufficiently to remain under 1.5°C or even 2°C[50].

Even if policy changes to make extraction unprofitable, sunk costs can make continuing to extract, even at a loss, attractive, as long as operating costs do not exceed revenues, so that producers can recoup as much of their upfront capital expenditures as possible. This behaviour is referred to as ‘carbon lock-in’, and the financial gains ultimately lost are referred to as ‘stranded assets’[51]. Recent research suggests that early retirements of fossil fuel infrastructure will be needed to curtail emissions fast enough to meet the objectives set out in the Paris Agreement[52], and likewise, that the stranding of assets (both in the form of unexploited reserves that were once seen as economically viable and fossil fuel infrastructure itself) will be unavoidable.

Fossil fuel supply and demand are closely interrelated. Infrastructure creates demand for supply, while increasing supply lowers fuel prices, which in turn incentivize building more fossil fuel infrastructure[53–55]. Choices regarding what to build now, as well as what fossil fuel exploration and development to invest in, are based on long-term price forecasts that naturally play off these market dynamics. For example, promises of abundant cheap coal from Australia will incentivize the construction of more coal power generation being built in India, as much as projections of energy demand from coal in India generate supply in Australia.

Price forecasts and demand for fuels have been systematically overestimated in recent years, leading to oversupply, which has in turn kept fuel prices even lower[56]. This tendency will continue to undermine the effectiveness of demand-side measures to curtail emissions on their own, with a growing number of researchers and members of civil society calling for a coordinated effort to limit fossil fuel supply to keep it aligned with demand commensurate with a global energy transition as implied by climate targets of the Paris Agreement[40].

Furthermore, deciding who gets to extract what is not part of international climate governance at present — even the words ‘fossil fuels’ themselves do not appear even once in the Paris Agreement. This does not mean that deciding which reserves remain extractable (or which countries should get to extract them) under Paris is not of prime importance to the Agreement’s success, as countries must agree sharing remaining reserves, like remaining emissions, in a way they collectively perceive as satisfactorily equitable for all parties[57,58]. In other words, countries with vast reserves that feel other countries are not constraining their own supply sufficiently will have little incentive to constrain theirs, which jeopardizes curtailment of supply needed to ensure the success of the Paris Agreement.

1.5 Tracking peril and progress

Having reliable estimates of committed emissions from fossil fuel production is necessary to estimate these emissions' possible impact on the climate. At present, we have estimates of viable reserves, and can compare the emissions that would result from them when combusted, and compare this directly to the carbon budget[55,59,60]. Developed reserves would be enough to raise global temperatures well past 1.5°C[60]. We can also track the amount of emissions embodied in extracted fuels and allocate these emissions to the nations who extract them[61]. These values are sometimes astonishing. For instance, Canada's net exports of fossil fuels embody as much CO_2 as it emits territorially[62]. Even when these 'exported' emissions are neglected, the upstream emissions alone from oil and gas extraction in Alberta would make its per capita emissions highest in the world if it were a country (about 70 t/CO_2e, much larger even when compared to other small oil producing states like Kuwait at 55 t/CO_2e and Qatar at 37 t/CO_2e). The oil and gas sector is also the fastest growing source emissions in the country, slated to comprise half of Canada's territorial emissions by 2030, which would necessitate unrealistic reductions from the rest of the economy to satisfy Canada's still insufficient national target[63].

Monitoring global emissions is further complicated by standards and practices in GHG accounting. There are many principles available to account for a nation's emissions. Traditionally, greenhouse gas accounting (and environmental impact accounting more generally) attributes emissions to the countries that produce commodities. This practice is referred to as production-based accounting. However, this perspective fails to consider emissions from many other important perspectives and allow for emissions 'leakage' to occur, where emissions reductions in one nation or sector of the economy are displaced to other countries or sectors, sometimes even leading to overall global emissions growth[64]. Leakage between nations due to rising international trade — with roughly a third of global GHG emissions now embodied in trade — has become a major problem, undermining the efficacy of global mitigation efforts[34]. In order to capture these dislocated emissions, an alternative approach attributes emissions to the countries that consume commodities, known as consumption-based accounting[65]. This approach, if employed in national emissions monitoring, could help reduce emissions leakage significantly, since it would not allow countries to report emissions reductions by dislocating emissions-intensive activities, like manufacturing, to other countries, while potentially also improving cost-effectiveness and equity in international mitigation[66,67].

Although it greatly improves our understanding of emissions linkages throughout the global economy, consumption-based accounting (or any single accounting approach used in isolation) fails to account for other important considerations, and leakage may still occur, for example due to dynamics between fossil fuel supply and demand, or between sectors when policies pursue emissions reductions that seek to reduce emissions by reducing energy demand or structural economic changes, respectively. Carbon leakage from isolated demand-side approaches has been discussed, with supply-side policy advocates calling for an integrated approach that aims to curtail energy demand and fossil fuel production in tandem, in order to reduce leakage effects[42], and leakage effects caused by renewable energy adoption explored, where it has been found that intermittent renewables have not displaced any fossil fuel electricity sources over the last fifty years, and all non-fossil fuel energy sources have displaced at most a quarter of what they have added to global energy production and consumption[68]. Emissions leakage between industries during structural changes has not yet been investigated. We have examined the potential effect of tertiarization on national or global emissions[69], but from a static perspective

(Section 5). Dynamic input–output or general equilibrium models could be used to further test this hypothesis (Section 6).

1.6 New insights call for more realistic sustainable development goals

Industrial impacts tend to be viewed as onsite and localized, even when considering the flows between industries using e.g. consumption-based accounts. This convention tends to create a distinction between 'cleaner' and dirtier' industries, i.e. clean industries tend to be more productive than dirtier ones per unit environmental impact. However, impacts related to 'dirtier' industries tend to be driven by consumption by people employed in 'cleaner' industries, especially high-wage service jobs, in both private and public sectors. Hence countries that import large amounts of goods and services also import not only their localized impacts, but also the impacts that are more distally-driven by the consumption of those employed in services which are purchased by foreign consumers. Countries that consume relatively large amounts of services tend to have higher climate impacts when viewed from this perspective. Prominent examples include countries with large social welfare states like many in Scandinavia and Europe[69].

The leakage becomes more apparent when viewed from an industrial perspective. When examining the impact of industries in absolute terms (attributing household consumption of labour to their employing industries), services (already the primary driver of GHG emissions) double in impact (from 22% to 45% of global GHG emissions). In terms of impact per unit production (which is needed to understand the potential for decoupling of GHG emissions from economic growth via a shift to services), services are no 'cleaner' (in this case, no less emissions-intensive) than other sectors. However, aggregation of public and private services obfuscates significant heterogeneity of impacts within the service sector. In absolute terms, the main drivers of emissions are located within the public sector[i], while per unit production, the emissions intensities of service industries vary widely, with low-wage service jobs such as hospitality having an order of magnitude less impact per dollar than technology, health and education jobs. Ultimately, there appears to be no structural way of getting around the need to reduce material and energy throughput, though as surely as they will occur, structural changes must play a role.

1.7 Advancing the state of policy research

The effectiveness of national and international climate action can only be improved by investigating these drivers and further refining our understanding of them and the accounting principles we base mitigation policy on. This brings us to the motivation for the research outlined in this doctoral thesis. I will now introduce the guiding research questions before moving into the chapters themselves.

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[i] Keep in mind much of the political narrative surrounding a just transition relies heavily on economic growth via a shift to 'green jobs' needed to build the infrastructure needed for the energy transition and jobs with lower onsite impacts in the care economy like teachers and nurses. That said, it seems that much of the income paid to workers in high-paying private sector service jobs, in particular in the finance industry, are not counted as wages in national accounts, and therefore, the impact of the private service sector may be substantially underestimated.

2 Research Questions

Paper 1: How do we craft fair and practical climate policy for Canada and beyond?

> What are equitable shares of greenhouse gas mitigation effort or emissions remaining under the Paris Agreement for Canada, and how do these compare to what is politically feasible and/or technically possible to achieve? How can what is fair be reconciled with what is deemed feasible through international climate governance mechanisms? In other words, what is Canada's climate debt expected to be under different rapid national decarbonization scenarios, and how can it be paid back to countries deprived of their fair shares of global emissions remaining under the Paris Agreement?

Paper 2: How do we determine or show whether new fossil fuel infrastructure is compatible with the Paris Agreement?

> How can Canada and other wealthy fossil fuel producing nations test whether proposed fossil fuel infrastructure fits within national targets or global efforts to stay below agreed-upon warming thresholds? How much emissions could be mitigated globally by efforts to limit the expansion of fossil fuel infrastructure?

Paper 3: Can shifting towards services help reduce environmental impacts throughout the global economy?

> In the absence of policies to rapidly decarbonize the global energy system, what GHG emissions leakage may result from pursuing tertiarization of the global economy? How important is structural change in a global energy transition, if at all? And how can the composition of the global and national (e.g. Canadian) economy change to best promote the just transition?

3 Paper 1: Reconciling equity and practicality in national climate policy of affluent nations: Case study of Canadian climate policy for a globally just transition

The following manuscript is being prepared for submission to Climate Policy *by the author and Matthews, H. D. An earlier version of the analysis herein was published in 2019 in the report 'From Paris to Projects: Clarifying the implications of Canada's climate change mitigation commitments for the planning and assessment of projects and strategic undertakings', available from https://uwaterloo.ca/paris-to-projects/sites/ca.paris-to-projects/files/uploads/files/p2p_full_report_23jan19.pdf*

3.1 Abstract

Top-down emissions sharing proposals often conflate what is believed to be fair with what is thought feasible. By attempting to craft fair and practical policy simultaneously, many of these emissions sharing approaches may ultimately compromise both equity and feasibility of proposed decarbonization outcomes. To avoid this problem, we propose that equity and practicality of emissions sharing be assessed independently, before comparing the two idealized approaches and finding ways to reconcile them. Our approach is divided into three steps: 1) determine what is the ideal fair share (or range of fair shares) for a country, 2) determine what it can feasibly do to decarbonize its economy as rapidly as possible, given a range of technical and political assumptions; and 3) find ways to redress the discrepancy between (1) and (2), which we refer to as a 'Paris gap'. We focus on affluent nations, since it is these countries whose efforts have been most insufficient and who continue to fall short of sufficient contributions to global mitigation. Further, the success of global climate action depends vitally on reconciling rich countries' Paris gaps. We use Canada to illustrate how this approach can be applied by collecting available modeling scenarios of possible emissions futures and compare them to a robust suite of fair emissions shares. We find a large Paris gap between equitable and practical outcomes, the median Paris gap amounting to between 6 and 52 GtCO$_2$e by 2100 for low and high equity shares, respectively. We then propose ways for this gap to be redressed via support for international mitigation and adaptation.

3.2 Introduction

Human activity is warming the planet and causing irreversible climatic changes that are already harming many vulnerable human populations and other species[12]. In order to limit the worst impacts of climate change and reduce the odds of passing perilous tipping points, the international community has agreed to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C[70]. Stabilizing global temperatures require reducing annual carbon dioxide (CO$_2$) emissions to near-zero levels[71]. This also means that there is a finite amount of CO$_2$ emissions remaining, often referred to as the remaining carbon budget (RCB)[72–74].

How these remaining emissions are shared is key to both the success of global decarbonization and the wellbeing of nations. Crucially, countries are more likely to cooperate if they believe others are doing their fair share[28,75]. It follows that if efforts were divided fairly, it would not only increase the odds of collective success but also promote positive development outcomes. However, contributions to global mitigation efforts by most countries fall short of what is needed to achieve the goals of the Paris Agreement[76]. Wealthy nations' current pledges are especially insufficient, falling far short of what are deemed fair contributions to global efforts, with many not contributing what is needed to limit warming to well below 2°C even if developing nations bear an inordinate amount of mitigation[77].

There have been many proposals as to how remaining CO_2 emissions, e.g., refs.[31,78,79], or GHG mitigation efforts, e.g., refs.[32,77,80], should be shared, referred to respectively as 'resource' and 'effort' sharing. Most of these approaches present themselves to be value-neutral, when in actuality, any emissions sharing approach is normative by design, and these unexamined biases, obscured in objective terminology and quantified metrics, often bias shares in favour of richer nations[81,82]. Robustly equitable emissions shares tend not to be technically feasible to achieve through domestic mitigation alone, but this should not be reason to dismiss them or contrive ways of striking 'compromises' that make them less equitable but more practical. Such approaches also conflate what is thought to be feasible with what is fair, and as a result, compromise both the equitability and the practicability of their proposals.

In the ensuing sections, we first review key emissions sharing approaches and then propose a way to formulate climate policy that is both ethically robust and pragmatic, i.e. without compromising equity or practicability. We use Canada as a case study to illustrate how this method could be applied to reconcile what a wealthy country could achieve through domestic emissions reductions with its fair share of global climate effort through contributions to international mitigation and adaptation efforts.

3.3 The distribution of past, present, and future GHG emissions

Most emissions have come from and continue to be emitted by a relatively small portion of the global population. There is a high amount of international and intranational emissions inequality. Historically, wealthy industrialized nations have emitted the most CO_2 and other greenhouse gas (GHG) emissions, and likewise caused most of the warming to date[23,25,26,83]. From 1960 to 1990, territorial emissions from these so-called developed countries accounted for 74% of global CO_2 emissions[84]. Over the last thirty years, developed and developing countries have each emitted roughly half of global CO_2 emissions. At present, so-called developing countries emit more annually than developed ones — 64% of annual global CO_2 emissions[84]. However, absolute national emissions obscure international inequality, since most people live in the developing world. In per capita terms, wealthy nations have always emitted much more than poorer ones and continue to do so, with developed nations emitting about three times as much as developing ones per person in 2019, or almost five times as much when averaged from 1990 to 2019 (ref.[24]). Keeping in mind that there is large variation within these groups as well, so-called least developed countries (LDCs) have emitted 10 times lower CO_2 per capita than in other developing countries and nearly 40 times less than developed countries[24].

To gain a historical perspective on emissions inequality between nations adjusted for population size, one can refer to the carbon debt, which is quantified as the deviation from a share of annual global emissions proportional to a country's population, summed over time. This means that if a country always had per capita emissions equal to the global average, it would never incur a carbon debt or credit. For example, Canada's carbon debt was 9 or 17 $GtCO_2$ when starting to count cumulative CO_2 emissions from 1990 or 1960 to 2013, respectively[27].

Emissions inequality between individuals is even more pronounced than between nations[85,86]. Globally, when accounting for emissions associated with household consumption, the wealthiest 10% of the population have emitted half of CO_2 emissions since 1990 and the richest 1% over twice that of the poorest 50%. Within a given developed country, for example in Canada, the richest 10% of Canadians emitted 24% of the country's CO_2 emissions from 1990 to 2015, almost as much as the poorest 50% (emitting 29%). The richest 5% of Canadians emit 47 tCO_2 per capita, nearly 16 times that of the poorest 5%, who emit 3 tCO_2 per capita[87]. The emissions of the poorest on the planet are by far the least, with carbon footprints of less than $1tCO_2$ per person, and eliminating extreme poverty would only raise global emissions by ~1-2% (ref.[88]). While keeping in mind the inequality of individuals within nations and globally, this study deals foremost with national responsibility.

3.4 The case for equitably sharing remaining emissions

There are strong practical and moral cases for why these emissions should be distributed equitably. Practically, since CO_2 emissions must fall to zero (and shorter-lived climate stressors like methane must also be drastically reduced), those who presently emit more must reduce their emissions levels more than those who emit less. Countries who have emitted more in the past are also usually wealthier than those with lower historical emissions, and likewise more economically capable of transitioning their economies as well as supporting mitigation and adaptation efforts in poorer, less advantaged and less responsible nations. As noted above, countries will only cooperate when they see others doing their fair share. Developing countries are therefore more likely to pursue low or no carbon development pathways if they believe that developed countries are acting in earnest to transition their own economies. Combined mitigation from developed and developing nations is needed to limit global temperature rise to agreed-upon levels.

Morally, those who have emitted more have gained wealth and power at the expense of those who have not reaped the benefits of fossil fueled industrialization. Those who have contributed least to climate change also stand to suffer the worst of its impacts[89]. It is also morally reprehensible to expect or insist that countries least culpable for causing, and coextensively, least capable of addressing the climate crisis, do as much as wealthier nations, since an equal share of mitigation is more than what is fair, and allows more culpable and capable (or taking together, more *responsible*) nations to continue to get a 'free ride'. These insights have been codified in international climate governance as the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), which guides negotiations of national mitigation efforts and climate financing.

3.5 Options for fairly sharing remaining emissions

Of course, not all countries are equally responsible. Unlike estimating the global carbon budget, deciding how to share remaining emissions is not a science[i]. Sharing global emissions is

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[i] To be more precise, even estimating the global carbon budget, which is indeed a physical quantity, is not an objective science. There are many normative decisions made, many of which are pre-analytic and often unbeknownst to the researcher. For example, in order to estimate the remaining carbon budget (RCB), one must decide on the temperature threshold, whether a temporary overshoot of this threshold is permissible, the odds of exceeding said

inherently normative, and should draw on insights from ethics, economics, international development, and other social sciences and humanities in a rigorous and transparent way. The spectrum of equity outcomes represents different priorities from the myriad ethical considerations inherent to the social drivers of climate change. While there is no objective way to divide remaining emissions, there are strong arguments for why some ways are more ethically robust than others (and why some are morally indefensible, or worse, reprehensible). Before attempting to advance existing approaches, we will reintroduce these concepts and critique some noteworthy examples.

Emissions can be shared in two ways: 1) in terms of emissions reductions ('effort sharing'), or 2) as a portion of the remaining carbon budget ('resource sharing')[90]. Effort sharing, as described above, shares reductions from a global emissions no-action baseline (e.g. using a 'business as usual' or 'frozen policy' scenario) between nations, such that total mitigation equates to reductions needed to limit temperature rise to a specified threshold. In doing so, efforts shares produce a national GHG emissions trajectory that can be considered 'fair' according to the chosen sharing approach. Effort shares may also be expressed in terms of cumulative emissions by integrating annual emissions over time, which allows policymakers to easily compare the merits of different decarbonization pathways and reduction targets[91]. National emission reduction targets can be compared to a fair decarbonization pathway to benchmark whether national efforts are sufficient (e.g. ref.[77]). In principle, nations could select their national emissions reduction targets from effort sharing trajectories. An alternative to effort sharing is resource sharing. As noted above, resource sharing instead shares a finite amount of remaining emissions, the remaining carbon budget (RCB), from a given time onwards. The starting time may be in the past, such that resource shares are negative. For example, a resource share that shares the RCB proportionally to population (an approach referred to as 'cumulative equal per capita' (CPC) sharing) from the year 1990 onwards may give a country a negative share when CO_2 emissions from 1990 to present are subtracted from its starting share, which is equivalent to a carbon debt as defined by Matthews[27]. Leading countries could use these top-down approaches to formulate their bottom-up nationally determined contributions (NDCs), and assuming they were transparent and forthright in their process, this would help assure other countries that they were doing their fair share, which could help foster greater international collaboration and encourage other countries to follow suit. To this day, it appears that countries do not rely on these top-down approaches to derive their climate policy, but regardless, emissions sharing approaches provide invaluable tools to assess national climate ambitions.

Emissions sharing approaches are generally based on the following three ethical principles: 1) responsibility (for emissions and warming), 2) capability (to pay for mitigation), and 3) equality (of access to means of development, which some approximate as the entitlement to emit, historically or immediately)[92]. 'Responsibility' in this sense could be more precisely referred to as 'fault' since it deals exclusively with retrospective responsibility, while capability refers to prospective responsibility for future actions. The distinction between equality and equity is as pertinent in climate policy as in any ethical venue. 'Equality' as defined in emissions sharing approaches can be taken to the extreme where the ideal would amount to equal emissions per person over all time. However, even if all nations had the opportunity to emit the same

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threshold. All of these choices tacitly amount to the level of risk one finds acceptable. That being said, we still argue that deciding on how the RCB is shared is far more of a subjective and normative pursuit than estimating the RCB itself, while recognizing the normativity of the scientific process at work in the latter.

amount of GHGs per person during the entire industrial age, this would not necessarily lead to an equitable outcome. As Dooley and colleagues clearly articulated: 'moral equality and an equal ability to lead decent lives is important, but equality without consideration of unequal needs and vulnerabilities, unequal capacities and unequal responsibility leads to equality for unequals, which philosophers since Aristotle have condemned as gross inequity'[82]. These dimensions far from reflect the full gamut of possible consideration, and in no way should be perceived as an exhaustive or authoritative list, even when selected by the IPCC, which tends to overrepresent perspectives from the western mainstream research community, and likewise helps to legitimize and lend authority to a biased perspective[82]. See Table 3.1 for a summary of these ethical principles and Figure 3.1 for a visual representation of emissions sharing following these ethical principles.

	Ethical principle	**Allocation approaches**
Capability	Those with more means should do more (to mitigate GHG emissions, in the context of climate change)	Capability approach: Sharing remaining carbon budget inversely to GDP, or mitigation proportionally to GDP
Equality	All are equally entitled to share economic benefits of natural world (fossil fuels, in the context of climate change)	Equal per capita approach Sharing cumulative GHG emissions proportionally to population, over different periods of time, or sharing emissions equally per capita starting today, which ignores historical emissions inequality
Responsibility	Those who have emitted more should do more (mitigate more, in the context of climate change)	e.g., Climate Equity Reference Framework (Responsibility setting): mitigation responsibility shared proportionally to cumulative emissions

Table 3.1 Summary of emissions sharing principles

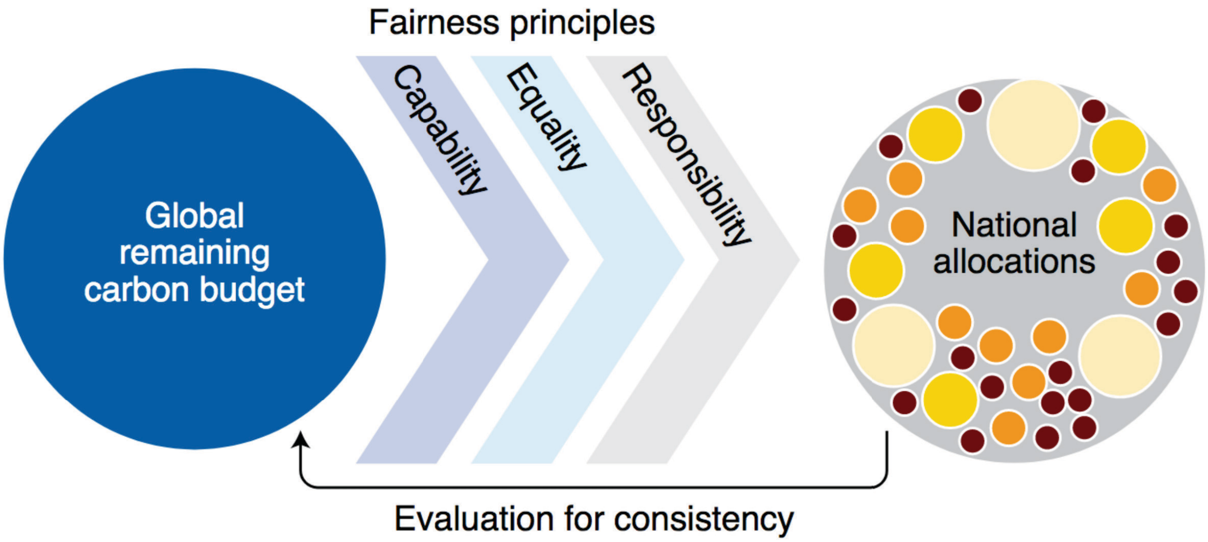

Figure 3.1 Ethical principles underlying emissions sharing approaches. Note that this diagram depicts sharing of remaining carbon budget, i.e., resource sharing. Reproduced from Ref.[74].

Next we evaluate a partial sample of emissions sharing approaches based on the three ethical principles defined above, which share emissions such that: 1) all countries emit the same amount per person cumulatively, making them equally culpable for climate change ('Cumulative equal Per Capita': CPC), 2) mitigation is shared proportionally to GDP per capita, so that wealthier nations have higher mitigation obligations ('Capability'), 3) remaining emissions are shared proportionally to population, ignoring historical inequalities in emissions ('Equal Per Capita': EPC), and any approaches that combine these principles, e.g., Climate Equity Reference framework (CERF), which allocations mitigation in proportion to historical emissions and/or GDP, with optional additional settings that refine these approaches. Details of the CERF are summarized below in Section 3.5.1. Approaches (1) and (3) can be used to share effort or resources, where mitigation is shared such that emissions per capita are equal over a specified time horizon, while (2) lends itself immediately to sharing effort but one could also share the RCB inversely proportionally to GDP per capita. Note that (3) is simply (1) with the start date at present, while CPC's date must be specified, e.g. from preindustrial time (~1850) onward. Also note that exact methods and parameters may differ across studies, and this plays a large role in determining the equitability of outcomes[82]. We detail our own selection and rationale in the methods (Section 3.7). We omit other approaches based solely on considerations of practicality, like cost-effectiveness, which apportions mitigation effort in a cost-optimal fashion. This selection is our best attempt to depict a representative equity spectrum, based on our judgment of the ethical rigour of emissions sharing approaches. See Höhne and colleagues[92] for a more comprehensive overview of the literature and Dooley and colleagues[82] for a critical discussion of the underlying ethical assumptions in emissions sharing literature.

3.5.1 Climate Equity Reference Framework

The Climate Equity Reference framework (CERF; a generalization of its predecessor, Greenhouse Development Rights, GDR) allocates mitigation obligations proportionally to a blend of historical responsibility and current capacity (default set to equal weighting)[32]. The CERF method also accounts for intranational wealth and emissions inequality, by excluding individual income under a development threshold (with a default value of $20 per person per day) from their measure of a country's economic capacity, and the emissions related to their income from historical responsibility[93]. For example, with 99.4% of Canada's population living over the development threshold, and substantial wealth and historical emissions, Canada's mitigation ambition would be amongst the highest in the world, suggesting a share of global mitigation of 2.9%, nearly six times its share of global population (~0.5%)[33]. The CERF also proposes what amount of mitigation obligation should be performed through domestic mitigation (Fig 3.2, dark yellow shaded region above green dashed line) and how much would need to be achieved through international mitigation (Fig. 3.2, dark brown-yellow bars below green dashed line). The maximum rate of domestic decarbonization was taken from a survey of literature on Canadian decarbonization pathways[i]. This approach provides a good starting point for the more detailed meta-analysis and intercomparison of decarbonization scenarios and emissions sharing proposals performed here.

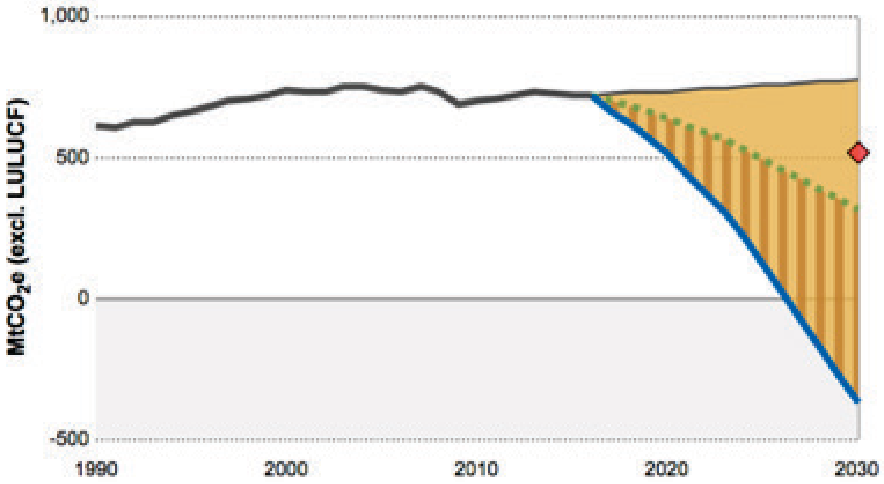

Figure 3.2 Canada's fair share of international mitigation according to the Climate Equity Reference Framework. The shaded region represents the reduction from baseline emissions (top thin dark line), where the green dashed line denotes the plausible amount of mitigation achievable through domestic emissions reductions, and the blue bottom line denotes Canada's fair share of total mitigation effort. The barred region below the green dashed line represents how much of Canada's fair share could be achieved through international mitigation. Reproduced from: https://calculator.climateequityreference.org/.

3.5.2 Paris Equity Check

The Paris Equity Check (PEC) provides another suite of effort sharing approaches, using different baseline emissions trajectories and parameterizations of effort sharing schemes[80,94]. Critics of the PEC argue that methodological choices made in its underlying work perpetuate

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[i] Personal correspondence with Christian Holz (Carleton University, Ottawa, Canada).

international inequities[81]. While the approaches underlying CERF and PEC are in ways fundamentally different, many of the conclusions drawn are the same. Canada, according to both the CERF and PEC, is required to ratchet up its ambition greatly to align with any defensible notion of fairly sharing remaining global emissions. The performance of the CERF versus PEC is compared in terms of cumulative emissions under different pathways in Figure 3.4. Naming conventions can cause some confusion here. Note that PEC's Constant Emissions Ratio (CER) is tantamount to grandfathering, and that the method allows for time for current emissions levels to converge to target ones, such that PEC's EPC is equivalent to Contraction and Convergence (C&C). PEC also only borrows broadly from GDR, and is not directly comparable with its original formulation (recall that GDR is now called CERF).

3.5.3 Carbon quotas

Raupach and colleagues presented a method for sharing a remaining carbon budget (RCB) between nations, referring to each country's share as their respective 'carbon quota' (ref.[31]). They also introduced hypothetical decarbonization pathways called 'capped emissions trajectories' that provided declining annual emissions parameterized using carbon quotas. Their approach provides three settings to share a RCB: 1) 'equity': sharing the RCB proportionally to population at a fixed time (analogous to the EPC approach defined above), 2) 'inertia': sharing the RCB proportionally to historic emissions (typically labeled 'grandfathering' which represents an inequitable outcome where high emitting countries perpetuate the status quo), and 3) 'blended': the mean of settings (1) and (2).

Unfortunately, this suite of approaches provides a misleading depiction of the equity spectrum by truncating the upper end of the equity spectrum at what they refer to as 'equity', a misnomer since it is actually an EPC share, and EPC sharing neglects differences of historic emissions and present capabilities between nations. The authors do not provide estimates for EPC shares that account for historical emissions, i.e. CPC shares, in their main text but do provide sensitivity analysis to historical start dates in their supplemental analysis. Ultimately, readers are led to believe that the blended equity setting (used as the default setting in their analysis) is a reasonable compromise between equity and practicability that countries should strive to fulfill.

We assert that by truncating the high equity end of the equity spectrum and including an indefensibly inequitable outcome as its lower limit, this approach arbitrarily skews emissions shares towards inequitable outcomes (Figure 3.3). This approach epitomizes what we problematize as the dangerous conflation between the equitable and practicable. We caution against such implicit compromise, since it can be used to justify insufficient levels of climate ambition that endanger successful decarbonization efforts and exacerbate international inequities.

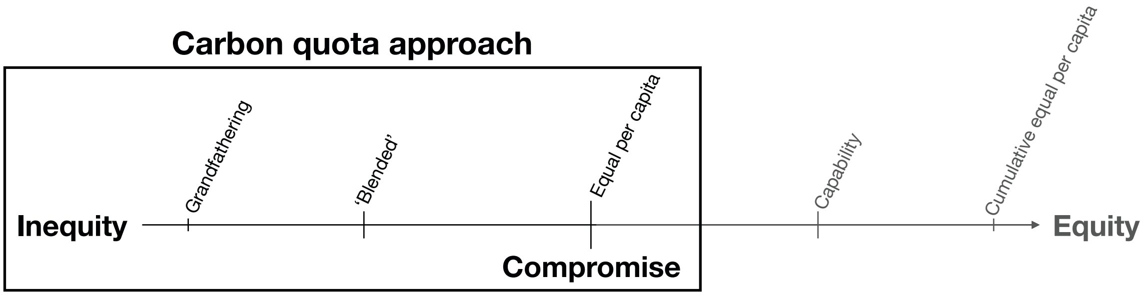

Figure 3.3 Example of biasing towards inequity in emissions sharing approaches via arbitrary truncation of equity spectrum. This spectrum uses the carbon quota proposal described by Raupach and colleagues. The carbon quota proposal (interval shown in the boxed region) excludes high equity sharing approaches while including low equity approaches, and centering its proposal around a share that greatly biases shares in favour of wealthier industrialized nations. Note that the positions (i.e. cardinal or ordinal ranking) of Capability and Cumulative equal per capita (CPC) approaches are not fixed, and will shift depending on parameterization (e.g. start date of CPC or whether subsistence income is excluded from GDP).

We note that this same process may have led to grandfathering being including in the suite of fair shares in the PEC project, which skews the mean towards greater inequity, biasing emissions shares in favour of wealthier nations[81]. Notice that recent work by Climate Action Tracker (CAT) or CERF does not include Grandfathering in its distribution of fair shares. We concur that these methodologies should produce more equitable shares. Finally, we acknowledge that works by Raupach and colleagues or Robiou du Pont and colleagues may wish to include grandfathering as a baseline extreme, however if future studies do wish to include such extremes for comparison, we recommend that they indicate this more clearly, and that it be excluded when calculating a mean share from a set of chosen approaches. Likewise, grandfathering's inclusion in a suite of approaches legitimizes it as an acceptable choice — even if it is considered a relatively inequitable extreme — and biases the central estimate of a set of fair shares towards an inequitable outcome.

Given the lack of explicit discourse on bridging what is deemed possible with what is fair, we maintain that approaches such as PEC and the carbon quota will likely mislead or be abused by policymakers. Proper disclosure is needed to prevent misrepresenting combinations of emissions shares that include unfair outcomes as attempts to present a distribution of fair shares or its central estimate. Instead, we recommend that these works be reframed as attempts to bridge practicability with equity, and that their policy proposals be presented not as fair shares but as a compromise. We also suggest that they propose ways to reconcile the practical and fair formally, for example, by tracking the discrepancy between purely fair and expected outcomes then proposing ways to redress this via international assistance, as we will explore in this study.

3.5.4 Other examples of emissions sharing

Donner and Zickfeld[95] use a method analogous to Raupach and colleagues[31] to define emissions shares left for Canada under 1.5°C, 2°C, and 3°C with varying likelihoods of success. Again, they do not account for historical emissions, presenting a truncated range of equity options. Gignac and Matthews use a global carbon budget to parameterize Contraction and Convergence (C&C) curves where countries' per capita emissions converge to a set value then contract to zero, while tracking accrued climate debts over time[78]. In contrast to the aforementioned proposals, theirs is able to preserve the possibility of international inequity being redressed through repayment of climate debts in the form of international emissions mitigation and adaptation financing. This can be used to rectify the original C&C proposal[79], which did not track disparities between fair shares and projected emissions, providing yet another example where goals of practicability and equity are conflated and compromised. Here we will build on Gignac and Matthews' important step of explicitly tracking disparities between fair and practicable outcomes.

3.5.5 Effort sharing versus resource sharing

There are advantages and drawbacks inherent to both effort sharing and resource sharing. Determining global emissions trajectories is also not a purely physical science, since it relies on economic models that must make many subjective choices. For example, models that optimize emissions trajectories according to least cost inherently express preferences for cost-optimality or GDP growth maximization. To date, integrated assessment models (IAM) used to determine emissions trajectories presuppose that economic growth will continue to be a core economic priority, which highly constrains emissions pathway spaces. These models usually prescribe growth exogenously. They must also make myriad assumptions about the efficacy of policies and technologies in order to arrive at emissions baselines and potential mitigation before and after their hypothetical implementations. IAMs also conventionally employ time discounting to express a preference for wealth (measured in terms of economic activity) now rather than later. Such discounting privileges the present over the future, promoting intergenerational inequity[96], and richer nations and people over poorer ones, exacerbating international and intragenerational inequities[97,98].

Many effort sharing approaches also presume that negative emissions under the global emissions pathways they use are achievable. The overreliance on late century negative emissions, which is basically an outcome of the use of high discount rates, in many of the models employed by effort sharing approaches is cause for concern, given the limited confidence in the ability to deploy these technologies at scale[99–102]. Future negative emissions can also be used to justify further delaying mitigation, which could result in less equitable outcomes while simultaneously jeopardizing collective efforts. This could be remedied by substituting these pathways with ones that have limited negative emissions, like those which only assume the viability of limited amounts of afforestation and Biomass Energy with Carbon Capture and Storage (BECCS), e.g. Low Energy Demand (LED) model by Grübler and colleagues[103] which excludes BECCS altogether. However the LED model instead relies on high amounts of decoupling to sustain economic growth, and the only models that do not require unprecedented decoupling or unproven negative emissions are those proposed by the degrowth community and have yet to be included in the core group of mitigation pathways[104].

Effort sharing's added complexity does allow for more precision and refinement, but may also come with compounded uncertainties. Effort sharing pathways are often derived by downscaling a global decarbonization pathway and therefore not specific to any individual country's specific economic or technical capabilities. Best practices, however, do incorporate national or at least regional BAU baselines, which take national/regional contexts into account to some extent. Effort and resource sharing can both yield negative shares, but the latter lacks the mechanics to prescribe when and how to mitigate. However, most resource sharing proposals thus far have been formulated to only yield positive emissions shares (see examples in section 3.5.2), producing weakly equitable outcomes by sidestepping conversations of historically rooted inequalities in emissions or capabilities. Resource sharing proposals also do not include a country-specific decarbonization plan, instead using an illustrative pathway that caricatures a decarbonization path, usually parameterized such that the area under the curve equals the emissions share.

When it comes to communicating emissions sharing, resource sharing may provide a more convenient alternative to effort sharing since its methodology is generally simpler to explain. While its reduced complexity may sacrifice methodological robustness, it still yields similar results to effort sharing approaches. Given the inherent uncertainty in underlying inputs for both effort sharing and resource sharing schemata (e.g. demographic projections of population, baseline emissions, carbon budget uncertainties), shares of emissions produced by either method will necessarily have limited precision, and so should only be regarded as illustrative rather than a precise prescription of a country's fair allocation of mitigation obligation or remaining emissions.

3.6 Reconciling fair and practicable policy proposals

Here we propose that, when possible, national decarbonization plans be compared directly with a country's fair share. That way, we can assess whether national mitigation potential is sufficient for a country to fulfill the entirety of its fair share, or if other means, like international mitigation will be required to fulfill it. Our fundamental approach is to ask 'what *should* be done' and 'what *can* be done' in isolation. We feel that this has not been adequately discussed previously, nor formalized as such, and so our emphasis and contribution in this work is the attempt to segregate the normative and positive realms of climate policy as much as possible, while acknowledging that the two will always necessarily overlap to some degree. By improving this distinction and treatment of policy options, we hope to improve both the equitability and practicability of emissions sharing proposals.

3.7 Methods

3.7.1 Quantifying fair shares for Canada

We first quantify 'fair shares' in terms of cumulative emissions remaining from 2020 onwards. There are two approaches employed here: 1) resource sharing and 2) effort sharing. Resource shares are derived by taking a fixed proportion of the remaining carbon budget at a given point in time under a maximum temperature threshold. We use the latest carbon budget estimate from Matthews and colleagues[72]. We parameterize shares using historical emissions and population share. For consistency with Raupach and colleagues[31], the population coefficient is calculated as a country's population divided by the global population, using the five-year mean centered around when global population reaches approximately 9 billion people (projected to be 2037). Cumulative equal per capita (CPC) and equal per capita (EPC) resource shares for Canada are then calculated as in equation 1, where the remaining carbon budget (RCB) at a given time is shared in proportion to a country's share of the global population for CPC and EPC (which is equivalent to CPC from present-day onwards), minus the cumulative emissions from that year to present, where t_i is the start year for counting cumulative emissions. For CPC start dates, we selected 1850 (the benchmark for preindustrial times) and 1990 (the year when global consensus to act on climate change was reached, and likewise, after which no country can claim that there was any ambiguity of the need to mitigate GHG emissions). As noted, $CPC(t_i)=EPC$ when t_i is the present year.

$$CPC(t_i) = \frac{p}{p_{global}} \times RCB(t_i) - \sum_{t_i} emissions(t) \qquad (1)$$

Grandfathered resource shares are quantified as a share of the present RCB that is proportional to a country's current rate of emissions at year *t*. Here we use the mean of the last five years of emissions from 2016 to 2020 as a nation's current emissions level.

$$Grandfathered = \frac{emissions}{emissions_{global}} \times RCB \qquad (2)$$

The second way to quantify emissions shares in terms of cumulative emissions presented in this study comes from taking the sum over time of annual effort shares, which are national shares of annual global GHG emissions under decarbonization pathways for a specified temperature threshold or target expressed as a share of mitigation relative to an emissions base case. If global emissions fall below zero, emissions for certain nations will also be negative such that the sum of individual nations' annual emissions equals the global negative emissions that year. Relatively lower or negative annual emissions shares represent an obligation to contribute relatively more to global mitigation efforts. For example, if dividing mitigation responsibility by national capacity to mitigate, using GDP as a proxy for economic capacity, mitigation relative to the baseline can be shared proportionally to national GDP per capita, i.e. countries with higher GDP per capita will have to mitigate more than those with lower ones. The Climate Equity Reference framework (CERF) refines this approach by accounting for intranational wealth distribution by excluding emissions below a 'development threshold' and weighting emissions from high-income earners more than lower income ones. For a detailed explanation of each effort sharing method's definition and parameterization, please see the cited documentation for the effort shares used here in e.g. ref.[32]. We also use effort sharing pathways from the Climate Action Tracker (CAT) from ref.[77] and Paris Equity Project (PEC) from ref.[80].

3.7.2 Meta analysis of decarbonization pathways for Canada

We survey the literature on possible decarbonization scenarios for Canada from the energy-economy modeling community. The Canadian-specific models chosen for this study include the Deep Decarbonization Pathway Project (DDPP) for Canada from ref.[105], the in-house macroeconomic–emissions model from the Energy and Materials Research Group (EMRG) from ref.[106], the Trottier Energy Futures Project (TEFP) from ref.[107], and the in-house modeling ensemble used by Environment and Climate Change Canada (ECCC) from ref.[108]. For a more comprehensive overview of traditional energy-economy models for Canada from public, private and non-profit projects, see an overview by Rhodes and colleagues[109]. In addition to these conventional energy-economy models, we include estimates of technical viability and emissions trajectories according to work by Jacobson and colleagues[110] (referred to here as the 'Solutions Project'), which provides a lower guard rail of technical viability of a transition to a fully wind, water (nearly all being hydropower) and solar powered grid, assuming no political or economics barriers to a rapid energy transition. However the viability of such a plan is contested within the modeling community, as it may be overly optimistic with regards to technical and economic feasibility e.g. the need for storage and overbuilding of capacity to compensate for intermittency of renewable energy infrastructure[111,112].

Note that even within this subset of conventional energy-emissions-economy (EEE) models, there are many sources of incongruity in design that cause an imperfect overlap of coverage and this complicates direct comparisons of model results. For example, models differ in how they classify industries into sectors, whether land use emissions are included, in their assumed elasticity of supply and demand of energy carriers, and in their forecasts of oil prices, energy demand, emissions intensities of energy uses, and rates of technological innovation. These differences reflect subjective choices that could otherwise be harmonized across models. We do our best to account for these discrepancies but caution the reader that model intercomparison necessarily yields imperfect results, and is subject to error that is difficult to quantify. For this reason, we remind readers that our approach is illustrative of broad trends in the energy transition modeling community and synthesized results (much like those of individual models) should not be taken as authoritative or prescriptive.

3.7.3 Comparing fair shares with possible decarbonization routes and quantifying Paris gap

Here we may compare emissions — either in annual emissions or cumulative emissions integrated over time — of both the suite of fair shares as defined in Section 3.9.1 and the ensemble of decarbonization models as described in Section 3.9.2. Here we define the 'Paris gap' as the difference, in terms of cumulative emissions from 2021 to either 2050 or 2100, between how much emissions a country is projected to emit along a given decarbonization path and how much is should emit according to a chosen fair share of global mitigation effort, i.e. projected actual emissions (E_a) minus fair emissions (E_f). A positive gap (i.e. $E_a > E_f$) denotes an expected emissions debt, while a negative one (i.e. $E_a < E_f$) denotes an expected emissions credit. The central estimate for the Paris Gap is given by the difference between the median E_a and the median E_f. This method is equivalent to calculating historical carbon debts as in Neumayer[21], Goeminne and Paredis[113], or Matthews[27], however we instead estimate the projected debts by taking the difference between the projected cumulative emissions along a specified pathway and a reference 'fair share'. Equation 3 proves this equivalence, starting with the formulation of a carbon debt in Matthews[27] and arriving at our own formulation where the carbon debt is the difference between cumulative emissions of a country (E) and its cumulative equal per capita (CPC) share with a start date t_i for a given country, where both are calculated over the same time horizon from start year t_i to $t_f = 2050$ or 2100.

$$\begin{aligned}\text{Carbon debt} &= \sum_{t=t_i}^{t_f}\left\{\mathrm{E}(t)-\mathrm{E}(t)_w \times \frac{\mathrm{P}(t)}{\mathrm{P}(t)_w}\right\} \\ &= \sum_{t=t_i}^{t_f}\mathrm{E}(t)-\sum_{t=t_i}^{\mathrm{t_f}}\mathrm{E}(t)_w \times \frac{\mathrm{P}(t)}{\mathrm{P}(t)_w} \\ &= \mathrm{E}-\mathrm{CPC}_{t_i}\end{aligned} \quad (3)$$

Here we generalize carbon debt to obtain the Paris Gap, which can use any cumulative emissions from any emissions sharing approach. Equation 4 substitutes a cumulative equal per capita (CPC) share in the historical carbon debt formula above (eq. 3) for the 'fair share' of one's choosing. The Paris Gap is then the projected emissions debt, which can now be quantified in terms of the difference between the cumulative emissions of a country (E_c) and a chosen fair share. Note that here we use cumulative emissions from decarbonization pathways where *cumulative emissions* = *historical emissions* + *cumulative emissions$_{decarb}$*, where *cumulative emissions$_{decarb}$* is the amount of cumulative emisisons under a chosen decarbonization pathway added to emissions preceding the model start date (*historical emissions*) to obtain total *cumulative emissions*. We then define the 'Paris Gap' as follows:

$$\begin{aligned}&\mathit{Paris\ Gap} = \sum_{t=t_0}^{\mathrm{t_f}}\mathrm{E}(t)-\sum_{t=t_0}^{\mathrm{t_f}}\mathrm{E}_{fair}(t) = \sum_{t=t_0}^{\mathrm{t_i}}\mathrm{E}_{hist}(t)+\sum_{t=t_I}^{\mathrm{t_f}}\mathrm{E}_{decarb}(t)-\sum_{t=t_o}^{\mathrm{t_f}}\mathrm{E}_{fair}(t) \\ &= \mathrm{E}-\mathrm{E}_{fair} = \mathrm{E}_{hist}+\mathrm{E}_{decarb}-\mathrm{E}_{fair}\end{aligned} \quad (4)$$

3.8 Results: Case study of Canada's fair share and possible decarbonization trajectories

We will now illustrate how to apply our approach by using Canada as a case study, laying out our procedure in three steps: 1) first we review what Canada's fair shares of emissions are (section 3.8.1), 2) then we examine Canada's possible emission futures based on economic modeling specific to Canada (section 3.8.2), and 3) lastly, we will compare the two and offer ways the discrepancy between what is fair and what is achievable through domestic mitigation can be reconciled.

3.8.1 Canada's fair shares

It is clear that Canada, by any defensible definition of equity, will not be able to achieve its fair share of international climate action through domestic mitigation alone[91]. This is true of most, if not all, wealthy industrialized nations, for reasons described above. As noted above, from a perspective of historical responsibility for climate change, Canada is already in carbon debt, having over-contributed 9 or 17 $GtCO_2$ when counting emissions from 1960 and 1990, respectively[27]. These debts will decrease if developing countries emit larger cumulative shares of emissions and/or Canada mitigates rapidly, allowing for a larger relative share of global emissions to go to countries currently holding carbon credits. In the following analysis we will estimate what the emission debts for all GHGs could be under a range of decarbonization scenarios. First we review a selection of emissions shares, representing relatively high equity ('fair') to low equity ('unfair') outcomes, for both effort sharing and resource sharing methods. Figure 3.4 provides a summary of emissions shares discussed herein, where effort shares have been integrated over time to render them into cumulative emissions values from 2020 to 2100 (see ref.[91] for more details), and resource shares are quoted as emissions remaining from 2020 until exhaustion. We express emissions shares in total GHGs in units of carbon dioxide equivalents (CO_2e) computed over a 100-year time horizon (using a 100-year global warming potential). We approximate CO_2-only resource shares in units of CO_2e by multiplying them by ratio of total GHGs to CO_2 in Canada averaged over the last five years. We note that this is a highly imperfect comparison and that non-CO_2 shorter lived forcers like methane cannot be readily compared across timescales since their atmospheric lifetimes differ significantly, we nevertheless posit that as long as the relative shares of GHG emissions over time are approximately unchanged, we may still compare the time-integrated total of these gases, at least for illustrative purposes to inform policy directions. We maintain that the results, while imperfect, are reliable enough to gain insights into the magnitude of how far countries fall short of their fair share of mitigation responsibility and how much they could contribute to redress this inequity.

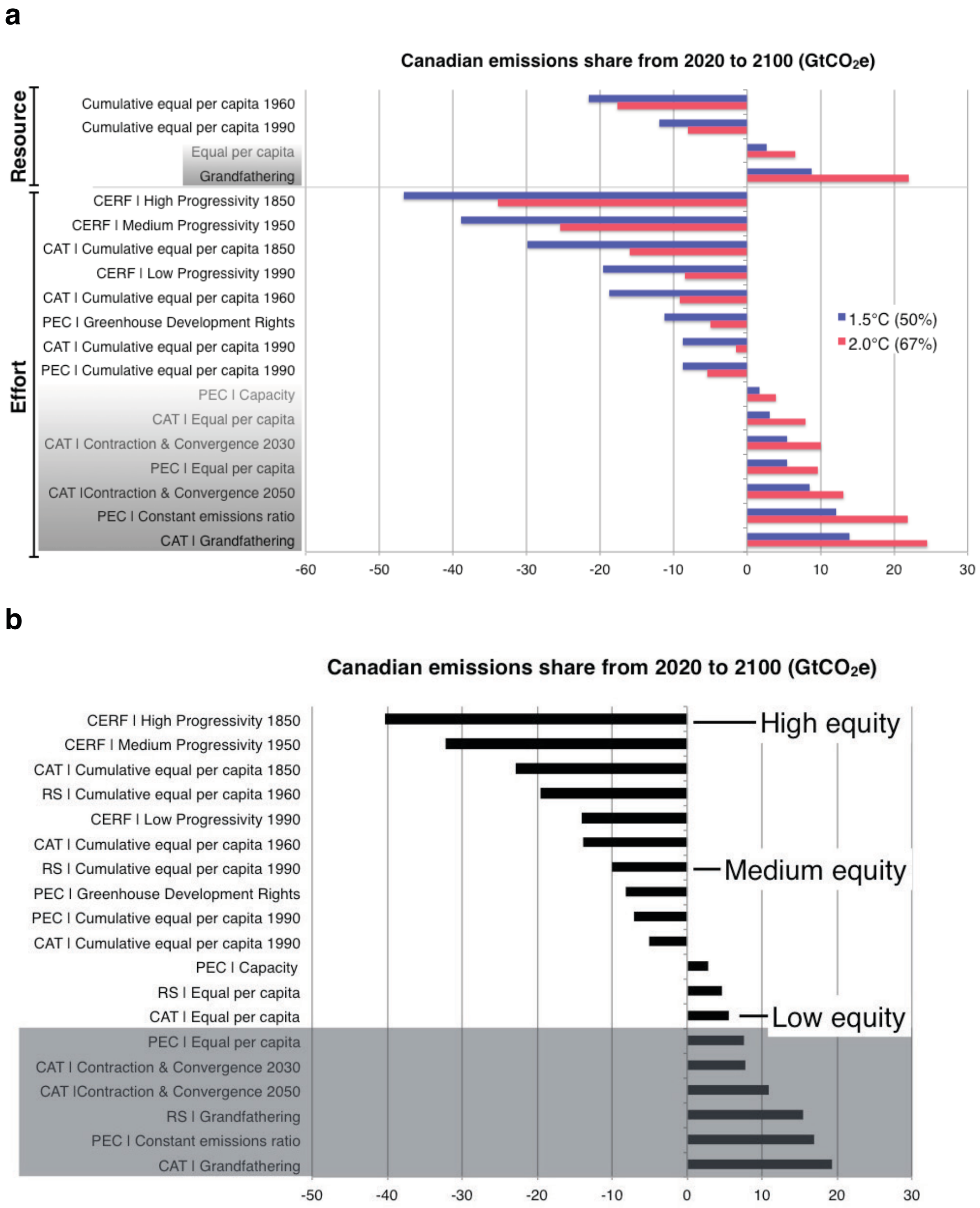

Figure 3.4 Cumulative Canadian allocations of global GHG emissions using resource shares from remaining carbon budgets and from effort sharing pathways, both for 1.5°C (50%) and 2°C (66%) scenarios (a) and for the mean of these two scenarios (b). Resource shares (RS) are calculated by the authors (see methods). Effort shares are taken from the Climate Equity Reference framework (CERF), Climate Action Tracker (CAT), and Paris Equity Check (PEC). Approaches shaded with a gradient from light to dark grey in (a) represent the bare minimal to unequivocally insufficient contributions to global climate efforts. Uniform grey shading in (b) shows approaches excluded from sample used in this study. After exclusion of unequivocally insufficient shares, low, medium (using median), and high equity approaches are classified according to order. Emissions from Land Use, Land Use Change, and Forestry (LULUCF) are included in CERF and CAT but not PEC. Values are in cumulative emissions of the remaining all-GHG emissions budget or 'effective carbon quota', and are derived by taking the sum of annual effort-shares of 1.5°C and 2°C pathways from 2020 to 2100.

3.8.2 Canada's imagined decarbonization pathways and emissions futures

Here we explore a selection of possible emissions futures for Canada, derived from decarbonization pathways produced by government, nongovernmental and academic research groups. All modeling approaches are informed by a combination of technological, economic, and social considerations. Figure 3.5 summarizes the annual and cumulative GHG emissions at the national level from the emissions scenarios sampled for this study. We have included forecasts from Environment and Climate Change Canada (ECCC)[108], an independent assessment of current policies from Climate Action Tracker[114], two projects led by researchers with university affiliations: the Deep Decarbonization Pathways Project (DDPP) for Canada model[105], the Energy and Material Research Group (EMRG) model[106], and the Trottier Energy Future Project (TEFP) model[107]. We summarize some of the key differences underlying these models assumptions and parameters in Table 3.2 below. Note that all models assume that economic growth will continue unabated. All energy-emissions-economy (EEE) model scenarios either assume or result in significant reductions in oil and gas production as a cost-effective measure of reducing GHG emissions. It is also important to keep in mind that all these models make implicit assumptions about what they believe to be technological possible or politically feasible. These are highly subjective choices that represent the worldview of the modelers. We have attempted to delineate the difference emphases on these dimensions in Table 3.2.

Decarbonization model	Selected scenario	Annual GHG emissions/ Reduction by midcentury	Key features and differences	Priority/emphasis or worldview
Deep Decarbonization Pathways Project (DDPP)	Low future oil prices and strong regulations	78 MtCO2e (88% below reference case)	Strong carbon price, high rate of technological improvement (especially for carbon capture and storage, CCS), heavy reliance on gas power	Political and technical viability
Energy and Material Research Group (EMRG)	Low future oil prices and some regulations	70%	Similar to DDPP but with much weaker carbon pricing	Political salability
Environment and Climate Change Canada (ECCC)	N/A	Only forecasts to 2030, 80% reduction based on midcentury target	Unknown, documentation not publicly available for proprietary model	Unknown, documentation not publicly available for proprietary model
Solutions Project	N/A	100%	Not energy-emissions-economy model. Focus on upper limit to what could be achieved without social or political constraints.	Technical viability
Trottier Energy Future Project (TEFP) model	Low future oil prices and some regulations, constrained oil and gas production	60%	Similar to DDPP, more emphasis on cost-optimization covers only 73% of economy	Political and technical viability

Table 3.2 Summary of decarbonization models

‘Projected’ emissions by ECCC represent GHG emissions in absence of policies, while the ‘Pan-Canadian Framework’ (PCF) represents emissions trajectory if the PCF were to be fully implemented, and ‘PCF additional measures’ represents PCF policies with added but yet to be realized measures required for Canada to close the 44Mt gap between the PCF scenario and its original NDC of reducing its emissions by 30% below 2005 levels by 2030. This NDC has since been enhanced to a reduction of 40% to 45%, as depicted in Figure 3.5. While there has been some broad modeling released recently by ECCC to corroborate the existence of sufficient decarbonization potential needed to meet Canada’s enhanced NDC[115], there has been no explicit modeling to show how Canada can achieve reductions required to meet its long-term target of net-zero emissions by 2050. Further, Canada’s definition of net-zero and how it may be achieved is still ill defined, and the government continues to intimate that missing emissions reductions could be achieved through measures such as planting trees and other nature-based climate solutions (NBCS). Recall that only bioenergy with carbon capture and storage (BECCS) remains plausible but limited source of reliable net negative emissions, especially when compared with afforestation of pasture or cropland or cutting down and replanting secondary forests[116], while many still warn of the unreliability of afforestation and more exotic NBCS, and negative emissions technologies (NET) in general, including BECCS[100–102,117].

The pathway modeled by EMRG (blue line) met the original NDC but does not meet the enhanced NDC target. The TEFP model (red-orange line) covers only 73% of GHG emissions, and therefore includes only a portion of the national economy. The DDPP pathway (dark green line) outperforms the other EEE models depicted here, and brings the economy to near (88% below its reference case, to lower emissions to 1.7 tCO_2e per person) but not full decarbonization by 2050. The Solutions Project[110] (light green line) is also included as a lower guard rail for what is considered technically feasible, though it is not a pathway derived from an EEE model. The Solutions Project also includes significant improvements to efficiency that enables demand reductions large enough to make up for upper limits to installed capacity. For a more in-depth discussion of the different merits and underlying assumptions of these models, see the methods above (section 3.7.2) and ref.[91,109,118]. We have also included committed emissions from existing and proposed fossil fuel infrastructure, which includes all utilities and transport, for comparison from ref.[49]. Note that we do not attempt to estimate the non-CO_2 GHGs associated with these emissions and quote them in units of CO_2-only. We assume that if no new infrastructure were built, emissions from the existing stock would decline linearly.

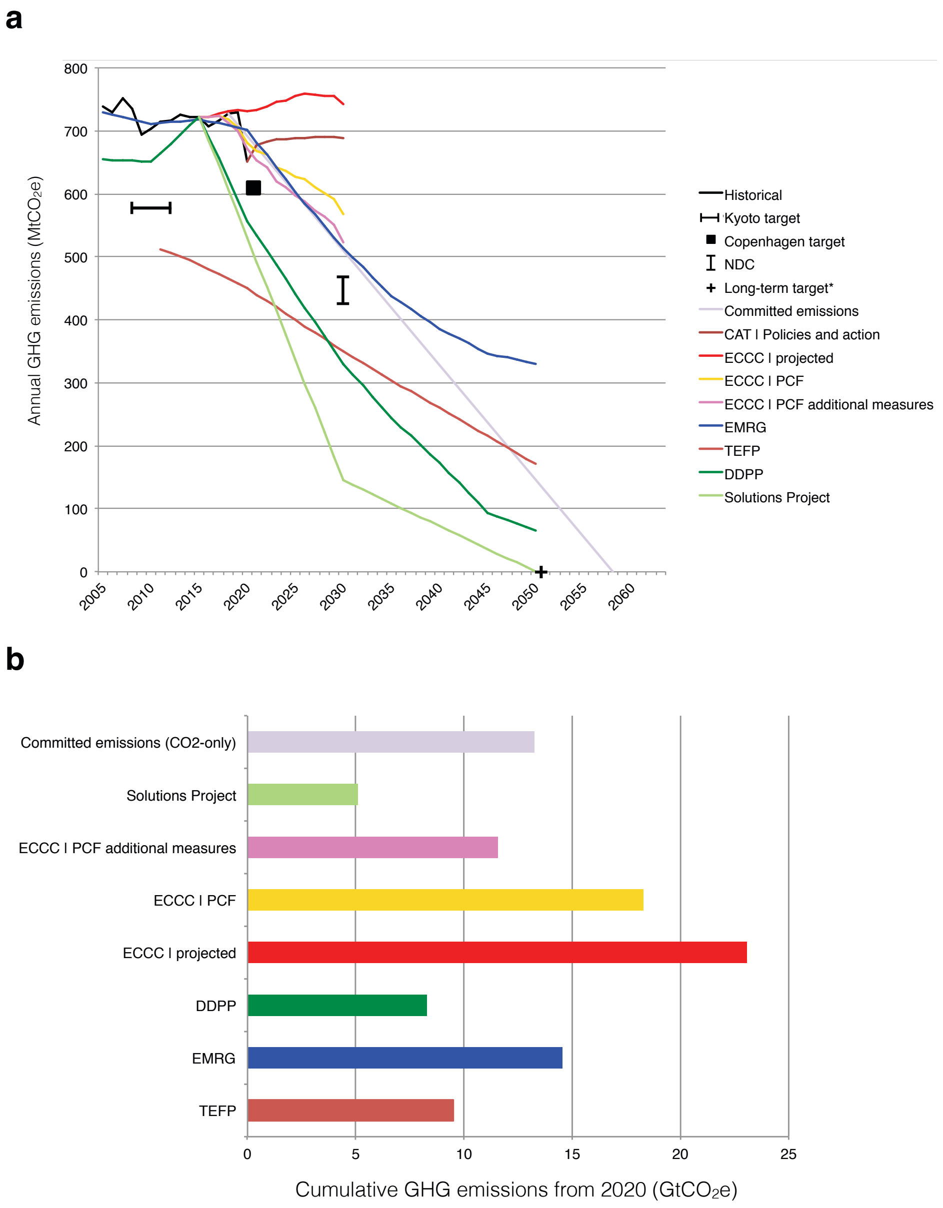

Figure 3.5 Comparison of decarbonization pathways (a) for Canada and corresponding cumulative emissions from 2020 onwards (b). All pathways are in million tonnes of carbon dioxide equivalents ($MtCO_2e$) for national aggregate. The 2030 Nationally Determined Contribution (NDC) range has been assessed by Climate Action Tracker (CAT). The Long-term target is noted by an asterisk to call attention to the ambiguity of the definition of net-zero emissions, but is represented as absolute zero above. Committed emissions are CO_2-only and include all downstream emissions from energy and transport infrastructure that was built or proposed as of 2018, and annual emissions are approximated as a linear decline from 2018 emissions levels to zero. Note that to obtain cumulative emissions (b) for Environment and Climate Change Canada (ECCC) models, trajectories are extended, where projected and Pan-Canadian Framework (PCF) scenarios plateau at 2030 levels and PCF additional measures declines linearly to zero by 2050. EMRG: Energy and Material Research Group, TEFP: Trottier Energy Future Project, DDPP: Deep Decarbonization Pathways Project.

3.8.3 Closing the gap between domestic mitigation potential and the fair share through international mitigation and adaptation potential

Using this set of emissions shares and decarbonization pathways for Canada, we can establish whether there is a discrepancy between what is considered fair and feasible. Immediately, one can see that there is a gap between emissions allotted to Canada under its fair share, by any account of equity we consider defensible, and what is thought Canada can do to decarbonize by the end of the century. Figure 3.6 compares both sets in terms of their cumulative emissions from 2020 to 2100, establishing a range of 'Paris gaps' that are emissions debts calculated as the difference between Canada's projected domestic emissions under decarbonization scenarios and its fair share of mitigation responsibility. Again, we use cumulative emissions from effort sharing pathways and resource shares, and cumulative emissions from decarbonization pathways. In other words, the Paris gap is a projected emissions debt.

The Paris gap varies according to global emissions remaining under ~1.75°C (note[i]), and the spread of cumulative emissions in the fair shares and decarbonization futures sampled herein. The Paris gap is taken as the difference of cumulative emissions between the fair share (excluding those that are untenable, see fig. 3.3) and a selected decarbonization pathway. When using the DDPP to provide decarbonization reference case, the Paris gap ranges from 2.8 $GtCO_2e$ (low equity) to 48.6 $GtCO_2e$ (high equity), with a central estimate of 18.3 $GtCO_2e$ (medium equity). One can readily monetize the Paris gap, for example, at $125/$tCO_2e$ (ref.[119], note[ii]), the central estimate (medium equity) would amount to a cost of $2.3 trillion (with a full range of $0.3 trillion to $6.1 trillion for low and high equity shares, respectively). For comparison, Canada's GDP in 2020 was approximately $2 trillion[iii], making the emissions debt about 20% higher than Canada's GDP. This debt would amount to approximately $59,000 per Canadian, or e.g. half that if paid over two generations. One may also compare this to the public debt. Canada's national debt in 2020 was $2.9 trillion,[iv] making this projected emissions debt about 20% lower than the fiscal debt. When using the median Paris gap (derived from extrapolating the PCF with additional measures trajectory to net zero emissions by 2050), Canada is projected to accrue a climate debt of 6 to 52 $GtCO_2e$ by 2050, which could be valued at $0.8 trillion to $6.5 trillion. For full Paris gap results, see Table S1.2 in the Supplementary Material.

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[i] Used here as a proxy for 'well below 2°C', taken from the mean of the above fair shares from 1.5°C (50%) and 2°C (66%) effort sharing pathways summed over time, as depicted in figure 3.4b. One could also use resource shares derived from a 1.75°C carbon budget. One could also use 1.5°C budgets to benchmark emissions futures against the highest ambition put forward in the Paris Agreement. Here we use the more forgiving 1.75°C target.

[ii] We do not attempt to select a precise value here for the social cost of carbon (SCC), or even more difficult, the social cost of GHG emissions that include non-CO_2 gases, but we use $125 per tonne as a rough benchmark for cost, which is considered conservative even for CO_2 alone. This value is taken from ref.[119], which found that all typical factors in SCC considered, $125 per tonne CO_2 is a realistic and conservative value, which still does not account for the worst case scenarios of extreme climate impacts, and this value would be much higher if more precaution was exercised.

[iii] Statistics Canada. Table 36-10-0222-01 Gross domestic product, expenditure-based, provincial and territorial, annual (x 1,000,000). DOI: https://doi.org/10.25318/3610022201-eng

[iv] The consolidated public debt across federal, provincial and territorial governments (i.e. the sum of all financial liabilities) reached $2,852 billion or $74,747 per capita in 2020. See Statistics Canada (November 22, 2021). "Consolidated Canadian Government Finance Statistics, 2020". Retrieved from: https://www150.statcan.gc.ca/n1/daily-quotidien/211122/dq211122a-eng.htm

Monetization of the Paris gap may provide a helpful illustration of the potential costs associated with unmet mitigation, in this case by Canada, and its population's potential ability to defray these costs using mechanisms such as a carbon tax or wealth tax. To ensure an equitable outcome within Canada, not all Canadians would be expected to contribute equally. Raising funds with a progressive income tax or a wealth tax would ensure that lower income Canadians would not be unfairly burdened by paying a debt that they or their forebears contributed little toward accruing. Furthermore, the debt could be paid out over multiple generations, to help lessen the burden on a single generation. Alternatively, it could be paid immediately from a wealth tax, since much of this same wealth can be expected to be passed on to future generations of wealthier Canadians, both directly through inheritance and less directly through other forms of bequeathing of wealth and other privileges. Wealthier Canadians paying more of a historical debt is still well justified, since today's wealth is largely predicated on historical fossil fuel emissions. We assert that this high-level argument holds well enough to expect the wealthy to pay more, while those who are living in poverty or just above it should not be expected to contribute since their personal emissions and the legacy of their ancestral emissions will usually be much less than wealthier people. In any case, some form of progressive taxation eschews blame for historical emissions in favour of garnering contributions from those most capable, and is in our opinion desirable as the most tractable and ethically robust option available.

However, we do not suggest quantifying the gap as such, since the social cost of CO_2 and other GHGs is subject to great uncertainty, varying by more than five orders of magnitude when accounting for the full spectrum of risk aversion, uncertain about damage estimates, and time preferences[119–122]. Likewise does not capture the costs of more calamitous climate events that fall on the extremes of impact distributions. More importantly, the social cost of carbon is a highly imprecise reflection of the costs of mitigation or adaptation, rather it is a measure of costs (or more precisely, forgone GDP) incurred due to CO_2 emissions. Prevention of marginal warming has been shown to be much more profitable from a cost-benefit perspective, and mitigation less expensive than adaptation to climate impacts[123]. Mitigation is also more fundamental to successful climate action. Even as adaptation becomes more necessary, mitigation efforts cannot be replaced with solely adaptation efforts. In other words, a single cost metric may suggest that mitigation and adaptation are interchangeable, but both are needed since adaptation cannot be a substitute for needed global mitigation. Indeed, in the context of this paper, we are interested in how much mitigation and adaptation efforts will cost in climate creditor countries[i]. Furthermore, monetary valuation and cost-benefit analysis that underpin the quantification of the social cost of CO_2 are based on inherently specious reasoning[124]. For instance, the social cost of CO_2 presupposes that value throughout in economy is fully encapsulated in monetary terms as measured by GDP, which overlooks the intrinsic value of much of the economy and rest of the living world that is not included in national accounts of economic activity, like unremunerated labour (most of which is care work performed by women)[125]. Monetary valuation also presupposes that exchange value is suited to compare the value of goods and services throughout an economy — which implies the perfect substitutability of all valued products — something that in real contexts often breaks down. For example, the social cost of CO_2 might suggest that it is more cost-effective and therefore desirable to allow a major drought effect in a developing nation

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[i] Or for the sake of simplicity, developing countries in general, which is where the vast majority of climate credits will continue to be held, even during a scenario where rapid decarbonization of affluent nations is successfully undertaken. For example, roll out costs in rapidly industrializing developing countries should be somewhat less than in developed nations, where e.g. labour is much more expensive.

that causes the starvation of thousands rather than mitigate the emissions to which this catastrophic is attributable to, since the activity that generates these emissions may produce more economic value (e.g. cars sold to people in the Global North) than the loss of food and even life associated with the drought. Outcomes such as these are baked into social cost of CO_2 and highlight the inherent bias towards richer people and capital in using social cost of CO_2 to decide on what climate action to take (or not bother taking).

With this in mind, we note that the monetary valuation of the Paris gap is inherently flawed but provide it so that its scale can be compared with other social costs of climate damages prevalent in climate policy literature. We suggest that the Paris gap of wealthy countries whose domestic mitigation efforts will invariably fall short of their fair contribution to global efforts be used to guide the needed ambition in both required scale of contribution to both international mitigation and adaptation. The simplest starting point we envision is as follows: the entirety of the gap, measured in terms of cumulative CO_2 emissions (or CO_2e emissions, allowing for approximations in mitigation timing of non-CO_2 emissions), could be used to determine the needed contribution to mitigation in countries that require assistance in their transition, especially where low carbon energy systems would not otherwise be deployed. Additionally, wealthy countries with positive Paris gaps could divide the projected adaptation costs associated with our current trajectory (which should be periodically updated) proportionally to their gap size. This means that countries that fall short of their fair share would not only need to mitigate abroad to compensate for this shortfall, but contribute proportionally to adaptation needs of developing nations. Adaptation needs in the affluent world could remain the financial responsibility of those same nations, though this does not preclude a discussion of whether some wealthy nations could be granted assistance from others, e.g., geographical considerations like large areas of land may warrant additional assistance from relatively wealthier nations or bioregional overlap of nations may require international cooperation between wealthy nations.

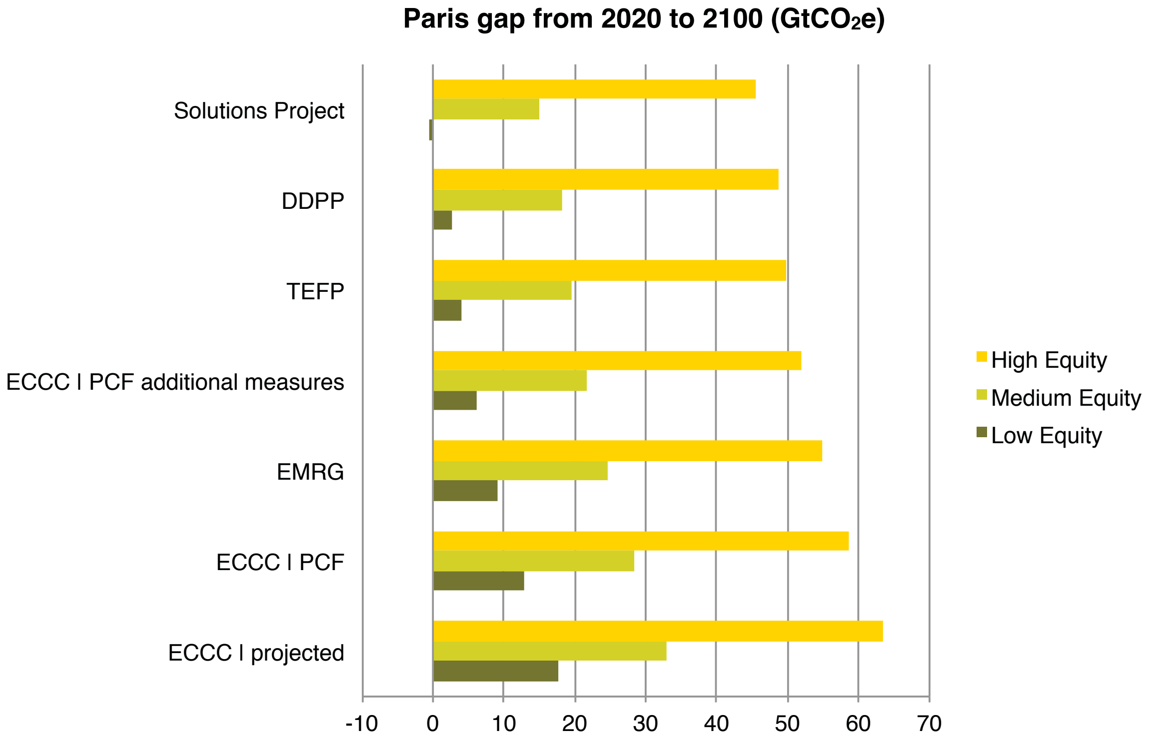

Figure 3.6 Paris gaps for each decarbonization pathway. Paris gap shown here uses cumulative emissions from each pathway (figure 3.5b) to benchmark fair shares, which come from the mean of acceptable shares from 1.5°C (50%) and 2°C (66%) scenarios (figure 3.4b). DDPP: Deep Decarbonization Pathways Project, TEFP: Trottier Energy Futures Project, ECCC: Environment and Climate Change Canada, EMRG: Energy and Materials Research Group.

Until all Paris gaps for nations are quantified, we cannot give an estimate of the projected adaptation contribution obligation. However, there are two shortcuts available to us. The first could be to divide current projected adaptation costs by current share of the global carbon or climate debt. Second, we could also approximate the Paris gaps of all nations, using a national decarbonization ambition in proportion to the global average required to limit global warming to 1.5°C or 1.75°C by 2100. This approach is similar to that taken in the CERF methodology. We leave these next steps for future research (section 3.9).

3.9 Conclusion and future research directions

Here we have provided a detailed analysis of possible Canadian decarbonization futures and their equity implications, and have suggested ways to reconcile decarbonization scenarios descriptive vision with the normative frame of emissions sharing. Our analysis refines previous approaches that have had to sacrifice precision in order to provide global analysis. Instead, our findings can inform Canadian policymaking with summarized metrics and recommendations that synthesize the latest research from climate science, ethics, and economic modeling. This technique can be reproduced for other countries where similar economic modeling is available. Moreover, our approach helps to elucidate an oft-confused conversation over what is equitable or what is practicable in domestic and international climate action. We hope that future efforts to outline proposals of fair and practical climate policy incorporate these insights. The most obvious next steps would be to 1) estimate the cost of international mitigation and propose ways for Canada to fulfill its projected international mitigation obligation, 2) estimate the projected international adaptation obligation for Canada, and 3) perform these estimates for other affluent nations and offer ways for them to fulfill these obligations. Step 1 could be achieved most simply by using the forecasted carbon debt (CO_2-only), and then estimate the amount of renewable energy and other non-emitting energy infrastructure that would be required to mitigate CO_2 emissions by this amount. A more sophisticated approach could incorporate non-CO_2 forcers like methane, however, an assessment of required non-emitting energy infrastructure in terms of mitigated emissions from combustion would be simplest to assess and probably adequate to describe how contributions to international mitigation support be apportioned. Mitigation could be illustrated in detail by offering different possible energy portfolios for developing countries based on the latest insights into what energy mix would be best suited to their geography and needs. Rather than offer options for international mitigation endeavours, we could also provide various cost estimates for this amount of mitigation based on latest estimates for the evolving costs of renewable energy and/or non-emitting energy implementation, based on a case study of a decarbonized energy mix for a given country or global average. Step 2, as discussed above, would require knowing what Canada's proportion of projected emissions debt (Paris gap) will be, and then allocating a share of the latest estimate of global adaptation costs under different warming scenarios to Canada. Step 3 would then repeat this analysis for other affluent nations. These insights could be used to inform suggested contributions to international climate finance e.g. under the auspices of the Green Climate Fund. It is worth reiterating that mitigation costs (step 1) and adaptation costs (step 2) are independent, and therefore it is not double counting to propose Canada both contribute to international mitigation on a scale that defrays their Paris gap while also contributing a proportional amount to foreseen adaptation expenses that will be incurred by countries with climate credits. It may be considered double counting if Canada were to quantify its Paris gap in monetary terms using the social cost of carbon, which could represent costs from both mitigation and adaptation, but as discussed above, the social cost of carbon is an imprecise combined measure of economic loss. Therefore, we suggest using specific cost estimates for mitigation and adaptation, perhaps even at the project-level.

4 Paper 2: Robust climate tests for energy decisions under the Paris Agreement

The following manuscript is being prepared for submission to Nature Climate Change *by the author and Matthews, H. D. Earlier analysis has been used in submissions to environmental assessment consultations for two proposed LNG export terminals, GNL Québec and Cedar LNG.*

4.1 Abstract

Contradictions between energy and climate policy hampers the coordinated planning needed to decarbonize economies. Diverse approaches have been used to assess whether countries' economic development and energy plans concur with their climate policy and commitments. However, these approaches vary in logic, formal definitions, and robustness. Here, we formalize a consistent and robust series of climate tests to evaluate whether individual energy projects, or the overall trajectory of a fossil fuel industry, are compatible with climate goals. The tests consider economic efficiency, equity, and techno-political feasibility spanning sectoral, national, and global scales. To demonstrate the utility of these tests, we apply them to a proposed LNG terminal and the gas industry in Canada. We found that forecasted gas production in Canada or the construction of new auxiliary infrastructure like LNG export terminals are incompatible with national or global reduction targets, as well as decarbonization scenarios that prioritize other assessed criteria. We argue that the exhaustiveness and interoperability of these climate tests makes them more reliable. The consistency and robustness of the suite tests as a whole also adds credibility to previous studies that have found expanding fossil fuel infrastructure to be at odds with climate goals, while also providing a reliable framework for assessing whether decisions are consistent with climate goals along multiple criteria. In failing all the tests, as in our illustrative case study, we argue that that the conclusion is much more reliable and transparent, since all criteria and how they interrelate are made explicit in the framework. These tests could also be applied to other sectors to assess their compatibility with climate goals.

4.2 Introduction

Many countries assert that their climate plans align with global efforts to limit warming to 1.5°C or well below 2°C, in accordance with the Paris Agreement. These countries also claim that their plans for economic development will allow them to meet their domestic emissions reduction targets. But there is a stark disconnection between climate and energy policy at national and global levels. Since three quarters of CO2 emissions come from fossil fuel combustion, successful mitigation requires dramatic reductions in fossil fuel consumption and production. However, many countries that espouse ambitious climate action continue to expand or resist phasing down fossil fuel extraction[44,126,127]. Such contradictions between mitigation and energy policy are a substantial contributor to the ongoing shortfalls in mitigation outcomes.

Climate tests, in which estimated emissions are compared with benchmarks, could provide ways to determine whether extraction or individual fossil fuel projects are compatible with various climate objectives[128]. Any project likely to generate emissions incompatible with climate action goals should fail an appropriately defined climate test[129]. Numerous analytic approaches that could form the basis for such climate tests have been proposed[57,58,130–136], emphasizing various combinations of biophysical constraints, economic efficiency, equitable outcomes, and technological or political feasibility. However, diversity in the logic and priorities of climate tests compromises their consistency and rigor as a tool for scrutinizing and regulating fossil fuel infrastructure and extraction. Furthermore, because a consistent framework for interpreting the diversity and interrelationship of climate tests is lacking, individual climate tests are often applied inconsistently or selectively.

Here, we propose formal definitions for six climate tests, a typology to describe their interrelationship, and formalize consistent methods for their execution. We then illustrate their application through the case study of a proposed liquefied fossil gas terminal in Canada and the Canadian fossil gas industry as a whole. Our novel characterization of climate tests provides a basis for critiquing and assimilating the results of climate tests that differ in logic and priorities. It also enables harmonizing assessments at federal and subnational levels with global objectives. As such, our framework helps minimize disjuncture between climate ambition and energy policy, and can serve as an important tool in cementing accountability around decision-making and harmonizing approaches in climate assessment.

4.3 Six climate tests

Our framework proposes six tests based on global and national benchmarks for whether forecasted fossil fuel projects (including new extraction and related fossil fuel infrastructure) are compatible with domestic emissions reduction targets or global climate goals. The first climate test (CT1) uses both a global and national benchmark, comparing committed emissions from existing and in-progress infrastructure to allowable emissions as constrained by agreed-upon limits to global heating. The second climate test (CT2) is also global but introduces economic efficiency, evaluating whether projects are compatible with a cost-optimal global energy transition. The third global-scale climate test (CT3) considers equity, assessing whether projects are compatible with Canada's fair share of global effort under 1.5°C. Finally, climate test 4 (CT4) evaluates whether projects are compatible with national decarbonization at the pace of the global average rate of mitigation required to limit global heating to 1.5°C, which may be considered a first-order approximation for achieving a technically feasible energy transition, though this approach still uses a global benchmark. The remaining two tests consider national climate goals. Climate test 5 (CT5) evaluates whether projects are compatible with country-specific decarbonization models, which incorporates judgments made by modeling experts knowledgeable about national-level opportunities and challenges, improving the specificity of technical and political feasibility embodied in benchmarks. Finally, climate test 6 (CT6) evaluates whether proposed fossil fuel infrastructure is compatible with domestic emissions reduction targets. We emphasize that not every one of these climate tests establishes whether decisions are aligned with limiting warming to agreed-upon global goals. Rather, climate tests are only as robust as their benchmarks, but all serve to test whether emissions are congruent with said benchmarks. These six climate tests are summarized in Table 4.1. The approach put forward in this study is most easily applied to other fossil fuel producing or consuming infrastructure but could be tailored to any economic decision that has a bearing on national or global GHG emissions, for example, phasing down meat and dairy consumption or other agricultural reforms.

After defining the tests, production and corresponding emissions quantities need to be estimated to operationalize the tests. Project, industry, national, and global emissions are compared against global (CT1-4), national (CT6), and industry-level (CT5) benchmarks.

				Test criteria					
Climate test	Compatibility with	Test subject	Benchmark	Biophysical constraints	Economic efficiency	Technological and political feasibility	Equitable outcomes	Paris-compliant?	Result (pass /fail)
1	Global and national infrastructure under 1.5°C	Committed CO_2 emissions from existing and proposed fossil fuel infrastructure	Remaining carbon budget	Yes	No	No	No	Yes	Fail
2	Cost-optimal global energy transition under 1.5°C and 2°C	Forecasted extraction	Remaining burnable fossil fuel reserves under cost-optimal global energy transition	Partial	Yes	Yes	No	1.5°C scenario only	Fail
3	National energy transition in line with fair share under 1.5°C	Emissions from forecasted extraction	Downscaled sectoral emissions from decarbonization ambition implied by fulfillment of fair share of global effort through domestic mitigation alone (i.e., without international mitigation)	Partial	No	No	Yes	Yes	Fail
4	National energy transition in line with global average under 1.5°C	Emissions from forecasted extraction	Downscaled sectoral emissions under global average decarbonization trajectory to limit warming to 1.5°C	Partial	Yes	Yes	No	Yes	Fail
5	National energy transition in line with national decarbonization models	Emissions from forecasted extraction	Sectoral emissions under proposed national decarbonization pathways	No	Yes	Yes	No	No	Fail
6	National emissions reduction targets	Emissions from forecasted extraction	Emissions implied by national emissions reduction targets	No	Partial	Partial	No	No	Fail

Table 4.1 Summary of design and results of proposed climate tests. Each test compares the test subject to the benchmark. Tests that are designed to assess whether CO_2 or GHG emissions from a project or pathway are compatible with a 1.5°C or well below 2°C (here 1.75°C) temperature scenario are deemed ‘Paris-compliant’. Satisfaction of remaining dimensions are rated on a scale from zero to one.

4.4 Establishing emissions scenarios from Canadian fossil gas industry

Here we establish GHG emissions scenarios from existing and planned projects for a given industry. For our case study, we select the GHG emissions related to Canadian gas extraction as forecasted by the Canada Energy Regulator (CER), and from liquefied fossil gas (typically referred to as liquefied natural gas (LNG)) projects currently under development. This allows us to situate LNG projects against a backdrop of other infrastructure deployed in the gas industry. We then compare emissions as forecasted by Environment and Climate Change Canada (ECCC) to our own estimates using revised emissions factors that incorporate the latest scientific findings from lifecycle analyses of fossil gas, most crucially fugitive methane emissions occurring during to its extraction (see Methods).

Figure 4.1a displays historical and forecasted gas extraction in Canada by volume, and Figure 4.1b and 1c display emissions related to gas production in annual and cumulative terms, respectively. GHG emissions include CO2, CH4 and N2O; and are expressed in aggregate over a 100-year time horizon (see Methods). These GHG emissions occur within Canadian borders from upstream and midstream sources, as estimated using forecasted emissions by ECCC, emissions factors calculated from emissions reported by ECCC and extraction volumes from the CER, and using lifecycle analysis (LCA) emissions factors estimated by the Centre international de référence sur le cycle de vie des produits, procédés et services (CIRAIG)[137] (see Methods). We use three emissions factors using CIRAIG's methodology for three corresponding well-to-gate fugitive emissions rates: 1) CIRAIG's default fugitive emissions rate of 1.2%, 2) the best estimate for industry average by Alvarez and colleagues of 2.7% (ref.[138]), and 3.7% for only unconventional gas by Howarth[139] (see Methods). We also include a hypothetical scenario where gas industry emissions follow ECCC forecasts then plateau at 2030 levels until 2050. This scenario is considered a low guardrail estimate that represents significant technological improvements that reduce emissions factors. Note that an upstream fugitive emissions rate of 2.7% may be overly conservative for the Canadian gas industry, as the share of shale and tight gas, or 'unconventional' gas (UG), already provides the majority of gas extracted in the US and Canada, and UG's share is expected to continue growing.

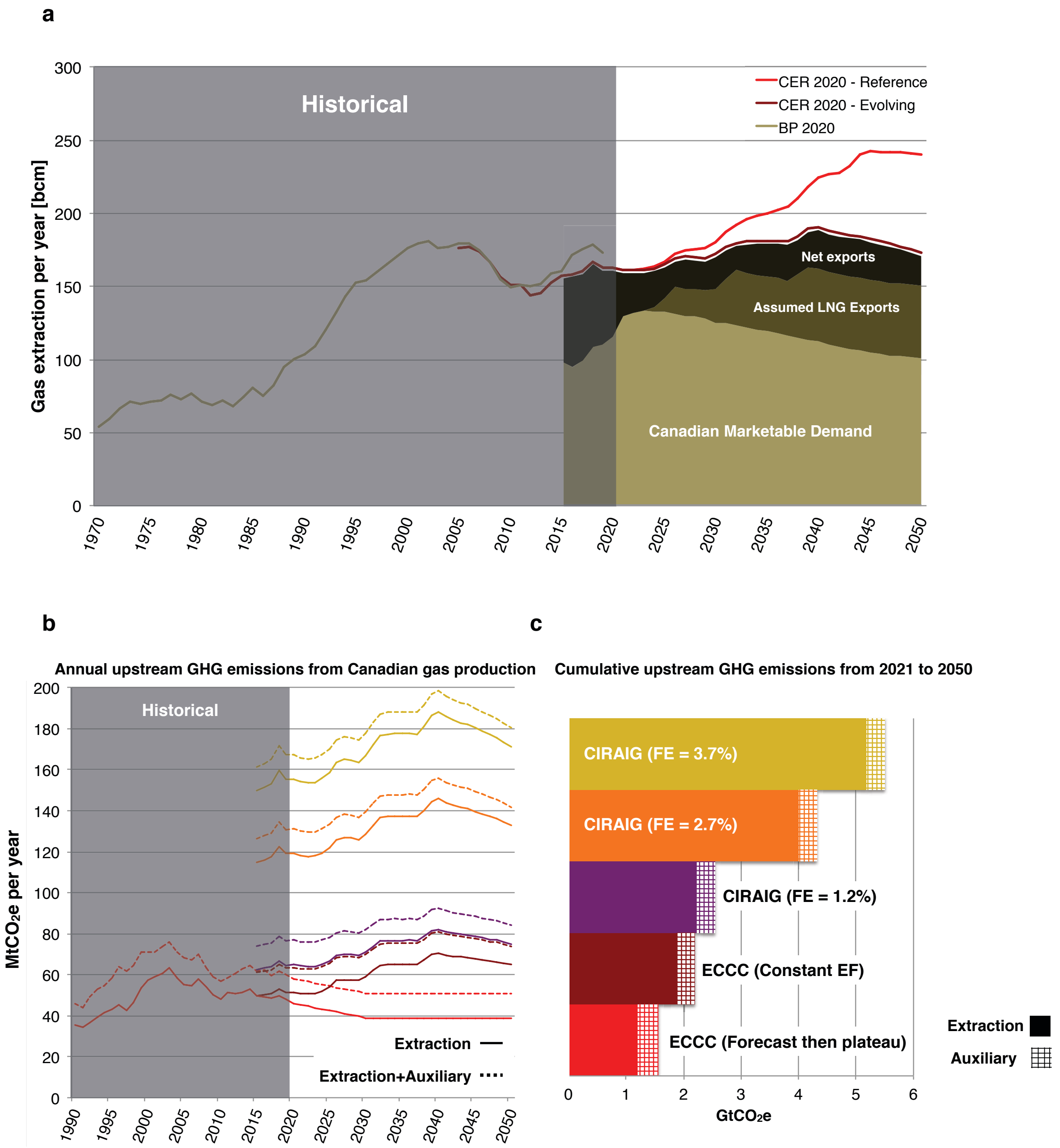

Figure 4.1 Historical and forecasted annual gas extraction in Canada (a), and annual (b) and cumulative (c) upstream GHG emissions related to gas extraction in Canada. Gas extraction is in billions of cubic metres (bcm) per year. Annual GHG emissions are in millions of tonnes (Mt) carbon dioxide equivalents (CO_2e) per year and cumulative GHG emissions are in billions of tonnes (Gt) of CO_2e. GHG emissions occurring during extraction are depicted by solid lines and bars, and those including additional auxiliary processes including processing and transportation are depicted by dashed lines and hatched bars, for annual and cumulative emissions, respectively. All upstream emissions occur within Canada. Historical emissions are as reported by Environment and Climate Change Canada (ECCC) as the sum of the gas extraction industry and other sources which include emissions associated with fugitive emissions during transmission and processing. Projected emissions are taken from ECCC forecast extended to 2050 assuming emissions plateau at 2030 levels (ECCC – forecast then plateau), and are obtained by taking the product of projected gas extraction volumes from Canada's Energy Future 2020 evolving scenario and a constant emissions factor for the mean of the final five years of historical emissions (ECCC – constant EF), and using emissions factors according to methodology used by CIRAIG with well-to-gate fugitive emissions (FE) rates of 1.2%, 2.7%, and 3.7%. CER: Canadian Energy Regulator, BP: British Petroleum.

4.4 GHG emissions from a representative fossil fuel infrastructure project

Here we select a representative infrastructure project to illustrate the application of our climate tests. *GNL Québec* and *Gazoduc* were a proposed LNG export terminal and accompanying pipeline that would have transported gas from Western Canada to the Saguenay fjord on the eastern shore of Québec, Canada. Both projects were recently subject to environmental review at federal and provincial levels. The province of Quebec rejected *GNL Québec* before the publication of this study[140], effectively cancelling the *Gazoduc* project as well. If *GNL Québec* had been approved, it was scheduled to begin operating in 2026 and would have exported 11 million tonnes (Mt) of LNG per year for at least 25 years. Table 4.2 summarizes the cumulative GHG emissions that would result from such a project. To calculate downstream emissions, we used the same market scenario used by the CIRAIG to determine the exported LNG's end-uses[137] (see Methods, Section 4.8). Estimates of downstream emissions are inherently conservative since they do not account for substantial leakages after well decommissioning. We strongly recommend only using emissions estimates with a fugitive emissions rates of the continental average of 2.7% or for unconventional gas only of 3.7%, meaning that the project could result in a total of 1260 to 1350 $MtCO_2e$ over its lifetime.

Note that we quantify emissions resulting from this project under the assumption that its addition to global gas supply would not displace other fuels or alternative energy sources. Neglecting displacement effects for marginal changes in gas supply is common practice because it is too difficult to determine whether additional gas will displace higher carbon fuels like coal or lower carbon alternatives like renewables[53]. The net effect has therefore been deemed negligible or unable to be quantified. However, this is not the case for oil and coal markets, which are more readily analyzed, and net displacement effects can and should be taken into account (e.g., ref.[53,54,141,142]).

		FE = 1.2%	FE = 2.7%	FE = 3.7%
EF (*gCO_2e/m^3*)	Upstream	518	852	1075
	Downstream	2480	2480	2480
	Global	2998	3332	3555
Annual (*$MtCO_2e/year$*)	Upstream	8	13	16
	Downstream	38	38	38
	Global	45	51	54
Lifetime (*$MtCO_2e$*)	Upstream	200	320	410
	Downstream	940	940	940
	Global	1140	1260	1350

Table 4.2 GHG emissions related to *GNL Québec*, for emissions factors (EF) in mass GHGs in carbon dioxide equivalents (CO_2e) per unit volume gas in cubic metres (m^3), annual emissions related to the terminal, and over its 25-year lifetime. All estimates use CIRAIG (2019) base methodology, with a default emissions fugitive emissions (FE) rate of 1.2%, and corrections to 2.7% and 3.7% for industry average and unconventional gas only, respectively. See Methods (Section 4.8) for more details. For clarity, EF and annual emissions values are rounded to the nearest one, while lifetime values are rounded to nearest ten.

4.5 Benchmarking GHG emissions from possible energy futures

We now can examine GHG emissions scenarios from possible energy futures and their implications on gas extraction and associated GHG emissions (Figure 4.2). See Methods (Section 4.8) for data sources and details of calculations. These emissions profiles will provide the backdrop against which to test forecasted gas extraction and proposed projects. Analogous profiles could be derived with which to test forecasted emissions and possible emissions from proposed infrastructure from other sectors.

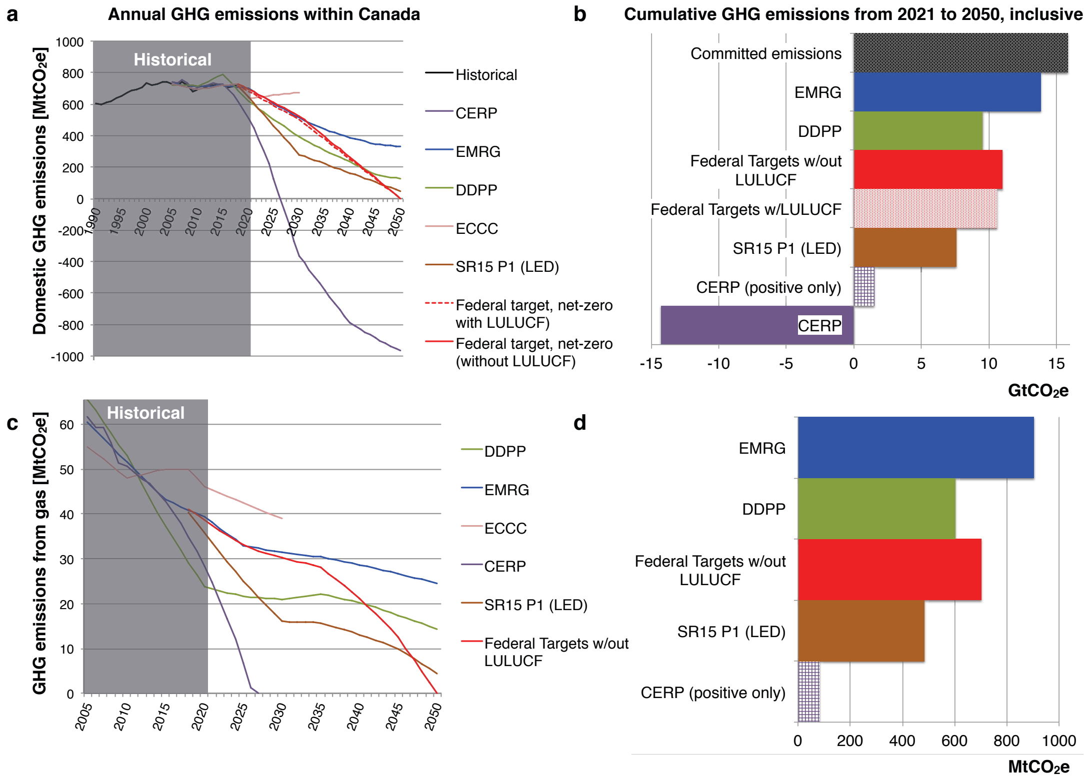

Figure 4.2 GHG emissions under various decarbonization scenarios for Canada and its gas industry. Annual emissions for Canada as a whole (a) and from gas extraction only (c) are brought together from historical data and forecasts from Canadian decarbonization models: Deep Decarbonization Pathways Project (DDPP), Energy and Materials Research Group (EMRG), and Environment and Climate Change Canada (ECCC); an effort sharing pathway from the Climate Equity Reference Project (CERP), and the global average is taken from the P1 pathway from the IPCC's Special Report on Global Warming of 1.5°C (SR15), which originated from the Low Energy Demand (LED) pathway. An additional policy scenario is obtained by linearly interpolating between federal reduction targets for 2030 and 2050. Cumulative emissions from 2021 to 2050, inclusive, are shown in bar graphs for the national total (b) and the gas industry for extraction alone, i.e. excluding auxiliary emissions (d).

4.6 Results of climate tests: case study of Canadian gas industry and representative gas infrastructure project

4.6.1 Climate test 1: Compatibility of new fossil fuel projects with committed emissions from global infrastructure under 1.5°C or national infrastructure under various decarbonization scenarios

Two forms of Climate test 1 (CT1) can be invoked: 1) a comparison of global committed emissions with carbon budgets remaining for a specified temperature goal, and 2) a comparison of a country's committed emissions with projected cumulative GHG emissions from various decarbonization trajectories. The first version can be used to determine whether new fossil fuel projects are compatible with global climate goals. The second tests whether new fossil fuel infrastructure is compatible with chosen domestic emissions scenarios, which may not themselves be compatible with global temperature goals.

Globally, committed emissions as of 2018 were 846 billion tonnes (Gt) carbon dioxide (CO_2)[49]. These emissions will exhaust the remaining carbon budgets (RCB) with a 67% and 50% chance of limiting global heating to 1.5°C, as well as the RCB with a 67% chance of limiting global heating to 1.75°C (taken as a proxy for 'well below 2°C'), and use up 86% of the median 1.75°C RCB (Figure 4.3). Note that committed emissions from existing and planned infrastructure are nearly triple (282%) that of the 1.5°C (67%) RCB. This implies that new infrastructure built anywhere globally jeopardizes limiting heating to the targets set out in the Paris Agreement.

Canada's CO_2-only committed emissions from existing and proposed infrastructure as of 2018 were approximately 15 $GtCO_2$[49], making up 1.7% of global committed emissions, which is over three times its share of the global population. Canada's committed emissions make up 5% and 2% of the remaining carbon budgets for 1.5°C and 1.75°C (67% likelihood) — ten and four times its proportion of the global population, respectively. Including non-CO_2 emissions, committed emissions from Canadian infrastructure amount to approximately 16 $GtCO_2e$, which exceed cumulative emissions projected under all decarbonization pathways considered here, including those implied by government emissions reduction targets (Figure 4.2b). This means that if Canada were to pursue decarbonization aligned with ambition represented by any of the above scenarios, existing fossil fuel infrastructure in Canada would need to be decommissioned before its projected economic lifetime. Emissions from the illustrative LNG project would add 320Mt CO_2e to Canada's committed emissions (Table 4.2), further adding to the challenge of decommissioning capital-intensive infrastructure prematurely, or overshooting emissions due to excessive lock-in[143].

Adding to insights from committed emissions estimates — which quantify future emissions on the demand-side — a recent study by the International Energy Agency (IEA) found new fossil fuel extraction projects are superfluous in a world targeting 1.5°C[144]. This general conclusion could be considered a supply-side (i.e. from the perspective of fossil fuel supply rather than energy demand) version of the first version of CT1 (i.e. global CT1), whereby new fossil fuel extraction projects are shown to be in excess of what is needed under a 1.5°C energy transition, and likewise can be said to be incompatible with the most ambitious target of the Paris Agreement. A recent study has also assessed the committed emissions from reserves already under development that shows existing extraction would already warm the planet by well over

1.5°C if realized[60], which provides a holistic supply-side view of extraction that complements the demand-side of previous infrastructural tallies.

We suggest that CT1 serve as an a priori ‘sanity check’ of whether any new fossil fuel extracting or combusting infrastructure is compatible with global climate action as agreed upon under the UNFCCC. Without any further analysis specific to proposed infrastructure, any new project automatically fails CT1 with respect to the 1.5°C climate target. The only way a new project could pass CT1 would be to retire other projects early to lessen committed emissions sufficiently to make room for commitments from new infrastructure. This outcome is unlikely, especially for privately-owned infrastructure, since it would voluntarily strand assets, which has not occurred unless politically or economically obliged and goes against the historical behavior of deceit and intransigence of the fossil fuel industry[29]. The same logic applies to fossil fuel reserves, which are not technically considered assets but are valuable nonetheless, and provide the basis for future assets.

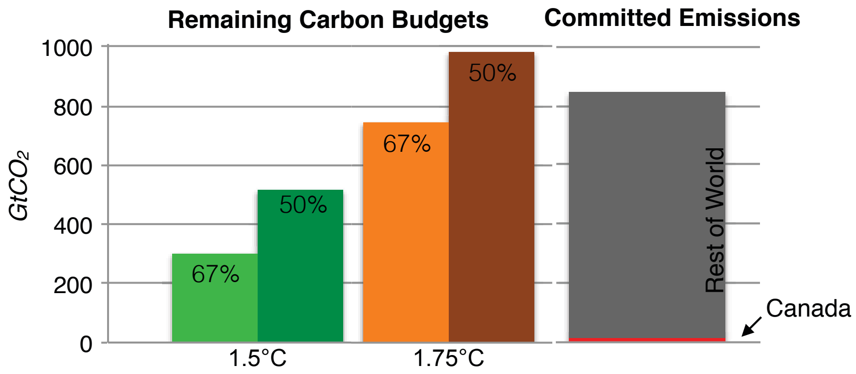

Figure 4.3 Climate test 1: Committed emissions from existing and proposed infrastructure versus remaining global carbon budgets. Both are in terms of cumulative CO_2 emissions, as of 2018. Proposed infrastructure is estimated for the Electricity sector only, whereas committed emissions for existing infrastructure includes all sectors.

4.6.2 Climate test 2: Compatibility with a cost-optimal global energy transition under 1.5°C and 2°C

Here we compare the fossil fuel related to a given project — either how much it would extract itself or facilitate the extraction of (i.e. extraction attributable to auxiliary infrastructure like a pipeline or processing facility), and the forecasted extraction of an industry as a whole — to the supply that would be extracted during a global energy transition where fuels are extracted in order of increasing cost until demand is met. Those in excess of what is needed to meet declining demand are deemed unburnable.

Under a 2°C transition, Canada had 0.95 trillion cubic metres (Tcm) of burnable gas reserves as of 2010 (ref.[132]). Comparing these remaining reserves to cumulative extraction since 2010 can tell us if Canada has already extracted what was then deemed burnable, or when it would exhaust its burnable gas. From 2010 to 2020, Canada extracted 1.7 Tcm of gas, having exhausted its cost-optimal burnable gas allocation in 2016, and was 0.8 Tcm over this allocation at the close of 2020 (Figure 4.4a).

However, if we would like to approximate what a cost-optimal allocation of remaining burnable global gas under 2°C might be starting today, we assume that the geographical distribution of burnable gas remains constant over time. Notice that even when allocating Canada a proportional share of global burnable gas starting in 2021, it would exhaust it in 2024 (Figure 4.4b), which is two years before the hypothetical LNG project was scheduled to come online. Since all Canadian gas extraction after 2024 would be in excess of a cost-optimal allocation under 2°C, the proposed project is incompatible with a cost-optimal global distribution of remaining burnable gas, and therefore fails climate test 2 (CT2). Although this is inherently a first-order approximation, it may prove useful to illustrate how much gas Canada might be able to extract under 2°C from today onward, noting that this version of CT2 is not compliant with the Paris Agreement, which requires limiting heating to well below 2°C. We do not expect Canada's share to vary enough to change the outcome of this test, which indicates that Canada will exhaust its cost-optimal share of remaining burnable gas within years at most, rather than decades, for which extraction is currently forecasted to continue.

Canada would extract 0.4 Tcm of gas under a cost-optimal global transition respecting a 1.5°C heating limit[133]. Canada would deplete this remaining gas in 2022 if it follows forecasted extraction (Figure 4.4c). This again demonstrates that planned extraction fails CT2, although in this instance, CT2 represents a stricter test that is complies with the goals of the Paris Agreement.

In sum, CT2 suggests that continued extraction of Canadian gas is generally incompatible with a cost-optimal global energy transition that limits temperature rise to 2°C or 1.5°C. Furthermore, CT2 suggests that forecasted Canadian gas extraction past 2024 (Figure 4.4b) is by default incompatible with lower temperature thresholds, like 'well below 2°C' or 1.5°C, and therefore incompatible with the Paris Agreement.

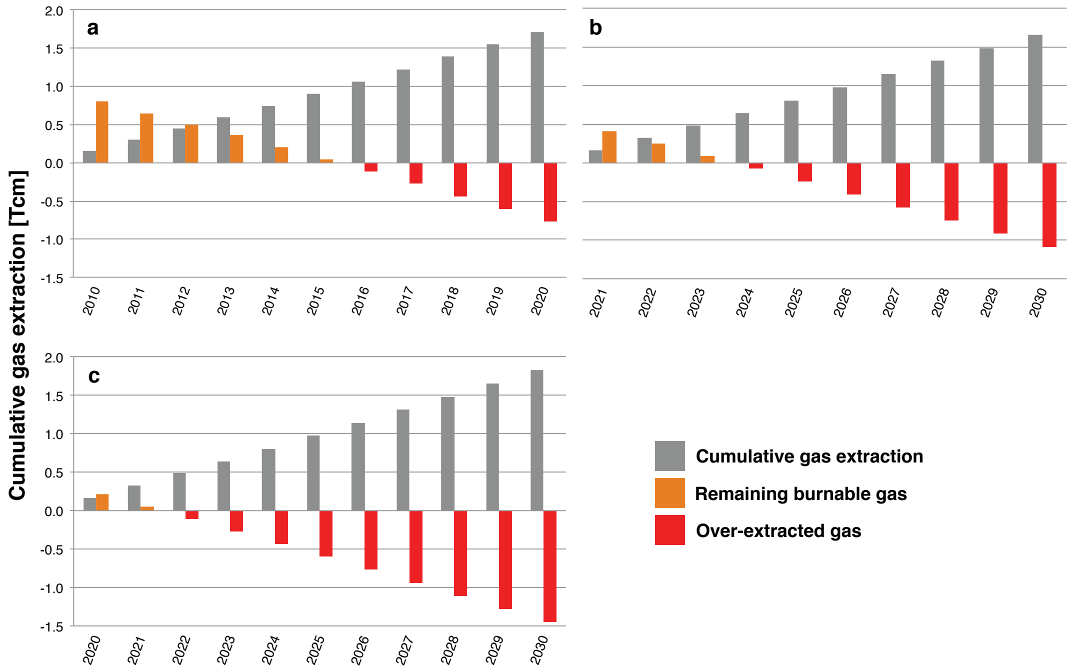

Figure 4.4. Climate test 2: Canada's cost-optimal allocation of remaining burnable gas under 2°C mitigation scenario from 2010 (a), proportional to 2010 geographical distribution from 2021 (b), and under 1.5°C from 2020 (c). Cumulative Canadian gas extraction in trillion cubic metres (Tcm) starts on first year shown, and is projected by the Canada Energy Regulator. Corresponding decline in remaining burnable Canadian gas depicts amount remaining at the end of that year.

4.6.3 Climate test 3: Compatibility with national energy transition in line with fair share under 1.5°C

Here we compare emissions from Canada's gas industry to those implied by a fair share of global effort under a 1.5°C scenario (see Methods). Note that Canada's cumulative emissions from 2021 to 2050 under this fair share (as described in ref.[32]) is negative (Figure 4.2b), which reflects its climate debt to other nations for historical overuse of GHG emissions as well as its related economic advantage obtained by outsized fossil fuel consumption. Since it is virtually impossible for a country like Canada to achieve their fair share through domestic mitigation alone, even at the most ambitious speed and scale possible, international mitigation will be required to supplement rapid domestic decarbonization. In this regard, CT3 illustrates what an equitable outcome without international mitigation would look like.

Canada's share of domestic emissions related to gas extraction under the selected 1.5°C fair share would be 82MtCO_2e as of 2021 (Figure 4.2d), which falls to 1MtCO_2e by 2026, the start date of the sample project, when subtracting projected extraction from 2021 to 2025. Any Canadian gas extraction, including that associated with the proposed project, beyond 2026 would soon exceed what remains under Canada's fair share pathway and is likewise incompatible with equitable outcomes that do not include substantial international mitigation. CT3 shows that growing upstream emissions from gas extraction are incompatible with fair decarbonization efforts, assuming that international mitigation by Canada will be highly limited, which accurately reflects Canada's present and pledged contributions[114].

The above provides a demand-side version of CT3, however we can also inquire if expanding gas extraction is compatible with fair efforts on the supply-side. Representing equitable outcomes quantitatively on the supply-side proves more difficult than on the demand-side, however we can explore them qualitatively. Canada is an example of a country relatively capable of transitioning away from fossil fuel production, since it is wealthier and more economically diverse than many other producers[57,58,145]. This strengthens the case for Canada to engage in a rapid wind down of oil and gas extraction, in order to leave room for countries more dependent on fossil fuel production to extract more fuels before global decarbonization of the energy system is complete. We therefore conclude that expanding gas extraction, and by extension, the sample project, fail CT3 from both demand-side and supply-side perspectives, signifying that both new projects and a general trend of sustained levels of Canadian gas extraction are incompatible with an equitable global energy transition.

4.6.4 Climate test 4: Compatibility with national energy transition in line with global average under 1.5°C

Here we compare emissions from Canada's gas industry to those implied by a national energy transition in line with the global average rate of decarbonizaton under a 1.5°C scenario (see Methods). Assuming a sectoral distribution of emissions proportional to the decarbonization scenarios surveyed, emissions from forecasted gas extraction are well in excess of what would be emitted under a national decarbonization scenario at the global average speed (Figure 4.5), and we therefore conclude that expanding gas extraction in Canada and any related infrastructure are incompatible with this level of ambition, and likewise, that forecasted Canadian gas extraction and the sample project fail CT4.

4.6.5 Climate test 5: Compatibility with national energy transition in line with national decarbonization models

Here we compare emissions from Canada's gas industry to those implied by a national energy transition according to various Canadian energy-emissions-economy (EEE) models, building on earlier work by Gibson and colleagues[146]. The Deep Decarbonization Pathways Project (DDPP) by Bataille and colleagues[105], and the Energy and Materials Research Group (EMRG) by Jaccard and colleagues[106] provide the two best suited models for determining what a phase down of oil and gas extraction in Canada might look like if it employed the policies proposed in these scenarios. However, neither of the models was able to fully decarbonize the oil and gas sector, or was constrained by emissions reduction targets. See the Supplementary Discussion for further explanation of the models and chosen scenarios.

For the Canadian gas extraction industry, the DDPP and EMRG find that from 2026 to 2050 the sector will emit 490 $MtCO_2e$ and 730 $MtCO_2e$, respectively (Figure 4.2d, Figure 4.5). For comparison, the cumulative upstream emissions related to gas extraction induced by the proposed LNG terminal over the same time period would be 320 $MtCO_2e$ and 410 $MtCO_2e$ for fugitive emissions rates from well to terminal of 2.7% (industry average) and 3.7% (unconventional gas only), respectively (Table 4.2). At a fugitive emissions rate of 2.7%, this project alone would result in cumulative upstream emissions occupying 66% and 45% of remaining gas extraction emissions in the DDPP and EMRG pathways, respectively.

For comparison, cumulative upstream GHG emissions from gas production excluding LNG are 1.1GtCO$_2$e over the same time period when using government emissions factors — which are on par with the original CIRAIG emissions factor using a fugitive emissions rate of 1.2% (Fig. 4.5, low estimate) — exceeding cumulative GHG emissions from gas extraction from both decarbonization models. Given the amount of export capacity expected to come online in BC, any additional LNG terminals, and even those already approved, appear at odds with decarbonization efforts such as those envisioned in the Canadian DDPP or EMRG scenarios. We note that the fugitive emissions rate of 1.2% is far too low to be considered plausible, and that this further reinforces the incompatibility of foreseen extraction and export infrastructure with even modest decarbonization efforts.

We therefore conclude that expanding gas extraction is inconsistent with decarbonization pathways as envisioned by Canadian EEE modeling, and therefore the sample project, or any new project that would facilitate additional gas extraction in Canada, fails CT5. We reiterate that the trajectories set out in the DDPP and EMRG scenarios are not ambitious enough to follow even the global average decarbonization trajectory needed to limit global heating to the Paris Agreement target range, so that extraction or individual projects that pass CT5 in other contexts do not necessarily comply with the goals of the Paris Agreement.

4.6.6 Climate test 6: Compatibility with national emissions reduction targets

Here we compare emissions from Canada's gas industry to those implied by a national energy transition aligned with national emissions reduction targets. Cumulative national GHG emissions are first estimated by interpolating annual emissions linearly between stated climate targets of 30% below 2005 levels by 2030 and net-zero (here approximated as zero) by 2050 (Figure 4.2a). As for CT3 and CT4, we distribute emissions proportionally to those derived from the decarbonization scenarios employed in CT5 (Figures 4.2c, d; 4.5), which yields cumulative upstream GHG emissions from gas extraction of 0.5 GtCO$_2$e from 2026 to 2050, inclusive. By comparison, cumulative emissions from gas extraction according to the CER's Canada's Energy Future 2020 evolving scenario vary from 1.9 GtCO$_2$e (Fig. 4.5, low) to 4.7 GtCO$_2$e (Fig. 4.5, high).

Substituting their scenario's LNG production with cumulative production from slated projects yields cumulative emissions ranging from 2.2 GtCO$_2$e to 5.3 GtCO$_2$e over the same period. If no new gas extraction or related infrastructure (including *GNL Québec*) is built, then the total emissions from gas extraction in Canada from 2026 to 2050 would be between 2.0 GtCO$_2$e and 4.9 GtCO$_2$e, which is approximately four to ten times what the industry's emissions would be if these national emissions reduction targets were met. However, we strongly believe that the low estimate, which is based on fugitive emissions estimates from government (ECCC) and from consulting firms like CIRAIG are far too low and therefore should be excluded from the range of plausible GHG emissions. We leave these estimates in our analysis for reference only and suggest that those using our values use only the mean to high range.

In other words — even when optimistic assumptions are made about improvements to infrastructure that significantly reduce fugitive emissions during extraction and transport of gas, and/or electrify extraction and auxiliary infrastructure — cumulative emissions from forecasted extraction would be nearly four times more than if Canada honoured its former Nationally Determined Contribution (NDC). We therefore conclude that forecasted extraction and plans to expand LNG capacity are also incompatible with more recent federal climate pledges — including the more ambitious revised reduction target in the 2021 enhanced NDC of 40% to 45% below 2005 levels by 2030 (ref.[147]), which fails by default as it uses a stronger threshold than the previous weaker one tested here — and the proposed project, or those like it that would lead to additional gas extraction, likewise fail CT6.

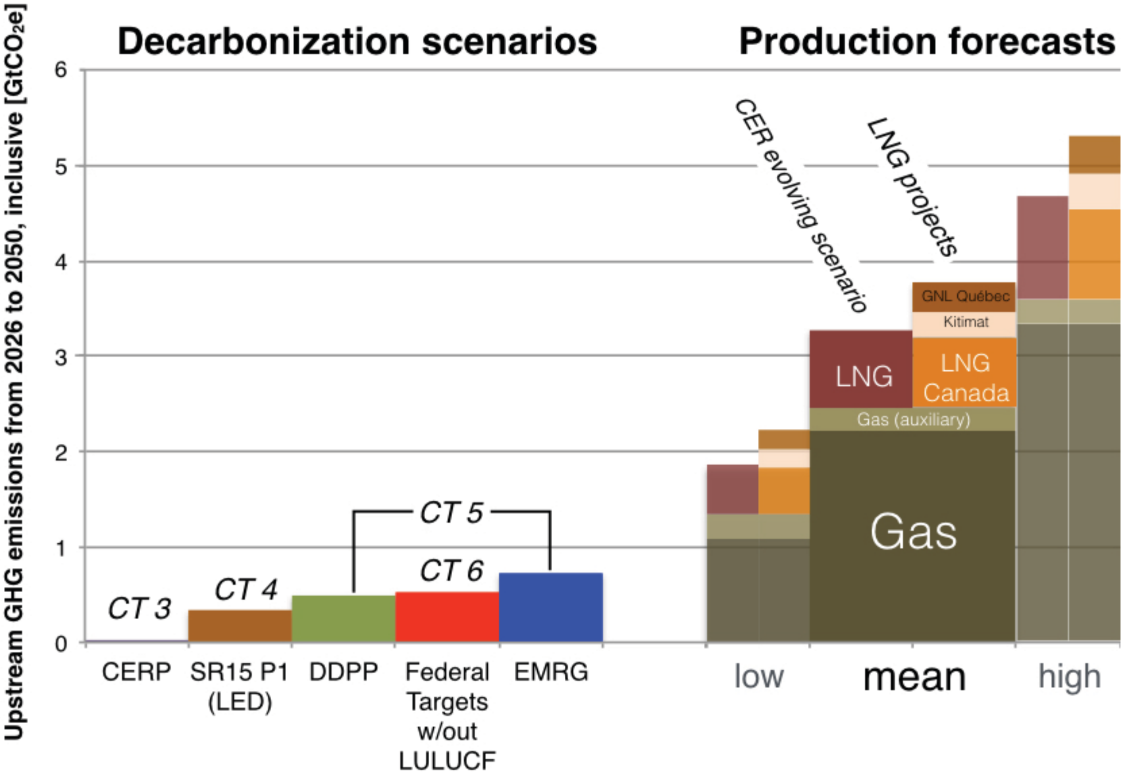

Figure 4.5 Climate tests 3-6: Comparison of cumulative upstream GHG emissions from gas extraction under different gas phase down scenarios and forecasted gas production. Left hand side bars depict cumulative GHG emissions from 2026 to 2050 for gas extraction in Canada under Canada's fair share of domestic abatement (climate test 3, CT3), under a decarbonization path with global average ambition under 1.5°C (climate test 4, CT4), under decarbonization pathways by Deep Decarbonization Pathways Project (DDPP) and the Energy and Materials Research Group (EMRG) (climate test 5, CT5), and implied by domestic emissions reduction targets (climate test 6, CT6). These quantities correspond to those depicted in Figure 2d, subtracting projected emissions from 2021 to 2025. On the right hand side, emissions from forecasted gas production are as depicted in Figure 1c, also subtracting projected emissions from 2021 to 2025, and excluding the 'ECCC forecast then plateau' scenario. Two sets of LNG estimates are included. LNG emissions on the left are from LNG production as forecasted by the Canadian Energy Regulator (CER), while the left is by project capacity for projects under development and the sample project. The low and high ends of emissions estimates for production forecasts correspond to 'ECCC constant EF' and 'CIRAIG FE = 3.7%' in Figure 4.1, respectively.

4.7 Discussion

4.7.1 Towards an integrated national climate policy

We have proposed a set of six climate tests for determining whether fossil fuel infrastructure and supply are compatible with different climate goals, each prioritizing various important considerations in climate policy; including biophysical limits, economic efficiency, techno-political viability, and equity. We have shown how these tests can be applied to a specific piece of infrastructure, or an industry as a whole, to determine whether projects or extraction plans are congruent with global energy needs in a world that respects the Paris Agreement or respective national goals, whether or not these goals adhere to the Paris Agreement itself. Further, failing global tests while passing national ones means national commitments are insufficient. If climate tests were applied consistently (e.g. under the UNFCCC) countries would be forced to reconcile national policies with global goals. Even in absence of an international harmonized approach, climate tests are also useful within countries, since they provide a robust and transparent means of assessing whether domestic decisions align with self-prescribed emissions reductions targets.

We also provide a case study of the Canadian gas industry, which serves as a template for other tests as well as a useable example for a key industry whose role in a transition is the subject of debate. We chose Canada because it is a key fossil fuel producing nation. It is the fifth and fourth largest producer of oil and gas, respectively, and ranks eighth in terms of extraction-based CO_2 emissions[127], exporting as much emissions in its fuel as it emits territorially[62]. Canada's outsized role in driving global heating as a major fossil fuel exporter makes it an excellent candidate for supply-side climate policy, starting with the adoption of climate tests in strategic assessment of energy and other important economic decisions. Canada also presents a challenge and opportunity typical of wealthy countries that are heavily dependent on fossil fuel production. Thanks to its diverse economy and substantial wealth, Canada is well positioned to transition away from fossil fuel production sooner and more quickly than relatively less wealthy and more economically dependent countries[57,58,145].

Countries are beginning to acknowledge the need for a coordinated economy-wide climate policy approach, and are moving towards integrating climate policy into all realms of decision-making. In the United States, the Biden administration has announced its intention to create a government meta-agency (called the 'National Climate Task Force') that will make climate goals central to domestic policy and foreign affairs strategies[148]. In Canada, a Strategic Assessment of Climate Change[149] offers a regulatory venue for climate testing new infrastructure[150], but as of yet does not possess the scope needed to ensure that such assessments reliably reject infrastructure incompatible with the Paris Agreement[129,151,152]. Using robust climate tests as the basis for a strategic assessment of climate change, would clarify whether new fossil fuel projects or extraction permits cohere with climate goals, providing a consistent framework for aligning energy decisions with climate goals. Outside of government, civil society could use climate tests in depositions for environmental assessments or as evidence in litigation against decisions believed to be at odds with effective climate action.

Through this case study, we have shown that that according to all the tests executed here, forecasted Canadian gas extraction and new gas infrastructure like LNG export terminals are incompatible with climate action under the Paris Agreement or the goals of the Canadian government, which are as of yet not sufficient, much less equitable, contributions to global efforts needed to limit warming to well below 2°C (e.g., ref.[114]). Table 4.1 also summarizes our results. It is also worth noting that based on our comparison of government reporting and emissions factors that account for underestimates in fugitive emissions reporting, annual GHG emissions from Canadian gas extraction and related activities could be 2.2 times higher than reported. Our analysis raises concerns over the accuracy of government reporting, which tends to rely on outdated methodology. GHG emissions underreporting from gas could likewise be widespread and systematic, as has been found for the Canadian oil and gas industries (e.g., ref.[153]).

CT1 used a comprehensive survey of committed emissions from existing fossil fuel infrastructure to assess whether new infrastructure is compatible with climate goals, and strongly suggests that new fossil fuel infrastructure of any nature in any locale would jeopardize meeting objectives set forth in the Paris Agreement. CT1 also shows how committed emissions at the national level jeopardize meeting less ambitious national climate targets.

CT2 employed robust modeling of economically-optimal fossil fuel supply under an energy transition needed to limit warming to 1.5°C or 2°C. Pursuing extraction that fails CT2 may suggest Canadian gas firms do not believe market dynamics will play a deciding role in which country's reserves are needed to satisfy demand during the energy transition, or that they intend to produce more than is required, or that they are willing to produce even if it is at a fiscal loss — or simply, like when failing any climate test — that they do not believe global climate action will be successful, and that their reserves will continue to be viable. Note that we rank CT2 lower along the dimension of biophysical constraints, as the carbon budget used is less constrained than the best estimate used in e.g. CT1.

CT3 downscaled a national fair share of global effort under 1.5°C to the gas industry to show how its GHG emissions would be constrained if Canada pursued a rapid decarbonisation in line with this pathway. We rank CT3 relatively high on the biophysical constraint scale, since it uses a robust 1.5°C scenario. Note that CT3 serves as the sole climate tests in our suite that attempts to represent decision-making aligned with equitable outcomes. It is by far the most constraining climate test, but as we note above, there is no requirement for a country to fulfill the entirety of its fair share of global effort through domestic mitigation alone. On the contrary, this result reinforces the need for internationally supported mitigation efforts. Our methods could be expanded to include other climate tests, for example a supply-side version of an equity test as described by Pye and colleagues[134] or Calverley and Anderson[154].

CT4 downscales GHG emissions from a reliable pathway for 1.5°C that comes from a global decarbonization pathway deemed economically and technically feasible. It could provide a heuristic method for establishing a reasonable expected level of domestic mitigation against which to test development plans.

CT5 has the distinct advantage of relying on a pathway specific to the country under investigation (here, Canada), which other tests lack. However, passing CT5 only means that planned extraction aligns with a country-specific decarbonization scenario, which may not necessarily align with global temperature goals under the Paris Agreement. In this sense, CT5 is a weaker test of compliance to global climate goals.

CT6 is informed by political, economic and technological considerations as assessed by the Government of Canada, however it too is not grounded in global objectives under the Paris Agreement. This is not a weakness of the test itself. We reiterate that CT5 and CT6 serve to assess compliance of fossil fuel development with stated national or subnational goals, which themselves may not comply with global ones.

The results of these climate tests show that the current trajectory of Canadian gas industry and any infrastructure that may further prolong gas extraction is at odds with national and global climate goals. Conversely, increases in gas in the stock of gas producing or auxiliary infrastructure like LNG export terminals may fit within scenarios where efforts are not made to align supply with declining demand implied by any level of climate action explored here. Supply-side policies like moratoria on new gas leases or infrastructure projects would help provide a clear exit plan from oil and gas production in Canada[41,44,126,155]. We reiterate that this approach can be modified to assess the climate-compatibility of development choices in other economic sectors, notably agriculture and forestry, which are both major secondary contributors to GHG emissions. For example, policies that may incentivize production or consumption of meat and dairy products could be analyzed. In theory, climate tests could also be applied to more distal drivers of climate change like subsidies and other financing of fossil fuel and agriculture industries.

4.8 Methods

4.8.1 Establishing scenarios for climate tests

For climate test 1, we obtained committed emissions estimates from Tong and colleagues[49], and compared them to carbon budget estimates from Matthews and colleagues[72] for emissions remaining as of 2020, adjusted to 2018 by adding emissions for 2018 and 2019 from the Global Carbon Budget 2021[84]. We approximate committed emissions of non-CO_2 GHGs by using a proportionality constant of CO_2 to CO_2e for Canada's national economy averaged over the most recent five-year period. National estimates of committed emissions do not divide neatly into sectors that permit us to compare them directly to emissions from fossil fuel extraction and related infrastructure. However, we are able to compare GHG emissions from an entire national economy under various scenarios to said committed emissions.

For climate test 2, we took estimates of burnable gas reserves from Welsby and colleagues[133] and McGlade and Ekins[132], and compared these reserves to historical and forecasted gas production from the Canada Energy Regulator (CER), using Canada's Energy Future (CEF) 2020 evolving scenario, available from CER's data appendices[156].

Climate tests 3 through 6 compare upstream emissions from gas production forecasted by the CER to those implied by the achievement of various national decarbonization scenarios. These national decarbonization scenarios were parsed down to the gas industry level using Canadian macroeconomic models, which provided the basis for climate test 5. We began by taking two macroeconomic decarbonization scenarios that model gas extraction explicitly, that of 1) the Canadian Deep Decarbonization Pathways Project (DDPP) for Canada by Bataille and colleagues[105], and the Energy and Materials Research Group (EMRG) by Jaccard and colleagues[106]. We also included Environment and Climate Change Canada's (ECCC) scenario[108], which provided a forecast to 2030. In order to compare it to longer-term scenarios, we extended it to midcentury (2031 to 2050, inclusive) by assuming emissions plateau at 2030 levels. However, we omitted these post-2030 values in our sample of emissions futures for the Canadian gas industry.

Out of several case studies provided by modeling teams of the DDPP and EMRG units, we selected their central scenarios, which assumed low future oil prices and imposed regulations deemed politically saleable. We note that in the near-term, oil prices may fluctuate dramatically, for example, returning to high prices during times of geopolitical strife that affects the reliability of supply. Assuming some level of serious climate action is taken, as has been currently pledged, fuel prices should trend downwards as declining demand outpaces waning supply. Therefore, we feel that the assumption of low oil prices in the long-term is well warranted.

To obtain an average estimate of annual and cumulative emissions from the gas industry, we took the mean of emissions from the DDPP, EMRG and ECCC scenarios, and used the average emissions from the gas industry as a percent of total national emissions to approximate emissions that would result in pathways for national emissions for scenarios that did not explicitly model sectoral decarbonization (climate tests 3, 4, and 6). These emissions scenarios for climate tests 3, 4 and 6 asked what annual and cumulative emissions due to gas extraction would be if Canada were to decarbonize its gas industry emissions proportionally to the mean of the gas industry explicitly modeled in the DDPP, EMRG, and ECCC (up to the year 2030) scenarios. A full data set is available in the Supplementary Data.

Climate test 3 used an internationally equitable outcome as described by the effort sharing pathway ('fair share') derived by the Climate Equity Reference Project (CERP), available from ref.[157], as discussed in e.g., ref.[32].

Climate test 4 used a national decarbonization pathway where Canada pursues the global average effort under 1.5°C as described by the Low Energy Demand (LED) pathway[103], denoted P1 in the IPCC's Special Report on Global Warming of 1.5°C (SR15, ref.[39]).

Climate test 5 used the Canadian decarbonization scenarios that represented what the Canadian DDPP and the EMRG groups believed to be techno-politically feasible outcomes for emissions reductions by midcentury at the time of publication. We note that since then, ambitions have improved and modelers would likely increase the speed and scale of decarbonization efforts in their modeling assumptions.

Climate test 6 used a decarbonization pathway that interpolated between national reduction targets. This approach can be changed to correspond with changes to national ambition. Increasing national ambition would constrain emissions across all sectors. Therefore if projects or extraction plans fail tests with weaker targets, they would by default fail more stringent ones. Future work could incorporate different targets or biophysical constraints that become relevant to policymakers.

4.8.2 Estimating the lifecycle emissions of Canadian gas

To estimate the lifecycle emissions of Canadian gas production, we combine data on production forecasts and lifecycle emissions of production. We used historical and forecasted production data from the CER. We also included estimates of historical production from BP Statistical Review of World Energy 2020, available from ref.[158]. We used reported annual GHG emissions by ECCC for historical and forecasted emissions to 2030 in addition to our own estimates extending to 2050, which were derived using a range of emissions factors (see below). We obtained emissions factors for carbon dioxide only (CO_2) from Canada's National Inventory Report (NIR) 2020 submission to the UNFCCC, available from ref.[159]. For scale, we compared cumulative CO_2 emissions from gas extracted in Canada from 2021 onward to the remaining carbon budget for 1.5°C with a 66% chance of limiting warming to threshold, as reported by Matthews and colleagues[72].

We chose to calculate emissions factors for total GHGs in carbon dioxide equivalents (CO_2e) over a 100-year time horizon using the global warming potential (GWP) method, as is the convention. We derived the first set of emissions factors (EF), labeled 'ECCC (Constant EF)', by taking the mean of the quotient of total GHG emissions as reported in NIR 2020 over the volume of gas produced over the last five years. We define auxiliary GHG emissions from activities related to gas extraction not directly attributable to extraction processes as emissions from gas processing and transportation, excluding emissions related to non-combustion processes, i.e. during the manufacturing of petroleum products from gas, which we would attribute to the petrochemical production industry.

We derived the remaining EFs using lifecycle analysis (LCA) performed by the *Centre international de référence sur le cycle de vie des produits, procédés et services* (CIRAIG). We based our EFs on their latest LCA study of the GHG emissions related to a proposed liquefied natural gas (LNG) terminal, *GNL Québec*[137], using their analysis of emissions throughout the global supply chain related to gas production in Canada. Our second set of EFs was derived using the default settings in CIRAIG's study, while differentiating between marketable gas and LNG. CIRAIG employed an upstream fugitive emissions (FE) rate of 1.2% of total product, including product lost during extraction and flaring, for the North American industry average[160]. This set of EFs is labeled 'CIRAIG, FE = 1.2%'. However, we find that this fugitive emissions rate is substantially lower than what it is currently understood to be, for example, as shown by Alvarez and colleagues[138], explained below. We derived two additional sets of EFs to account for this underestimate, one for the industry average and the other for unconventional gas alone.

Alvarez and colleagues correct for systemic underestimates of fugitive emissions by harmonizing bottom-up estimates with top down measurements for a representative sample of the United States industry, reporting an average fugitive emissions rate of 2.3%, or 2.7% when including emissions lost throughout the continental distribution network[138 SM], which we refer to as the well-to-gate fugitive emissions. The US industry is presumed to be on par with the Canadian industry, as CIRAIG also assumes in their analysis[137]. Using Alvarez and colleagues' industry average fugitive emissions rate in place of the CIRAIG's default, we derive the third set of EFs, labeled 'CIRAIG, FE = 2.7%'. However, since the majority of forecasted gas extraction in Canada is slated to come from unconventional sources (see ref.[156], Section 2.1), we also derive a fourth set of EFs for unconventional gas alone. We used estimates by Howarth[139] for fugitive emissions from unconventional gas extraction, which found that upstream CH_4 losses are between 2.2% and 4.3% (mean of 3.3%) of final product. We add an additional 0.4% for losses throughout the continental distribution network when calculating fugitive emissions from well to destination, as estimated by Alvarez and colleagues, which yields an upstream FE rate of 3.7%. This set of EFs is labeled 'CIRAIG, FE = 3.7%'. Emissions estimates produced using this EF can be regarded as an upper bound as the gas extraction mix tends towards 100% unconventional sources.

We calculated total FE as the mass of lost product, as $mass_{gas} \times \%CH_4 \times \%FE \times GWP$, where $mass_{gas}$ is the total mass of gas extracted or used, $\%CH_4$ is the percentage of CH_4 in industry standardized gas by mass (~90%), $\%FE$ is the fugitive emissions rate, and GWP is the GWP value, where we use a factor of 34 for GWP100. For example, the fugitive emissions from gas feeding a LNG project the size of *GNL Québec*, which would have processed 11 Mt gas per year, would amount to approximately 9MtCO_2e annually at a FE rate of 2.7% over a 100-year time horizon.

In order to estimate lifecycle emissions related to gas production and a proposed LNG terminal, we need to adapt the EFs used in LCA studies from a downstream (demand-side) to an upstream (supply-side) perspective, since LCA studies of the climate impact of energy infrastructure commonly report their results from the downstream perspective. These EFs are estimates of the GHG emissions (or other impacts) produced per unit output, which in the case of energy carriers like LNG are electricity (emissions per unit electricity generated), heat (emissions per unit heat generated), or mobility (emissions per unit distance traveled). To convert them to units of emissions per unit gas extracted, we needed to convert the LCA EFs to the upstream (supply-side) perspective using the efficiency of the end process, which will determine how much gas will be used in the process. Equation 1 shows how we calculate total GHG emissions by converting demand-side coefficients to their supply side equivalents.

$$GHG = \frac{GHG}{E_{delivered}} \times E_{delivered} = \frac{GHG}{E_{delivered}} \times \alpha E_{fuel} = \frac{GHG}{E_{delivered}} \times \alpha \frac{E_{fuel}}{V_{fuel}} \times V_{fuel} \qquad \textbf{Equation 1}$$

The first term, mass of GHG emissions per unit energy delivered ($GHG/E_{delivered}$), is the EF as reported in LCA literature (in units of g or kg of CO_2e per kWh or MJ, here gCO_2e/kWh unless otherwise noted). The second term ($E_{delivered}$) is the total energy delivered, which is equal to the energy content of the fuel (E_{fuel}) times the efficiency of the process (α). When fuel is measured in terms of volume, we use the energy embodied per unit volume of fuel (E_{fuel}/V_{fuel}) times the volume of fuel (V_{fuel}) to estimate E_{fuel}.

For example, if a power plant is 60% efficient it would require 1/0.6=1.7 times the amount of gas to produce a unit of electricity. From the supply-side perspective, one unit of gas would produce 60% of a unit of electricity. This means that for every unit of gas, one produces 0.6 units of electricity, and likewise 0.6 units of GHG emissions (or whatever associated impact one is concerned with), when using EFs prepared using LCA and presented in terms of impact per unit electricity produced (in our case GHG emissions per kWh).

Note that we do not correct for underestimates from downstream FE, which Howarth[139] estimated to be an additional loss of 2.5% of final product, nor underestimates from orphan gas wells, which are likely underestimated by 150% in Canada, according to recent research[161]. If adjusted, these additional losses would increase the climate impact of gas extraction or related infrastructure accordingly. We also did not harmonize GWP100 conversion factors, and these may vary across studies, but we did not expect them to qualitatively alter our results. Some uncertainty due to varying parameters like GWP values is common in LCA studies, which sometime perform sensitivity analysis to determine the effect of differing GWP factors on climate impact (see e.g., refs.[162,163]). We decided to not include a more exhaustive meta-analysis of lifecycle emissions from gas production since this was not the primary purpose of the study, and left further refinement of EF estimates for future research on climate test implementation. That being said, we are confident that the EF estimates included are up to the standard of LCA studies used in environmental assessment, and are confident that this study can provide a reliable operationalization of the climate test framework outlined here.

5 Paper 3: Shifting economic activity to services has limited potential to reduce global environmental impacts due to the household consumption of labour

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5.1 Abstract

The tertiary (or 'service') sector is commonly identified as a relatively clean part of the economy. Accordingly, sustainable development policy routinely invokes 'tertiarization' — a shift from primary and secondary sectors to the tertiary sector – as a means of decoupling economic growth from environmental damages. However, this argument does not account for environmental impacts related to the household consumption of tertiary sector employees. Here we show using a novel analytical framework that when the household consumption of labour is treated as a necessary and endogenous input to production, the environmental impacts of all sectors converge. This shift in perspective also exacerbates existing disparities in the attribution of environmental impact from economic activity among developed and developing economies. Our findings suggest that decoupling of economic activity from environmental impacts is unlikely to be achieved by transitioning to a service-based economy alone, but rather, that reducing environmental damages from economic activity may require fundamental changes to the scale and composition of consumption across all economic sectors.

5.2 Introduction

Human activity is driving a dramatic acceleration of global environmental degradation[11,164,165]. Decoupling economic activity from environmental impacts has been proposed as a solution, mitigating environmental damage while preserving economic growth ('green growth'). There are two fundamental pathways to such decoupling — technological advances that reduce the quantity of resources used or wastes produced per unit of economic output ('dematerialization'), and shifting the composition of economic activity from primary and secondary sectors to the tertiary sector ('tertiarization'). We focus on the second of these pathways and evaluate the potential for structural change in economic activity towards tertiary sectors to alleviate the environmental impacts generated by the global economy.

Tertiarization, or the 'structural change hypothesis', is a core part of Environmental Kuznets Curve (EKC) theory positing an inverted U-shaped relationship between average income and various measures of environmental quality[166]. This relationship, demonstrated by the experience of the developed nations in their transitions toward post-industrial service economies, is frequently alluded to in the context of sustainable development, offering a model pathway to grow economic prosperity while fostering environmental sustainability at the global level[167–178]. Several recent studies attribute various positive environmental trends observed in recent decades, in part, to structural change in the composition of economies and an overall shift toward services[179–182]. The environmental promise of tertiarization is premised on the ostensibly lower environmental impacts per unit of economic output ('impact intensity') of industries within the tertiary sector, particularly those producing knowledge-intensive services[169,174,183,184]. In contrast, the agricultural and manufacturing industries are frequently identified as the most prominent culprits in the generation of environmental impacts[172,185]. This framing can be understood as part of the broader 'green growth' narrative, influencing goals for sustainable development at the highest level, such as the United Nation's Sustainable Development Goal 8.2, to "achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors"[186].

Here, we suggest that this perspective overlooks the role of labour in economic production. Specifically, it neglects how household consumption is a prerequisite to economic production, and hence a relevant driver of the environmental impacts of sectoral output. In practice, tertiarization occurs by increasing the number of people employed in higher wage sectors, alongside increasing consumption with rising income[187]. Both the labour intensity of production and level of household consumption vary considerably from industry to industry, and likewise between sectors of the economy. Therefore, heterogeneity of labour (and wages) should strongly influence the attribution of environmental impacts when consumption by employed persons is included in estimates of sectoral impact.

In this study, we examine the potential for reducing the environmental impacts of economic activity through tertiarization, separate from dematerialization of production or changes in the composition of demand. The inclusion of household consumption in the production supply chain of employing sectors is justified on the basis that the provision of labour is fundamental to production and wages paid to households provide the bulk of household income directed towards consumption. Therefore, labour must be included in intermediate consumption for the attribution of sectoral environmental impacts. We show that when labour is treated as an input to production, distributions of environmental impacts by sector tend to converge. Endogenizing labour as an economic input also reveals consumption in developed countries to be the dominant driver of environmental impacts — to a greater degree than is already revealed by the shift from conventional production-based accounting to consumption-based accounting[65,188,189]. Implementing this change within environmental impact accounting frameworks provides a more causally accurate representation of economic sectors needed to assess the potential of tertiarization for economy–environment decoupling (see Section S1 for further discussion).

While we acknowledge the possibility of green growth through dematerialization, it is equally plausible that economic growth will outpace reductions in impact intensity leading to rising aggregate ecological burdens, even allowing for unprecedented technological innovation[190]. Instances of decoupling growth from specific pollutants and resource inputs have been observed in the past, and some aggregate measures such as global land use and biomass consumption have plateaued. However, these achievements are typically mixed successes, for example, the substitution of wood with fossil fuels has alleviated land-use impacts while exacerbating climate impacts from rising greenhouse gas emissions[191]. When measured in terms of total material footprint, the developed world has not decoupled (from 1990 to 2008), although certain industrializing nations have exhibited relative and even absolute decoupling over the same period[192]. This experience suggests that while important uncertainties remain, the feasibility of long-term absolute decoupling of economic activity from environmental impacts cannot be taken for granted. Here, we seek to better characterize the potential for green growth through the tertiarization pathway, while acknowledging important uncertainties in future dematerialization via technological change.

5.3 Materials and Methods

5.3.1 Experimental Design

We perform consumption-based accounting (CBA) using the environmentally extended multi-regional input–output (EE-MRIO) model provided by the EXIOBASE 3 project[193,194], modified to treat labour as an endogenous input to production. Labour is represented in terms of household consumption by employed persons. We aggregate 163 industries of the global economy into eight sectors describing consumption categories following Ivanova and colleagues[195], and select three common metrics representing diverse environmental impacts: greenhouse gas (GHG) emissions, water consumption, and land use. This method of 'closing' the input–output (IO) model with respect to labour allocates the environmental impacts associated with household consumption by employed persons to the economic sectors employing them, allowing for a novel accounting of consumption-based environmental impacts across economic sectors[196]. For the purposes of our study, we define tertiarization to be the structural economic change from primary and secondary sectors to the tertiary sector, measurable as an increase in the relative proportion of services to manufacturing, resource extraction, and agricultural industries.

We compare consumption-based accounts (CBA) generated from the standard 'open' (exogenous labour) and our proposed 'closed' (endogenous labour) versions of the detailed multi-region tables with environmental extensions. To close the model, we use a method of endogenizing households into the inter-industry transaction matrix similar to that described by Miller and Blair[197]. Input–output (IO) models incorporating industry-household linkages are known as 'semi-closed', 'extended', or 'Type-II' models, and are commonplace in macroeconomic analysis. Our analysis extends this established technique to the allocation of environmental impacts to economic sectors across the global economy.

We use *pymrio*, an open source code package in Python designed for use with this and other environmentally extended multi-regional input–output (EE-MRIO) databases[198]. We use the industry-by-industry (*ixi*) classification scheme, which describes the global economy as 163 industries based in 44 countries and 5 rest of world (RoW) regions, interlinked by industry and location. Temporal analysis is made possible by the recent addition of time series data provided in EXIOBASE 3 for the years 1995 to 2011. In order to compare output from different years, output in nominal terms was inflation adjusted to real Euros with 2005 as the base year.

EXIOBASE 3 contains a multitude of environmental indicators, with resource inputs and waste outputs described as both terms of raw values ('emissions'), as well as characterized measures of impacts. We selected a small representative group of three impacts: 1) aggregate GHG emissions in units of carbon dioxide equivalents (CO_2e) using the global warming potential method with a 100-year time horizon (GWP 100), 2) total water consumption (blue water, i.e. net water use), and 3) total land use.

We employ the Leontief demand-pull transformation in two ways: open and closed with respect to labour. The first method is identical to that conventionally used to derive CBA, which we refer to as the 'open model'. The second method involves closing the model with respect to labour, which endogenizes wages paid and the household consumption of labour into the transaction matrix (the 'closed model'). Wages paid to employees by industry and location are inserted as rows and household consumption as columns in the global transaction matrix, while simultaneously subtracting this consumption from final demand, leaving only non-household purchases (e.g. government). This modification of conventional IO methodology follows the approach described by ref.[197]. The corresponding closed-CBA results in an attribution of the household consumption by labour to employing industries (equivalent to adding labour as an additional branch to each step of the production supply chain; see Section S3.5 for a more detailed explanation of this process). Impacts are derived using emissions extensions and conversion factors provided in the database.

Note that we do not differentiate between employment skill levels (in practice, employees of differing income levels, e.g. low- vs. high-skilled) within industries or sectors, since it is aggregate wages that correspond with household income that drive impacts. To clarify, when we refer to 'high-wage sectors', we are describing aggregate wages paid to employees of a sector, not what is colloquially understood as high individual wages (i.e. wages per worker). While salary is a reliable proxy of personal impact[199], aggregate wages are the key variable for determining total environmental impacts related to consumption[187], as studied here. It is therefore not strictly necessary to differentiate between skill levels unless one wants to know how much impact is attributable to each labour category. We consider homogenous representation of labour within industries as a valid approximation when income distributions within industries are approximately stable over time. That way, although the proportion of income saved tends to increase with rising wages, impacts per unit growth in economic output should not substantially change for incremental increases.

Industry-level data is aggregated into sectors according to the Consumption Categories outlined in the *DEvelopment of a System of Indicators for a Resource efficient Europ*e (DESIRE) classification scheme (for details, see ref.[200]). Alternative groupings can be used, and results are somewhat sensitive to the choice of grouping. The same analysis presented in the paper's main results performed with the International Standard Industrial Classification (ISIC) scheme can be found in the Supplementary Information (Figs. S3.1 and S3.2). The qualitative findings of the results are largely unchanged, though constituent industries within aggregate groupings sometimes exhibit different behavior from the mean change for the grouping. See Section S3.2 for a discussion of how aggregation classification choice affects results.

We then compare the CBA derived environmental impacts before and after model closure, to examine the change in their global distribution by sector (figure 5.1) and by geographic location (figure 5.3). Figure 5.1 contains annual values for the full data set of 17 years (1995 to 2011) and the mean of the last five years of available data (2007 to 2011) in an adjacent box. Wages per unit output shown in figure 4.1(b) are calculated as total wages for each Consumption Category divided by Final Output for the mean of the last five years, in 2005 Euros. Choropleth maps in figure 5.3 assume aggregated RoW regions have a homogeneous distribution of impacts, as is assumed for the distribution of measured quantities within countries. Percent change is defined as the change from open to closed models as *(closed-CBA – open-CBA)/open-CBA x 100%.*

We also examine the distributions of sectoral impacts before and after closure with respect to labour when normalized by output ('impact intensity'). Box plots shown in figure 5.2 use whiskers with maximum and minimum values within 1.5 IQR of the 75th and 25th percentiles, respectively. Outliers have been omitted for legibility.

5.3.2 Statistical Analysis

Differences in impact intensities among sectors were assessed using non-parametric tests because normal assumptions were violated. Kruskal-Wallis tests were used to compare full sets, and comparisons of individual sectors were made using Wilcoxon pairwise tests. Lastly, in all cases we have verified that all monetary and physical quantities are conserved under closure, i.e. global totals of all monetary and environmental extensions are the same for both open and closed models.

5.4 Results

5.4.1 Household consumption and global environmental impacts

The reallocation of household consumption to employing industries reveals increased absolute environmental impacts for the Service, Manufacturing and Construction sectors, with corresponding decreases in the impacts originating from the Food, Clothing, Shelter, and Mobility sectors (figure 5.1). We find this pattern is time invariant (1995 to 2011) and consistent across all selected indicators: GHG emissions (figure 5.1a), land use (figure 5.1c) and water consumption (figure 5.1d). Changes in absolute impacts from 'open' to 'closed' models are not significantly correlated with wage intensity, however, the sectors where wages exceed a third of final output — Services and Construction have wages per unit production (measured in total output) of 0.36 and 0.33, respectively — exhibit marked increases in allocated impacts (figure 5.1b). By far, the largest aggregate wages paid occur within Services, which comprise 54% of total global wages annually, followed distantly by Manufactured Products with 15% of global wages (see Supplementary Data, available from ref.[69]) for summary tables of wage intensity and percentages by sector. Wages alone are insufficient predictors of impact when accounting for household consumption by employees. For example, emissions from Manufactured Products remain relatively unchanged (figure 5.1a), which suggests that increased impacts attributable to household consumption by labour in this sector are offset by impacts embodied in products consumed by labour employed by other sectors.

When examining impacts averaged over the most recent five-year period available (2007 to 2011), the Service and Construction sectors show the largest overall increases after closure, with increases in GHG emissions of 102% and 71%, increased land use of 213% and 203%, and increased water consumption of 208% and 394%, respectively. Impacts associated with the Food sector decrease more than any other sector consistently across all three metrics (GHG: –85%; land use: –85%; water: –90%).

The Service sector occupies the largest proportion of GHG emissions in both the open and closed models, and approximately doubles from 22% to 45% of the global total upon IO model closure. The Service sector also rises to the top position in land use and water consumption from third and second place, respectively, rising from 15% for both to 48% and 46% shares of global totals. The Food sector falls from the top driver of both land use and water consumption in the open model to fifth place for both in the closed model (48% to 4% and 68% to 1%, respectively). In other words, food production is shown to be much less environmentally burdensome than conventionally thought when it is not attributed with impacts generated by consumption supporting employees working in other sectors.

Specific industries with the largest relative increases (measured in percent change) in impact after model closure are concentrated in the Construction, Manufactured Products, Service, and Shelter sectors. In the Service sector, ‘Computer and related activities’ increases by the largest amount: by 292%, 680%, and 770% for GHG emissions, land use, and water consumption, respectively. The next largest increases in industrial impacts in Services (in decreasing order) are ‘Public administration, defense and compulsory social security’, ‘Education’, and ‘Research and development’, with increases of approximately 125% to 175%, 350% to 550%, and 450% to 650% in GHG emissions, land use and water consumption, respectively (see Supplementary Data for full analysis). We find up to 1100% increases in land use for industries in the Construction sector, and up to 1200% increases in water consumption for industries in the Shelter sector. Industries with the largest relative decreases in impacts are overwhelmingly found in the Food sector, along with industries closely related to food production or food services (classified as part of other sectors), and select Clothing and Manufactured Products industries; with some industries specific to food processing and electricity production exhibiting declines of –99.8%, –99.7%, and –99.5% of their original (i.e. open-CBA) values for GHG emissions, land use, and water consumption, respectively. Note that these percent differences are true for absolute impacts as well as impact intensities (Section 5.4.2).

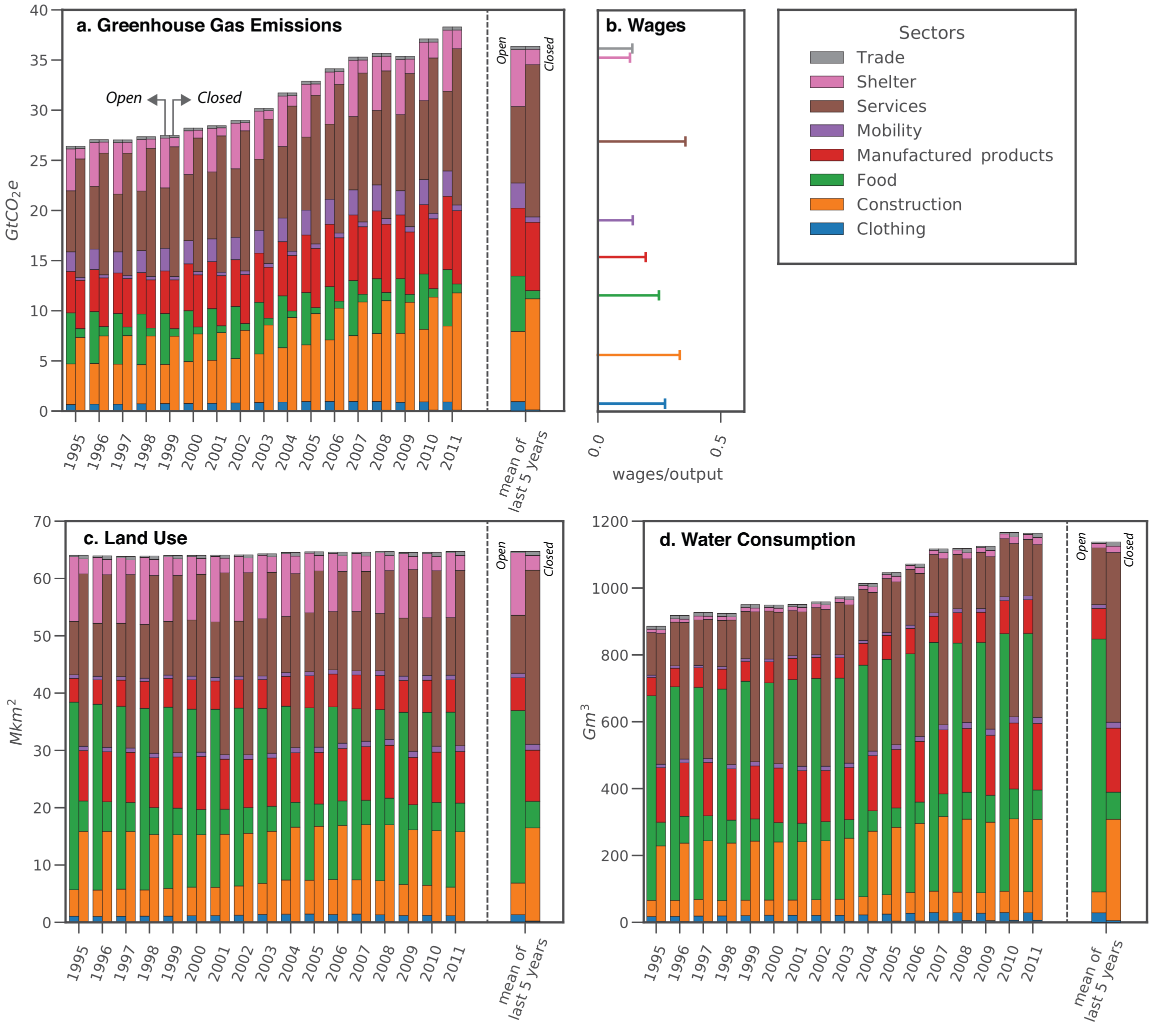


Figure 5.1 Time series of selected environmental impacts by economic sector before (open model) and after (closed model) labour is made endogenous in consumption-based accounts: (a) GHG emissions, (c) land use, and (d) water consumption. Wage intensities (**b**, calculated as wages in Euros per unit sectoral economic output) are shown for comparison with the magnitude of the change in impacts between open and closed models. Industries have been grouped and aggregated into sectors corresponding to consumption category. The final bar in each plot shows the mean distribution of impacts over the most recent five-year period. The Services and Construction sectors show the most pronounced increase in absolute terms under closure across all measured impacts, while Manufactured Products exhibits notable growth in land use and water consumption. Conversely, Food, Shelter, Clothing and Mobility sectors show clear decreases in absolute impacts under closure. High wage intensities, particularly where wages comprise more than half of a sector's total output, is a strong indicator that a sector's environmental impact will grow substantially under closure. Relative proportions of impacts remain relatively stable over time, even with growth of overall magnitude of impacts for GHG emissions and water consumption.

5.4.2 Environmental impact intensities of sectors

We find a dramatic convergence in sectoral impact intensities when household consumption of labour is endogenized (figure 2). In the open model, differences in environmental impact intensity among sectors are statistically different for all three environmental metrics (Kruskal-Wallis: p = 2e-7 for GHG emissions; p = 7e-10 for land use; p = 3e-10 for water consumption), with the Food, Clothing, Mobility, and Shelter sectors showing statistically higher impact intensity than the Construction, Manufacturing, Service, and Trade sectors (Mann-Whitney pairwise comparison, $p<0.05$, figure 2a). By contrast, in the closed model, sectoral differences in environmental impact intensity are generally not statistically significant (Kruskal-Wallis: p = 0.3 for GHG emissions; p = 0.7 for land use; p = 0.04 for water consumption), with the exception of water consumption in which the Food sector remained statistically higher per unit economic output than that of Shelter (Mann-Whitney pairwise comparison: $p < 0.05$, figure 2b).

Although the results show that overall, sectors do not differ significantly in their impacts, the aggregated figures mask a wide spread of impact intensities intra-sectorally. Simply said, industries within sectors do not all have the same impact. In Services, due to the heterogeneity of wages within the sector, impacts of employment vary dramatically. Intuitively, industries that employ more low-skilled labour (with correspondingly lower total wages paid) have lower impact per unit production than high-skilled, high-wage industries. For example, within Services, the closed impacts of 'Computer and related activities' (GHG: 0.5 kgCO_2e/€, land use: 0.9 µm^2/€, water: 20 nL/€) are 20 to 25 times larger than that of the 'Hotels and restaurants' industry (0.02 kgCO_2e/€, land use: 0.04 µm^2/€, water: 1 nL/€). A full account of the open and closed impact intensities is presented in the Supplementary Data (available from ref.[69]).

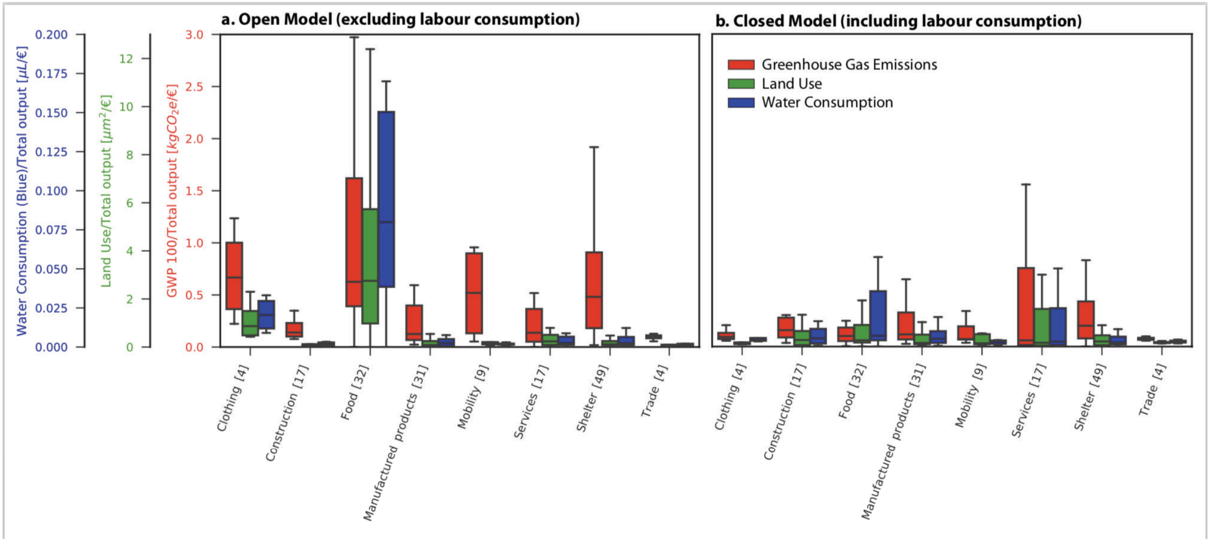


Figure 5.2 Distributions of sectoral (consumption category) impact intensities for the three selected environmental impacts (mean of most recent five-year period, 2007 to 2011). Sample sizes (number of industries per sector) are shown in parentheses. Impact intensities under (a) conventional CBA (open) are significantly different from one another (GWP: Kruskal-Wallis chi-squared = 44.357, df = 7, p-value = 1.8e-07; LU: Kruskal-Wallis chi-squared = 56.599, df = 7, p-value = 7e-10; Water: Kruskal-Wallis chi-squared = 58.569, df = 7, p-value = 2.9e-10). After (b) model closure (labour made endogenous), differences of impact intensities are statistically insignificant for GWP and LU (GWP: Kruskal-Wallis chi-squared = 8.2427, df = 7, p-value = 0.3; LU: Kruskal-Wallis chi-squared = 4.86, df = 7, p-value = 0.7), and are considerably less different for Water (Kruskal-Wallis chi-squared = 14.712, df = 7, p-value = 0.04). Median values from the boxplot and the results of pair-wise statistical comparisons among categories are available in the Supplementary Data. Central bars indicate the median, with boxes depicting interquartile ranges. Whiskers show maximum and minimum values within 1.5 IQR of the 75th and 25th percentiles. Note that outliers have been omitted for legibility, and that annual output is in real terms (inflation adjusted; 2005 Euros).

5.4.3 International distribution of environmental impacts embodied in trade flows

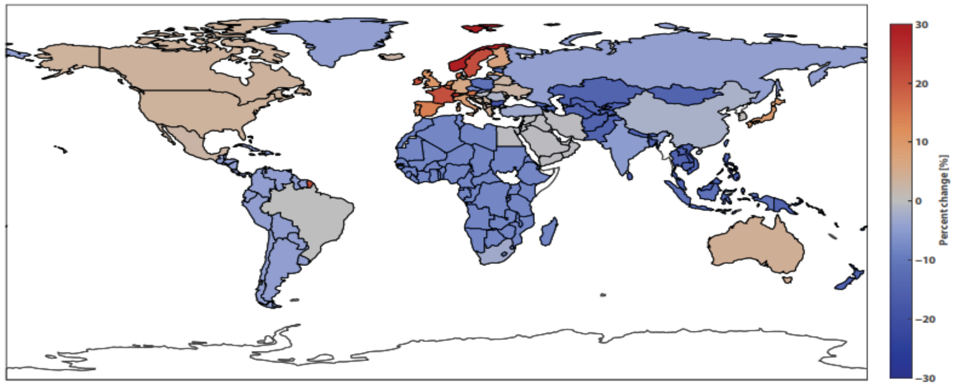
The shift from an open to closed model amplifies the allocation of environmental impacts resulting from final consumption to wealthy countries with a corresponding decrease in allocation to developing countries (figure 3). Country-level results follow sectoral patterns — countries with a high proportion of service-based industries tend to exhibit increases in impacts, while those with high proportions of primary and secondary production, such as agriculture and manufacturing, show marked decreases in impacts. When compared to the open model (which represents a typical consumption-based accounting of environmental impacts), Scandinavian and Western European countries, Japan, and the United States show prominent increases in impacts associated with economic production, while countries in Africa, Eastern Europe, and South, Central, and Southeast Asia show notable decreases (figure 3).

In absolute terms, closed-CBA reveals China and India as the largest exporters of GHG emissions embodied in goods and services, while the United States and Japan are the largest importers for all three impacts studied. The largest exporters of embodied land use include Russia and Brazil, and the largest exporters of embodied water consumption are India and China (Supplementary Data, ref.[69]). Note that the rest of world (RoW) regions exhibit declines in impacts on the same scale or higher than individual countries identified; the largest decreases in GHG emissions and land use would be by RoW Asia and Pacific and RoW Africa, respectively, if these regions are compared directly to countries.

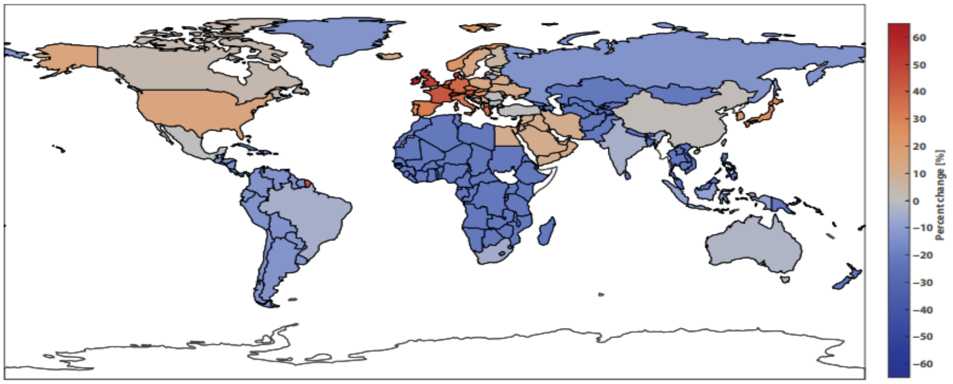
When switching from open to closed models, annual international transfers of environmental impacts increase by approximately 3.3 Gt CO_2e for GHG emissions, 8.8 Mkm^2 for land use, and 170 km^3 for water consumption (using mean values for the 2007 to 2011 period). This represents an additional shift on top of that which occurs when moving from production- to consumption-based accounting of impacts in an open model configuration. For comparison, there are 36 $GtCO_2e$ of GHG emissions, 65 Mkm^2 of land use, and 1100 km^3 of water consumption embodied in trade from a conventional consumption-based perspective (i.e. when switching from PBA to open-CBA). In percentage terms, the total amount of GHG emissions, land use, and water consumption embodied in trade (when switching from PBA to open-CBA) has been estimated at approximately 27%, 30%, and 28% of global totals for the mean of the 2007 to 2011 period; consequently, the trade flows in our closed model increase to 36%, 44%, and 43% of global totals (from PBA to closed-CBA; i.e. an increase of 9, 14, and 15 percentage points, respectively, from open- to closed-CBA). Note that most of the shifts in impacts comparing open and closed models are concentrated in a small number of developing and emerging economies, and a larger number of developed ones. This pattern is broadly similar to that of GHG emissions embodied in trade when moving from production- to consumption-based accounting.

Geographic changes due to model closure are largest for water consumption (changes of up to ±90%) followed by land use (up to ±60%), and GHG emissions (up to ±30%). For example, the largest increases in GHG emissions upon model closure occur in Norway (+30%), Switzerland, Luxembourg, Sweden, and France (each approximately +20%), with 'Education' as the largest single driving industry for all five countries (Supplementary Data, ref.[69]). This predominance of increased impacts in the high-wage service-oriented economies in northern climates is likely due to high net imports of labour-intensive goods in these countries. Over recent decades, more affluent nations have increasingly imported consumption goods from regions where labour costs are lower. Closing the EE-MRIO model with respect to labour thus exacerbates existing disparities in environmental impacts between richer and poorer nations. The shift in environmental impacts among nations that results from changing from production- to consumption-based accounting is therefore likely underestimated in conventional consumption-based accounts[65,201].

a. Greenhouse Gas Emissions



b. Land Use



c. Water Consumption

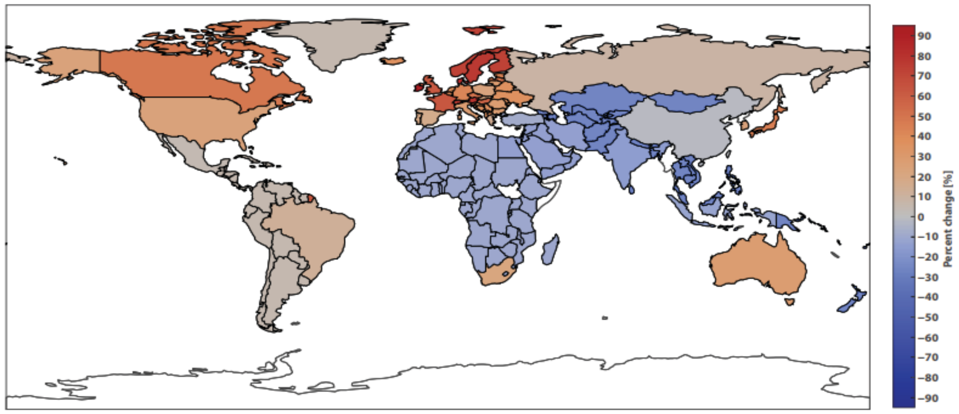


Figure 5.3 Percentage change in selected environmental impacts: (a) Greenhouse Gas Emissions, (b) Land Use, and (c) Water Consumption from open (labour exogenous) to closed (labour endogenous) national consumption-based accounts. Closure of the model with respect to labour amplifies existing inequalities in the distribution of environmental impacts between the wealthier and poorer nations. This analysis implicitly accounts for the embodied impacts in internationally traded goods and services (attributed to the country of consumption). Countries with the highest average income levels tend to show the most pronounced effects, such as in the Scandinavian countries and other parts of Europe. Food imports are likely responsible for the notably higher changes in water consumption and land use under closure.

5.5 Discussion and conclusions

5.5.1 Summary of results and comparison with previous literature

After endogenizing labour in global supply chains, we show that industries typically labelled 'dirty' (i.e. high impact per unit value) are not the main drivers of environmental pressures (figure 5.1), and are also no 'dirtier' than services (figure 5.2), which are typically thought of as high productivity sectors with low environmental burdens. Instead, we find that all sectors are roughly equivalent in terms of climate, land and water impacts per unit production (figure 5.2). In other words, the distributions of sectoral impacts per unit production converge, and in almost all instances, become indistinguishable from one another.

Our findings are consistent with recent research that has highlighted hidden sources of environmental impacts in the ostensibly 'clean' knowledge-based service industries[166,184,202]. This research also supports the argument that the effect of international trade can be to offshore the more impact-intensive components of global supply chains to low-wage developing countries, making the developed economies appear to be getting cleaner[170,189,203–206]. We show that a reallocation of impacts to account for labour and household consumption amplifies the effect of offshoring, owing to disparities in income and consumption between developed and developing nations.

We speculate that India and China are still among the largest net exporters of impacts because they are the factories of the world, though their largest workforce does not imply they have the largest purchasing power. Rich countries import more than they export, and this is compounded when labour's upkeep is included. For example, much of the cotton grown in India is woven there or in China but ultimately is bought by affluent people in other countries, and the water embodied in it follows it there.

5.5.2 Assessing potential for green growth via a shift to services

The operation of any economic sector both requires and supports household consumption, which in turn generates environmental impacts. Therefore, we argue that in order to assess the potential for green growth via a shift to services (or any other sector), one must estimate the sector's total impact including the sector's influence on employment and aggregate demand. We demonstrate that when the associated impacts are ascribed to the employing sectors, the scope for absolute economy–environment decoupling is considerably more limited than is typically assumed.

Based on our analysis, we argue that the environmental burden of high-wage, labour-intensive (i.e. tertiary) industries has been significantly understated. Conversely, primary and secondary industries producing significant direct impacts but with lower reliance on high-wage labour have been overemphasized in relation to their environmental impact, since the demand for products from these industries is generated by the household consumption supporting production in other economic sectors, notably in Services. Our results are in line with those of Stern[207], Henriques and Kander[208], Parrique et al.[209], and Fix[210], all of whom note a relative lack of importance of structural economic changes for environmental outcomes.

5.5.3 Limitations and caveats

Limitations of our study include those inherent to all EE-MRIO analyses. For example, the precision of our estimates is limited by national data quality and inconsistencies when harmonizing data across countries. Industries are approximated as being homogenous in composition (producing a single, aggregate product), while inter-industry transaction coefficients and environmental impact coefficients are treated as constant for each year. Specific to our study, model closure with respect to labour assumes that a static proportion of income is allocated by households to consumption during a given year (i.e. static savings rates). Changes in economic structure associated with tertiarization would in fact likely raise aggregate household consumption through higher wages, but would also raise savings rates, which tend to increase alongside income. As such, aggregate impacts can be expected to grow somewhat more slowly than wages paid as a result of tertiarization. To clarify, we are interested in impacts related to household expenditures, not due to economic activity that is driven by investments (made with household savings). We acknowledge that savings may drive impacts, but we expect them to be less correlated with savings rates. We leave the verification of this hypothesis to future inquiry.

The composition of aggregate household demand can be expected to change in line with tertiarization and increased aggregate wages, with a growing level of demand for services. This change is not modeled explicitly in our closed-EE-MRIO formulation but is unlikely to invalidate our findings, as additional service demand would typically add to, rather than substitute for, absolute demand for primary and secondary goods[209]. Rather, people tend to maintain spending on necessities like food, energy, and shelter, while simultaneously increasing their spending on services (for example, see ref.[211]). We therefore expect that primary and secondary output would increase with a growing tertiary sector. In other words, we expect proximate economic drivers of environmental impacts to be relatively unaffected by tertiarization, barring unprecedented disruptions to trends in technological or behavioural factors in the near term, which we feel to be an acceptable assumption given the evidence provided to date. Furthermore, as our analysis shows similar levels of environmental impact intensity across sectors, the effects of modest changes in demand composition can be safely assumed to have a minor effect. Ultimately, a dynamic closed-EE-MRIO model would be required to assess the effect of more radical long-term changes in demand composition, which we leave for future study.

5.5.4 Possible roles of tertiarization in sustainable development

We show the effect of tertiarization on global environmental impacts to be statistically insignificant, all else being equal. However, this does not imply that tertiarization cannot play a beneficial role in sustainable development. Tertiary industries typically entail higher levels of employment and remuneration, and so we expect that impacts determined via closed-CBA will be more responsive to decreases in impact intensity (through technological improvements) and consumption levels per capita, than open-CBA, since household consumption is a primary driver of environmental impacts. If it were to occur alongside cleaner production and reductions in aggregate demand, tertiarization may augment the mitigation of environmental burdens. Conversely, this greater sensitivity means that tertiarization may exacerbate environmental impacts if household consumption continues to increase in line with historical trends.

It is important to note that dematerialization via technological changes, the first pathway mentioned in the introduction, would reduce total impacts irrespective of structural changes in economic composition. However, we are concerned that dematerialization on the scale required to achieve absolute reductions in environmental impacts may be implausible on relevant timelines[209,212], particularly given that efficiency gains from technological improvements often translate to productivity increases rather than a reduction of the environmental impacts of production[213,214]. As such, our results suggest that tertiarization will not help to reduce global environmental impacts or assist sustainable development without simultaneous reductions in household consumption.

To date, attempts to identify pathways towards sustainability have focused heavily on proximate, rather than structural causes of environmental pressures. The service sectors of developed economies foster higher than average material standards of living, stemming from high wages and consumption-oriented social norms. The patterns of consumption required to maintain the provision of labour, regardless of industry, face the same complex web of economic interdependencies implicated in the generation of environmental impacts. As such, increases in income (and aggregate economic output) cannot easily be reconciled with sustainable development[215–218]. Rather, our results suggest that, barring unprecedented technological innovation, the patterns of consumption behavior that currently permeate the social fabric of contemporary societies will need to change in order to alleviate the environmental harm caused by economic activity. A broader range of research perspectives should therefore be directed to assess how the United Nations' Sustainable Development Goals (SDGs) can be achieved, and notably to how we can "create the conditions that allow people to have quality jobs that stimulate the economy while not harming the environment." (SDG 8)[219]. Closed formulations of EE-MRIO models could also be prioritized in studies of economic change and environmental impact, and be used alongside standard IO analysis for environmental accounting more generally to better inform macroeconomic analysis and decision-making. As discussed by Ottelin and colleagues[220], the discussion of appropriate policy instruments in alignment with the broader CBA perspective is lacking. Our findings support this assessment — future research should be directed towards exploring appropriate policy instruments for the amelioration of environmental impacts stemming from economic activity while recognizing the limitations of proposed pathways for decoupling of economy and environment.

6 Conclusion

Here I have shown ways for Canada to do its fair share of global climate action while respecting limits to domestic mitigation, proposed ways to 'climate test' fossil fuel infrastructure to assess its compatibility with domestic or international climate goals, and explored the limited potential for economic tertiarization to reduce climate and other environmental impacts. Through the work collected in this dissertation, I hope to provide some insights into what paths to sustainable futures are available to Canada and other similar countries. While the qualitative insights presented here are likely common sense to many informed or otherwise sensible (namely those not indoctrinated by many counterintuitive and increasingly baseless assertions of mainstream economics), there is still value in stating the obvious with increasing precision and clarity. And yet, I wish it was only so simple, but even so, there are many who need convincing of what are now nearly self-evident truths. Specifically, the papers here debunk several common misconceptions in the policy community. I will use these concluding remarks to restate the most important findings of my work and speak frankly of their implications.

Paper 1 showed that there is no way for Canada to do its fair share of climate action without supporting international efforts. This may follow simply from the fact that Canada has, like every other wealthy industrialized nation, accrued a 'climate debt' to those who have not had the privilege of using inordinate amounts of fossil fuels (both via extraction and combustion) to develop their economies. It is also fairly intuitive that barring some technological *deus ex machina*, like direct air capture of CO_2 that is sufficiently energy efficient (thermodynamically implausible) or the long-awaited arrival of for effectively infinite energy from nuclear fusion that could be used to remove carbon from the atmosphere regardless of the energetic cost, Canada and other so-called developed nations will not be able to decarbonize rapidly enough to contribute sufficiently to global efforts required to stay below the Paris goal of well below 2°C. But this is not a reason to despair. Indeed, this conclusion behooves us to increase attention to the international component of climate action, which receives relatively little focus in discourse and policymaking. International adaptation is discussed but remains woefully underfunded. International mitigation receives almost no attention whatsoever, and when it does, it is framed as a possible means of offsetting failures to meet domestic emission reduction targets. This is unacceptable. International mitigation support must be made in addition to the most ambitious domestic mitigation efforts possible, not as a means of weakening the resolve to pursue them, which the promise of emissions offsetting can often invoke. It is my hope that discussions of this nature soon grow in frequency and sophistication. Future research would be well directed to elaborating findings here, as suggested in the conclusion of paper 1, I would extend this analysis to estimate international mitigation and adaptation obligations for Canada and other wealthy nations.

Paper 2 showed another highly intuitive result: that there is no way to make new fossil fuel extraction or infrastructure compatible with meeting climate goals. This conclusion has been articulated in other ways before but still falls on deaf ears. Self-proclaimed climate leaders like Prime Minister Justin Trudeau still cannot accept the paradox of fossil fuel expansionism and climate stabilization. For this reason, we prepared a careful assessment of a crucial fossil fuel industry — fossil gas and its liquefied form for export — and generalized the method so that a gamut of climate tests can be applied to any fossil fuel sector, and perhaps even generalized further to be fit to assess other industries' effects on GHG emissions. I hope that such tests can serve as a basis for robust strategic assessments, if not by the government, then by nongovernmental actors who can independently assess their decisions. Perhaps they may also serve as credible testimony in legal cases brought against governments who are willfully acting against their climate pledges, wherever there exists a basis for such litigation. Such opportunities will likely proliferate as legal theory advances and as courts become more progressive.

Paper 3 showed why employing more people in services in well-paying jobs, or more generally, why growing services relative to other sectors, is not enough to mitigate climate or other environmental impacts alone. Indeed, the inquiry summarized in this paper was borne out of an intuition that services cannot be 'greener' if they stimulate consumption in other parts of the far more material parts of the economy. But even though its results may be unsurprising to many, they are crucial in combatting the illusion that growth can be infinite if pegged to the limitless fountain of human knowledge and ingenuity. I want to stress that I have no quarrel with knowledge and innovation *per se*, but it is this kind of fantastical thinking that I wish to confront. While the merits of more sophisticated technology and a growing knowledge economy can be debated (and if such a trajectory amounts to Progress can also be subject to debate), I leave these discussions to be had elsewhere. I only wanted to provide a rigorous empirical study of the premise of whether, *ceteris paribus*, growing services will lead to better climate and environmental outcomes. After assessing the literature and adding to it my own inquiry, I conclude that it will not. As for future research, dynamic input–output or general equilibrium models could be used to further test this hypothesis, especially when changing the composition of the global energy system, other industrial methods, and human behaviour in substantial (non-marginal) ways. Perhaps then structural changes could help enhance the benefits of decarbonization and lower demand. But this requires further study. I emphasize further that this study necessarily assumes that there will be only marginal changes to the economy, over short periods of time in the near future, while holding everything else constant. This is sufficient to critique proposals for green growth by technophilic futurists who propose that high-paid high-tech jobs are totally benign. I wanted to combat this notion and feel that I have succeeded in dismantling it. I still believe that structural changes will be instrumental to building an ecologically sound economy, but only if they are accompanied by technological change (which may be transitioning to low or appropriate technology, rather than more sophisticated and/or yet to be invented technologies) and changes to consumption patterns of affluent people. For example, a transition to a greater amount of care work and agriculture concomitant with cultural and lifestyle changes would conceivably lower environmental impacts substantially, in line with the changes needed to realize a just and ecological future.

By now the reader should understand the motivation for such inquiries. I hope to have convinced you that Canada cannot do its fair share through domestic mitigation alone, that (from every possible angle worth considering) more fossil fuel infrastructure is not conducive to meeting climate goals, and that employing more people in well-paying jobs, without changing anything else about how affluent people live, won't help stop climate change or reduce environmental pressures. I also would like to acknowledge that without broader support and a paradigmatic cultural shift, well-reasoned policy options alone are unlikely to provoke any meaningful change. This is why it is incumbent upon everyone to take these realizations and fight for meaningful change in whichever way they can. Strategies for sustainability should not be limited to the policy world. Regardless of whether these policies are politically feasible, idealized scenarios outlined herein should first and foremost be used to inform the climate justice movement and the broader public, since wide public support is often a precondition for policy adoption.

7 References

1. Malm, A. *Fossil Capital: The Rise of Steam Power and the Roots of Global Warming*. 496 (Verso Books, 2016).
2. Wright, R. *A Short History of Progress*. (House of Anansi Pr, 2004).
3. Bendell, J. *Deep Adaptation: A Map for Navigating Climate Tragedy*. https://lifeworth.com/deepadaptation.pdf (2020).
4. Goldin, I. The limitations of Steven Pinker's optimism. *Nature* **554**, 420–422 (2018).
5. Mason, B. Man has been changing climate for 8,000 years. *Nature* (2003) doi:10.1038/news031208-7.
6. NOAA. Carbon dioxide peaks near 420 parts per million at Mauna Loa observatory. *NOAA* https://research.noaa.gov/article/ArtMID/587/ArticleID/2764/Coronavirus-response-barely-slows-rising-carbon-dioxide (2021).
7. NASA. NASA, NOAA Analyses Reveal 2019 Second Warmest Year on Record. *Climate Change: Vital Signs of the Planet* https://climate.nasa.gov/news/2945/nasa-noaa-analyses-reveal-2019-second-warmest-year-on-record (2020).
8. Imster, E. EarthSky | Northern Hemisphere just had its hottest summer on record. https://earthsky.org/earth/northern-hemisphere-2020-hottest-summer-on-record/ (2020).
9. NOAA. More Near-Record Warm Years Are Likely On Horizon. *National Centers for Environmental Information (NCEI)* http://www.ncei.noaa.gov/news/projected-ranks (2020).
10. NOAA. 2021 was world's 6th-warmest year on record. *NOAA* http://www.noaa.gov/news/2021-was-worlds-6th-warmest-year-on-record (2022).
11. Crutzen, P. J. The "Anthropocene". in *Earth system science in the Anthropocene* (eds. Ehlers, E. & Krafft, T.) 13–18 (Springer, 2006).
12. IPCC. *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2021).
13. IPCC. *Summary for Policymakers. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (Cambridge University Press, 2022).
14. Bush, E. *et al. Canada's Changing Climate Report in Light of the Latest Global Science Assessment*. (2022).
15. Prairie Climate Centre. One degree and its impacts. *Climate Atlas of Canada* https://climateatlas.ca/video/one-degree-and-its-impacts (2019).
16. Philip, S. Y. *et al.* Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. *Earth System Dynamics Discussions* 1–34 (2021).
17. British Columbia Coroners Service. *BC Coroners Service (BCCS) Heat-Related Deaths – Knowledge Update*. https://www2.gov.bc.ca/assets/gov/birth-adoption-death-marriage-and-divorce/deaths/coroners-service/statistical/heat_related_deaths_in_bc_knowledge_update.pdf (2021).
18. Halofsky, J. E., Peterson, D. L. & Harvey, B. J. Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology* **16**, 4 (2020).
19. Reidmiller, D. R. *et al. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II*. https://nca2018.globalchange.gov/ (2018) doi:10.7930/NCA4.2018.

20. IPCC. Press release: IPCC Sixth Assessment Report, Mitigation of Climate Change. https://www.ipcc.ch/report/ar6/wg3/resources/press/press-release/ (2022).
21. Neumayer, E. In defence of historical accountability for greenhouse gas emissions. **33**, 185–192 (2000).
22. Höhne, N. & Blok, K. Calculating Historical Contributions To Climate Change – Discussing The 'Brazilian Proposal'. *Climatic Change* **71**, 141–173 (2005).
23. Höhne, N. *et al.* Contributions of individual countries' emissions to climate change and their uncertainty. *Climatic Change* **106**, 359–391 (2011).
24. Stoddard, I. *et al.* Three Decades of Climate Mitigation: Why Haven't We Bent the Global Emissions Curve? *Annual Review of Environment and Resources* **46**, 653–89 (2021).
25. Matthews, H. D. *et al.* National contributions to observed global warming. *Environmental Research Letters* **9**, 014010 (2014).
26. Ward, D. S. & Mahowald, N. M. Contributions of developed and developing countries to global climate forcing and surface temperature change. *Environmental Research Letters* **9**, 074008 (2014).
27. Matthews, H. D. Quantifying historical carbon and climate debts among nations. *Nature Climate Change* **6**, 60–64 (2016).
28. Klinsky, S. *et al.* Why equity is fundamental in climate change policy research. *Global Environmental Change* **44**, 170–173 (2017).
29. Frumhoff, P. C., Heede, R. & Oreskes, N. The climate responsibilities of industrial carbon producers. *Climatic Change* **132**, 157–171 (2015).
30. Westfall, S. Why has it been so hard to get fossil fuels mentioned in U.N. climate deals? *Washington Post* https://www.washingtonpost.com/world/2021/11/10/fossil-fuels-mention-cop-draft-paris/ (2021).
31. Raupach, M. R. *et al.* Sharing a quota on cumulative carbon emissions. *Nature Climate Change* **4**, 873–879 (2014).
32. Holz, C., Kartha, S. & Athanasiou, T. Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *Int Environ Agreements* **18**, 117–134 (2018).
33. Athanasiou, T., Kartha, S. & Baer, P. Greenhouse Development Rights. An approach to the global climate regime that takes climate protection seriously while also preserving the right to human development. (2006).
34. Kanemoto, K., Moran, D., Lenzen, M. & Geschke, A. International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change* **24**, 52–59 (2014).
35. Peters, G. P. *et al.* Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. *Nature Climate Change* **2**, 2–4 (2012).
36. Friedlingstein, P. *et al.* Global Carbon Budget 2020. *Earth System Science Data Discussions* **12**, 3269–3340 (2020).
37. Davis, S. J. *et al.* Emissions rebound from the COVID-19 pandemic. *Nat. Clim. Chang.* **12**, 412–414 (2022).
38. Le Quéré, C. *et al.* Fossil CO2 emissions in the post-COVID-19 era. *Nat. Clim. Chang.* **11**, 197–199 (2021).
39. IPCC. *Special Report on the Global Warming of 1.5°C.* https://www.ipcc.ch/sr15/ (2018).
40. Asheim, G. B. *et al.* The case for a supply-side climate treaty. *Science* **365**, 325–327 (2019).
41. Erickson, P., Lazarus, M. & Piggot, G. Limiting fossil fuel production as the next big step in climate policy. *Nature Climate Change* **8**, 1037–1043 (2018).

42. Green, F. & Denniss, R. Cutting with both arms of the scissors: the economic and political case for restrictive supply-side climate policies. *Climatic Change* **5**, 1–15 (2018).
43. Lazarus, M. & van Asselt, H. Fossil fuel supply and climate policy: exploring the road less taken. *Climatic Change* **150**, 1–13 (2018).
44. Piggot, G., Verkuijl, C., van Asselt, H. & Lazarus, M. Curbing fossil fuel supply to achieve climate goals. *Climate Policy* **20**, 881–887 (2020).
45. Piggot, G., Erickson, P., van Asselt, H. & Lazarus, M. Swimming upstream: addressing fossil fuel supply under the UNFCCC. *Climate Policy* **18**, 1189–1202 (2018).
46. Matthews, H. D. A growing commitment to future CO2 emissions. *Environmental Research Letters* **9**, 111001 (2014).
47. Davis, S. J. & Socolow, R. H. Commitment accounting of CO2 emissions. *Environmental Research Letters* **9**, 084018 (2014).
48. Davis, S. J., Caldeira, K. & Matthews, H. D. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science* **329**, 1330–1333 (2010).
49. Tong, D. *et al.* Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature* **572**, 373–377 (2019).
50. Guivarch, C. & Hallegatte, S. Existing infrastructure and the 2°C target. *Climatic Change* **109**, 801–805 (2011).
51. Seto, K. C. *et al.* Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources* **41**, 425–452 (2016).
52. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters* **13**, 054019 (2018).
53. Erickson, P. & Lazarus, M. Would constraining US fossil fuel production affect global CO2 emissions? A case study of US leasing policy. *Climatic Change* **150**, 29–42 (2018).
54. Erickson, P. & Lazarus, M. Impact of the Keystone XL pipeline on global oil markets and greenhouse gas emissions. *Nature Climate Change* **4**, 778–781 (2014).
55. Muttitt, G. *et al. The Sky's Limit: Why the Paris Climate Goals Require a Managed Decline of Fossil Fuel Production*. (2016).
56. Muttitt, G., Scott, A. & Buckley, T. *Off Track*. http://priceofoil.org/content/uploads/2018/04/Off-Track-IEA-climate-change1.pdf (2018).
57. Kartha, S., Caney, S., Dubash, N. K. & Muttitt, G. Whose carbon is burnable? Equity considerations in the allocation of a “right to extract”. *Climatic Change* **150**, 117–129 (2018).
58. Muttitt, G. & Kartha, S. Equity, climate justice and fossil fuel extraction: principles for a managed phase out. *Climate Policy* **20**, 1024–1042 (2020).
59. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* **458**, 1158–1162 (2009).
60. Trout, K. *et al.* Existing fossil fuel extraction would warm the world beyond 1.5 °C. *Environ. Res. Lett.* **17**, 064010 (2022).
61. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences* **108**, 18554–18559 (2011).
62. Lee, M. Extracted carbon and Canada's international trade in fossil fuels. *Studies in Political Economy* **99**, 114–129 (2018).
63. Hughes, J. D. *Can Canada Expand Oil and Gas Production, Build Pipelines and Keep Its Climate Change Commitments?* (2016).
64. Peters, G. P. Policy Update: Managing carbon leakage. *Carbon Management* **1**, 35–37 (2014).

65. Davis, S. J. & Caldeira, K. Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences* **107**, 5687–5692 (2010).
66. Steininger, K., Lininger, C., Droege, S. & Roser, D. Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies. *Global Environmental Change* **24**, 75–87 (2014).
67. Steininger, K. W., Lininger, C., Meyer, L. H., Muñoz, P. & Schinko, T. Multiple carbon accounting to support just and effective climate policies. *Nature Climate Change* **6**, 35–41 (2015).
68. York, R. Do alternative energy sources displace fossil fuels? *Nature Climate Change* **2**, 441–443 (2012).
69. Horen Greenford, D., Crownshaw, T., Lesk, C., Stadler, K. & Matthews, H. D. Shifting economic activity to services has limited potential to reduce global environmental impacts due to the household consumption of labour. *Environmental Research Letters* **15**, 064019 (2020).
70. UNFCCC. Paris Agreement. (2015).
71. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophysical research letters* **35**, L04705 (2008).
72. Matthews, H. D. *et al.* An integrated approach to quantifying uncertainties in the remaining carbon budget. *Commun Earth Environ* **2**, 1–11 (2021).
73. Matthews, H. D., Zickfeld, K., Knutti, R. & Allen, M. R. Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets. *Environmental Research Letters* **13**, 010201 (2018).
74. Matthews, H. D. *et al.* Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nature Geoscience* **13**, 769–779 (2020).
75. IPCC. *Summary for Policymakers. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar5/wg3/ (2014).
76. United Nations Environment Programme. *Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered*. (2021).
77. New Climate Institute & Climate Analytics. Climate Action Tracker: Countries. *Climate Action Tracker* https://climateactiontracker.org/countries/ (2022).
78. Gignac, R. & Matthews, H. D. Allocating a 2 °C cumulative carbon budget to countries. *Environmental Research Letters* **10**, 075004 (2015).
79. Meyer, A. *Contraction and Convergence: The Global Solution to Climate Change*. (Green Books, 2000).
80. Robiou du Pont, Y. *et al.* Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change* **7**, 38–43 (2017).
81. Kartha, S. *et al.* Cascading biases against poorer countries. *Nature Climate Change* **8**, 348–349 (2018).
82. Dooley, K. *et al.* Ethical choices behind quantifications of fair contributions under the Paris Agreement. *Nature Climate Change* **11**, 300–305 (2021).
83. den Elzen, M. G. J., Olivier, J. G. J., Höhne, N. & Janssens-Maenhout, G. Countries' contributions to climate change: effect of accounting for all greenhouse gases, recent trends, basic needs and technological progress. *Climatic Change* **121**, 397–412 (2013).
84. Friedlingstein, P. *et al.* Global Carbon Budget 2021. *Earth System Science Data Discussions* 1–191 (2021) doi:10.5194/essd-2021-386.

85. Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A. & Gore, T. *The Carbon Inequality Era: An assessment of the global distribution of consumption emissions among individuals from 1990 to 2015 and beyond*. https://oxfamilibrary.openrepository.com/bitstream/handle/10546/621049/rr-carbon-inequality-era-210920-en.pdf (2020).
86. Chancel, L. & Piketty, T. Carbon and inequality: from Kyoto to Paris. *Paris School of Economics* (2015).
87. Kartha, S., Kemp-Benedict, E., Ghosh, E., Nazareth, A. & Gore, T. *Carbon inequality: Canada*. https://oxfam.app.box.com/s/gsrhhjkee8p3630fp21a3k1y3pz1ozjo (2021).
88. Bruckner, B., Hubacek, K., Shan, Y., Zhong, H. & Feng, K. Impacts of poverty alleviation on national and global carbon emissions. *Nat Sustain* **5**, 311–320 (2022).
89. Althor, G., Watson, J. E. M. & Fuller, R. A. Global mismatch between greenhouse gas emissions and the burden of climate change. *Scientific Reports* **6**, 20281 (2016).
90. van den Berg, N. J. *et al.* Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change* **162**, 1805–1822 (2020).
91. Gibson, R. B. *et al. Summary Report: From Paris to Projects: Clarifying the Implications of Canada's Climate Change Mitigation Commitments for the Planning and Assessment of Projects and Strategic Undertakings*. https://papers.ssrn.com/abstract=3511925 (2019).
92. Höhne, N., den Elzen, M. & Escalante, D. Regional GHG reduction targets based on effort sharing: a comparison of studies. *Climate Policy* **14**, 122–147 (2014).
93. Kemp-Benedict, E. Calculations for the Greenhouse Development Rights Calculator. (2008).
94. Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Christoff, P. & Meinshausen, M. National contributions for decarbonizing the world economy in line with the G7 agreement. *Environmental Research Letters* **11**, 054005 (2016).
95. Donner, S. & Zickfeld, K. *Canada's Contribution to Meeting the Temperature Limits in the Paris Climate Agreement*. 3 https://blogs.ubc.ca/sdonner/files/2016/02/Donner-and-Zickfeld-Canada-and-the-Paris-Climate-Agreement.pdf (2016).
96. Toth, F. L. Intergenerational equity and discounting. *Integrated Assessment* **1**, 127–136 (2000).
97. Emmerling, J. Discounting and intragenerational equity. *Environment and Development Economics* **23**, 19–36 (2018).
98. Anthoff, D. & Emmerling, J. Inequality and the Social Cost of Carbon. *Journal of the Association of Environmental and Resource Economists* **6**, 243–273 (2019).
99. Anderson, K. Duality in climate science. *Nature Geoscience* **8**, 898–900 (2015).
100. Anderson, K. & Peters, G. The trouble with negative emissions. *Science* **354**, 182–183 (2016).
101. Fuss, S. *et al.* Betting on negative emissions. *Nature Climate Change* **4**, 850–853 (2014).
102. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters* **13**, 063002 (2018).
103. Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat Energy* **3**, 515–527 (2018).
104. Keyßer, L. T. & Lenzen, M. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nature Communications* **12**, 1–16 (2021).
105. Bataille, C., Sawyer, D. & Melton, N. *Pathways to deep decarbonization in Canada*. (2015).

106. Jaccard, M., Hein, M. & Vass, T. *Is Win-Win Possible? Can Canada's Government Achieve Its Paris Commitment . . . and Get Re-Elected?* (2016).
107. Trottier Energy Futures Project. *Canada's Challenge and Opportunity*. https://davidsuzuki.org/wp-content/uploads /2017/09/REPORT-canada-challenge-opportunity-transformations-major-reductions-GHG-emissions.pdf (2016).
108. Environment and Climate Change Canada. Canada's Greenhouse Gas and Air Pollutant Emissions Projections 2018. (2019).
109. Rhodes, E., Craig, K., Hoyle, A. & McPherson, M. How Do Energy-Economy Models Compare? A Survey of Model Developers and Users in Canada. *Sustainability* **13**, 5789 (2021).
110. Jacobson, M. Z. *et al.* 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* **1**, 108–121 (2017).
111. Clack, C. T. M. *et al.* Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences* **114**, 6722–6727 (2017).
112. Jacobson, M. Z., Delucchi, M. A., Cameron, M. A. & Frew, B. A. The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims. *Proceedings of the National Academy of Sciences* **114**, E5021–E5023 (2017).
113. Goeminne, G. & Paredis, E. The concept of ecological debt: some steps towards an enriched sustainability paradigm. *Environment Development and Sustainability* **12**, 691–712 (2010).
114. Climate Action Tracker: Canada. https://climateactiontracker.org/countries/canada/.
115. Canada, S. 2030 Emissions Reduction Plan: Clean Air, Strong Economy. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030.html (2022).
116. Field, J. L. *et al.* Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences* **117**, 21968–21977 (2020).
117. Vaughan, N. E. & Gough, C. Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters* **11**, 095003 (2016).
118. Bataille, C. Review of Canadian Deep GHG Emission Reduction Studies: Some Near-Term Lessons for Stakeholders and Policy Makers. (2016).
119. van den Bergh, J. C. J. M. & Botzen, W. J. W. A lower bound to the social cost of CO2 emissions. *Nature Climate Change* **4**, 253–258 (2014).
120. Anthoff, D., Tol, R. S. J. & Yohe, G. W. Risk aversion, time preference, and the social cost of carbon. *Environmental Research Letters* **4**, 024002 (2009).
121. Tol, R. S. J. The Social Cost of Carbon. *Annual Review of Resource Economics* **3**, 419–443 (2011).
122. van den Bergh, J. C. J. M. & Botzen, W. J. W. Monetary valuation of the social cost of CO2 emissions: A critical survey. *Ecological Economics* **114**, 33–46 (2015).
123. Burke, M., Davis, W. M. & Diffenbaugh, N. S. Large potential reduction in economic damages under UN mitigation targets. *Nature* **557**, 549–553 (2018).
124. Victor, P. A. Cents and nonsense: A critical appraisal of the monetary valuation of nature. *Ecosystem Services* **42**, 101076 (2020).
125. Saunders, C. & Dalziel, P. Twenty-Five Years of *Counting for Nothing* : Waring's Critique of National Accounts. *Feminist Economics* **23**, 200–218 (2017).

126. Tudela, F. Obstacles and opportunities for moratoria on oil and gas exploration or extraction in Latin America and the Caribbean. *Climate Policy* **20**, 922–930 (2020).
127. SEI, IISD, ODI, EG3, & UNEP. *The Production Gap Report 2021*. http://productiongap.org/2021report (2021).
128. Noble, D. & Brady, K. *NEB Modernization: Aligning Energy Project Assessment with Climate Policy*. (2017).
129. Doelle, M. Integrating climate change into impact assessments: key design elements. *The Transformation of Environmental Law and Governance* 111–128 (2021) doi:10.4337/9781800889378.00017.
130. Bošković, B. & Leach, A. Leave it in the ground? Oil sands development under carbon pricing. *Canadian Journal of Economics/Revue canadienne d'économique* **53**, 526–562 (2020).
131. Jaccard, M., Hoffele, J. & Jaccard, T. Global carbon budgets and the viability of new fossil fuel projects. *Climatic Change* **150**, 15–28 (2018).
132. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517**, 187–190 (2015).
133. Welsby, D., Price, J., Pye, S. & Ekins, P. Unextractable fossil fuels in a 1.5 °C world. *Nature* **597**, 230–234 (2021).
134. Pye, S. *et al.* An equitable redistribution of unburnable carbon. *Nature Communications* **11**, 1–9 (2020).
135. Bjørn, A., Lloyd, S. & Matthews, D. From the Paris Agreement to corporate climate commitments: evaluation of seven methods for setting 'science-based' emission targets. *Environmental Research Letters* **16**, 054019 (2021).
136. McElroy, M. W. & van Engelen, J. M. L. *Corporate Sustainability Management*. (Routledge, 2012).
137. CIRAIG. *Rapport préliminaire analyse du cycle de vie du terminal de liquéfaction de gaz naturel du Saguenay*. https://www.ree.environnement.gouv.qc.ca/dossiers/3211-10-021/3211-10-021-4.pdf (2019).
138. Alvarez, R. A. *et al.* Assessment of methane emissions from the U.S. oil and gas supply chain. *Science* **361**, 186–188 (2018).
139. Howarth, R. W. A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Science & Engineering* **2**, 47–60 (2014).
140. Gouvernement du Québec. Décret 1071-2021. *Gazette Officielle du Québec* 5059–5061 (2021).
141. Erickson, P. & Lazarus, M. *Examining risks of new oil and gas production in Canada*. https://www.sei.org/wp-content/uploads/2020/06/examining-risks-of-new-oil-and-gas-production-in-canada.pdf (2020).
142. Erickson, P. Confronting carbon lock-in: Canada's oil sands. *Stockholm Environment Institute* (2018).
143. Erickson, P., Kartha, S., Lazarus, M. & Tempest, K. Assessing carbon lock-in. *Environ. Res. Lett.* **10**, 084023 (2015).
144. International Energy Agency. *Net Zero by 2050*. https://www.iea.org/reports/net-zero-by-2050 (2021).
145. Horen Greenford, D. Why Ending Oil and Gas Production in Canada is Essential to a Just Transition Both at Home and Abroad. in *Local Activism for Global Climate Justice: The Great Lakes Watershed* (ed. Perkins, P. E.) (Routledge, 2019).

146. Gibson, R. B. *et al. From Paris to Projects: Clarifying the implications of Canada's climate change mitigation commitments for the planning and assessment of projects and strategic undertakings*. https://uwaterloo.ca/paris-to-projects/sites/ca.paris-to-projects/files/uploads/files/p2p_full_report_23jan19.pdf (2019).
147. Canada, E. and C. C. Government of Canada confirms ambitious new greenhouse gas emissions reduction target. https://www.canada.ca/en/environment-climate-change/news/2021/07/government-of-canada-confirms-ambitious-new-greenhouse-gas-emissions-reduction-target.html (2021).
148. White House. Executive Order on Tackling the Climate Crisis at Home and Abroad. *The White House* https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/ (2021).
149. Government of Canada. Strategic Assessment of Climate Change. https://www.canada.ca/en/services/environment/conservation/assessments/strategic-assessments/climate-change.html (2020).
150. Gibson, R. B., Péloffy, K. & Doelle, M. Challenges and Opportunities of a Forthcoming Strategic Assessment of the Implications of International Climate Change Mitigation Commitments for Individual Undertakings in Canada. *Sustainability* **10**, 3747 (2018).
151. Wright, D. V. Climate Change Considerations in the Federal Impact Assessment Act: Steps Forward… on a Path to Business As Usual? SSRN Scholarly Paper at https://doi.org/10.2139/ssrn.3710960 (2020).
152. Wright, D. V. Final Strategic Assessment on Climate Change: Zero Net Effect? *ABlawg* https://ablawg.ca/2020/08/10/final-strategic-assessment-on-climate-change-zero-net-effect/ (2020).
153. Chan, E. *et al.* Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada Are Nearly Twice Those Reported in Inventories. *Environ. Sci. Technol.* **54**, 14899–14909 (2020).
154. Calverley, D. & Anderson, K. *Phaseout Pathways for Fossil Fuel Production Within Paris-compliant Carbon Budgets*. https://www.research.manchester.ac.uk/portal/files/213256008/Tyndall_Production_Phaseout_Report_final_text_3_.pdf (2022).
155. Carter, A. V. & Dordi, T. *Correcting Canada's 'one eye shut' climate policy*. https://cascadeinstitute.org/technical-paper/correcting-canadas-one-eye-shut-climate-policy/ (2021).
156. Canada Energy Regulator. Canada's Energy Future 2021: Energy Supply and Demand Projections to 2050. doi:https://doi.org/10.35002/zjr8-8x75.
157. Climate Equity Reference Project. Climate Equity Reference Calculator.
158. bp. Statistical Review of World Energy. (2021).
159. UNFCCC. Canada. 2020 National Inventory Report (NIR). (2020).
160. Bureau d'audiences publiques sur l'environnement. File 358, DT5, 6211-19-030. 38 (2020).
161. Williams, J. P., Regehr, A. & Kang, M. Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States. *Environmental Science & Technology* **55**, 563–570 (2021).
162. Kasumu, A. S., Li, V., Coleman, J. W., Liendo, J. & Jordaan, S. M. Country-Level Life Cycle Assessment of Greenhouse Gas Emissions from Liquefied Natural Gas Trade for Electricity Generation. *Environmental Science & Technology* **52**, 1735–1746 (2018).

163. Abrahams, L. S., Samaras, C., Griffin, W. M. & Matthews, H. S. Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses. *Environmental Science & Technology* **49**, 3237–3245 (2015).
164. Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* **2**, 81–98 (2015).
165. Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
166. Kaika, D. & Zervas, E. The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO2 emissions case. *Energy Policy* **62**, 1392–1402 (2013).
167. Shafik, N. & Bandyopadhyay, S. *Economic growth and environmental quality: time-series and cross-country evidence*. vol. 904 (World Bank Publications, 1992).
168. De Bruyn, S. M., van den Bergh, J. C. J. M. & Opschoor, J. B. Economic growth and emissions: reconsidering the empirical basis of environmental Kuznets curves. *Ecological Economics* **25**, 161–175 (1998).
169. Romm, J., Rosenfeld, A. & Herrmann, S. The internet economy and global warming. (1999).
170. Dinda, S. Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics* **49**, 431–455 (2004).
171. Dinda, S., Coondoo, D. & Pal, M. Air quality and economic growth: an empirical study. *Ecological Economics* **34**, 409–423 (2000).
172. Panayotou, T. *Economic Growth and the Environment Economic Survey of Europe 2003 vol 2*. https://www.unece.org/ead/pub/surv_ 032.html (2003).
173. OECD. *Globalisation and the Environment*. (OECD, 1998).
174. OECD. *The Service Economy*. http://www.oecd.org/industry/ind/2090561.pdf (2000).
175. OECD. *Environmental Strategy for the First Decade of the 21st Century*. https://www.oecd.org/environment/indicators-modelling-outlooks/1863539.pdf (2001).
176. Medhurst, J. & Henry, N. *Impacts of Structural Change: Implications for policies supporting transition to a Green Economy*. https://ec.europa.eu/environment/enveco/resource_efficiency/pdf/transition_costs.pdf (2011).
177. UNEP. *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth*. (United Nations Environment Programme, 2011).
178. UNEP. *Decoupling 2: Technologies, Opportunities and Policy options*. (United Nations Environment Programme, 2014).
179. Haas, C. & Kempa, K. Directed Technical Change and Energy Intensity Dynamics: Structural Change vs. Energy Efficiency. *The Energy Journal* **39**, 127–152 (2018).
180. Mulder, P. & de Groot, H. L. F. Structural change and convergence of energy intensity across OECD countries, 1970–2005. *Energy Economics* **34**, 1910–1921 (2012).
181. Mulder, P., de Groot, H. L. F. & Pfeiffer, B. Dynamics and determinants of energy intensity in the service sector: A cross-country analysis, 1980–2005. *Ecological Economics* **100**, 1–15 (2014).
182. Omri, A. Entrepreneurship, sectoral outputs and environmental improvement: International evidence. *Technological Forecasting and Social Change* **128**, 46–55 (2018).
183. Jacobs, M. *The green economy: environment, sustainable development, and the politics of the future*. (Pluto Press, 1991).
184. Djellal, F. & Gallouj, F. Services, Service Innovation and the Ecological Challenge. in *in Faïz Gallouj and Faridah Djellal (eds) (2018), A Research Agenda for Service Innovation, Edward Elgar Publishers* (2018).

185. Clift, R. & Wright, L. Relationships Between Environmental Impacts and Added Value Along the Supply Chain. *Technological Forecasting and Social Change* **65**, 281–295 (2000).
186. United Nations. Promote inclusive and sustainable economic growth, employment and decent work for all. *United Nations Sustainable Development Goals* https://www.un.org/sustainabledevelopment/economic-growth/ (2018).
187. Rosa, E. A. & Dietz, T. Human drivers of national greenhouse-gas emissions. *Nature Climate Change* **2**, 581–586 (2012).
188. Peters, G. P. From production-based to consumption-based national emission inventories. **65**, 13–23 (2008).
189. Dolter, B. & Victor, P. A. Casting a long shadow: Demand-based accounting of Canada's greenhouse gas emissions responsibility. *Ecological Economics* **127**, 156–164 (2016).
190. Hickel, J. & Kallis, G. Is Green Growth Possible? *New Political Economy* **4**, 1–18 (2019).
191. Blomqvist, L., Nordhaus, T. & Shellenberger, M. Nature Unbound: Decoupling for Conservation. 106 (2015).
192. Wiedmann, T. O. *et al.* The material footprint of nations. *Proceedings of the National Academy of Sciences* **112**, 6271–6276 (2015).
193. Wood, R. *et al.* Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability* **7**, 138–163 (2014).
194. Stadler, K. *et al.* EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *Journal of Industrial Ecology* **22**, 502–515 (2018).
195. Ivanova, D. *et al.* Mapping the carbon footprint of EU regions. *Environ. Res. Lett.* **12**, 054013 (2017).
196. Rugani, B., Panasiuk, D. & Benetto, E. An input–output based framework to evaluate human labour in life cycle assessment. *The International Journal of Life Cycle Assessment* **17**, 795–812 (2012).
197. Miller, R. E. & Blair, P. D. *Input-Output Analysis: Foundations and Extensions*. (Cambridge University Press, 2009). doi:10.1017/CBO9780511626982.
198. Stadler, K. Pymrio. (2022).
199. Moser, S. & Kleinhückelkotten, S. Good Intents, but Low Impacts: Diverging Importance of Motivational and Socioeconomic Determinants Explaining Pro-Environmental Behavior, Energy Use, and Carbon Footprint. *Environment and Behavior* **50**, 626–656 (2017).
200. European Commission. Final Report Summary - DEvelopment of a System of Indicators for a Resource efficient Europe (DESIRE). https://cordis.europa.eu/project/id/308552/reporting (2016).
201. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences* **108**, 8903–8908 (2011).
202. Nansai, K. *et al.* Material and Energy Dependence of Services and Its Implications for Climate Change. *Environ. Sci. Technol.* **43**, 4241–4246 (2009).
203. Simas, M., Wood, R. & Hertwich, E. Labor Embodied in Trade. *Journal of Industrial Ecology* **19**, 343–356 (2015).
204. Moreau, V. & Vuille, F. Decoupling energy use and economic growth: Counter evidence from structural effects and embodied energy in trade. *Applied Energy* **215**, 54–62 (2018).
205. Lenzen, M. Environmentally important paths, linkages and key sectors in the Australian economy. *Structural Change and Economic Dynamics* **14**, 1–34 (2003).

206. Wiedmann, T., Minx, J., Barrett, J. & Wackernagel, M. Allocating ecological footprints to final consumption categories with input–output analysis. *Ecological Economics* **56**, 28–48 (2006).
207. Stern, N. *The Economics of Climate Change: The Stern Review*. (Cambridge University Press, 2007). doi:10.1017/CBO9780511817434.
208. Henriques, S. T. & Kander, A. The modest environmental relief resulting from the transition to a service economy. *Ecological Economics* **70**, 271–282 (2010).
209. Parrique, T. *et al. Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability*. https://eeb.org/wp-content/uploads/2019/07/Decoupling-Debunked.pdf (2019).
210. Fix, B. Dematerialization Through Services: Evaluating the Evidence. *BioPhysical Economics and Resource Quality* **4**, 6 (2019).
211. Government of Canada, I. C. Consumer Trends Report – Chapter 9: Consumer Spending. https://www.ic.gc.ca/eic/site/Oca-bc.nsf/eng/ca02118.html (2005).
212. Smil, V. *Making the Modern World: Materials and Dematerialization*. (Wiley, 2013).
213. Arvesen, A., Bright, R. M. & Hertwich, E. G. Considering only first-order effects? How simplifications lead to unrealistic technology optimism in climate change mitigation. *Energy Policy* **39**, 7448–7454 (2011).
214. Galeotti, M. *Environment and Economic Growth: Is Technical Change the Key to Decoupling? Working Papers* https://ideas.repec.org/p/fem/femwpa/2003.90.html (2003).
215. Daly, H. E. Economics In A Full World. *Scientific American* **293**, 100–107 (2005).
216. Krysiak, F. C. Entropy, limits to growth, and the prospects for weak sustainability. *Ecological Economics* **58**, 182–191 (2006).
217. Ward, J. D. *et al.* Is Decoupling GDP Growth from Environmental Impact Possible? *PLoS ONE* **11**, e0164733 (2016).
218. Buchs, M. & Koch, M. Critiques of Growth. in *Postgrowth and Wellbeing: Challenges to Sustainable Welfare* 39–56 (Palgrave Macmillan, 2017).
219. UN Department of Economic and Social Affairs. Sustainable Development Goal (SDG) Goal 8. *United Nations* https://sdgs.un.org/goals/goal8.
220. Ottelin, J. *et al.* What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications. *Environ. Res. Lett.* **14**, 093001 (2019).
221. Grossman, G. M. & Krueger, A. Economic Growth and the Environment. *The Quarterly Journal of Economics* **110**, 353–377 (1995).
222. Stern, D. I. Progress on the environmental Kuznets curve? *Environment and Development Economics* **3**, 173–196 (1998).
223. Dasgupta, S., Laplante, B., Wang, H. & Wheeler, D. Confronting the Environmental Kuznets Curve. *Journal of Economic Perspectives* **16**, 147–168 (2002).
224. Arrow, K. *et al.* Economic growth, carrying capacity, and the environment. *Ecological Economics* **15**, 91–95 (1995).
225. Salzman, J. Peer Reviewed: Facing the Challenges of a Service Economy. *Environ. Sci. Technol.* **33**, 512A-514A (1999).
226. Hettige, H., Mani, M. & Wheeler, D. Industrial pollution in economic development: the environmental Kuznets curve revisited. *Journal of Development Economics* **62**, 445–476 (2000).
227. Pasche, M. Technical progress, structural change, and the environmental Kuznets curve. *Ecological Economics* **42**, 381–389 (2002).

228. Roy Chowdhury, R. & Moran, E. F. Turning the curve: A critical review of Kuznets approaches. *Applied Geography* **32**, 3–11 (2012).
229. Özokcu, S. & Özdemir, Ö. Economic growth, energy, and environmental Kuznets curve. *Renewable and Sustainable Energy Reviews* **72**, 639–647 (2017).
230. Kovacic, Z., Spanò, M., Piano, S. L. & Sorman, A. H. Finance, energy and the decoupling: an empirical study. *J Evol Econ* **28**, 565–590 (2018).

8 Supplementary Material

8.1 Paper 1 supplementary material

There is high agreement between DDPP and EMRG models, as judged by the sectoral comparison depicted in Figure S1.1. This is noteworthy, especially since there are variations in how sectors are defined in each of the models. TEFP was not included in the sectoral comparison since the sectoral definitions and economy sample modeled varies too greatly from the other two models. Agriculture (Figure S1.2) is not included in the sectoral inter-comparison, where EMRG and TEFP are shown but include very different aspects of the sectors, while DDPP aggregates agriculture into other sectors. Regardless, agriculture is fairly inelastic to mitigation efforts, differing very little in modeled pathways to a business as usual projections. Sectors that show promising amount of achievable reductions are the largest emitting sectors in mining, industrial processes and oil and gas extraction. It is virtually impossible to mitigate emissions in any substantial way, for example, sufficiently to meet even original NDC targets, without making substantial cuts in these key sectors. Residential and commercial sectors show much promise for decarbonization under existing political and economic conditions, as shown by the behaviour of the DDPP and EMRG models. We also include a supplementary figure showing the time series of a sample of effort sharing approaches employed in the study (Figure S1.3).

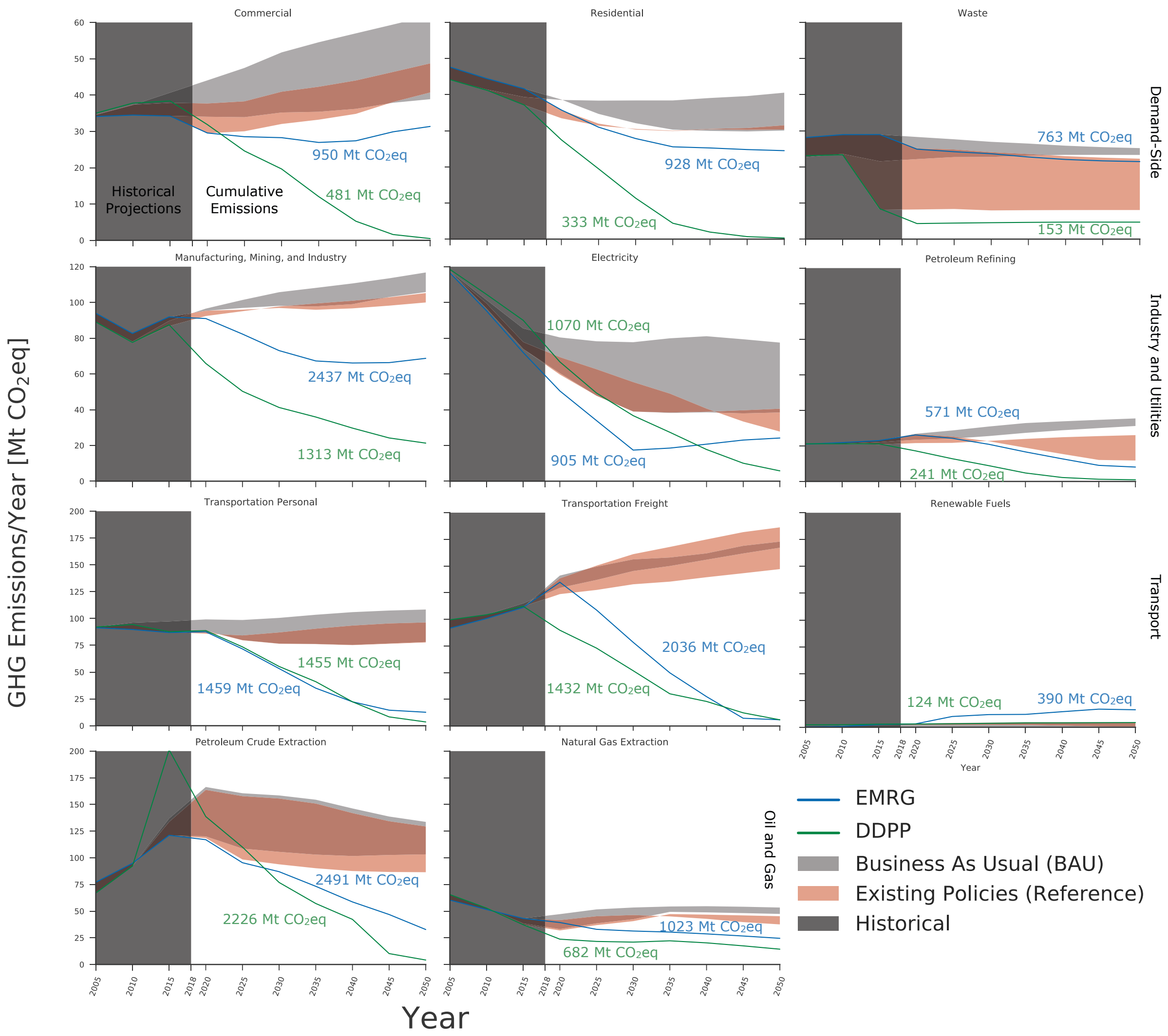


Figure S1.1 Select sectoral decarbonization pathways for Canada. Blue lines denote results from the Energy and Materials Modeling Group (EMRG) and green lines show the Deep Decarbonization Pathways Project (DDPP). "Business As Usual" (BAU) and Existing Policies (Reference) projections are shown as ranges given by the combination of both modeling projects, denoted by the shaded area in grey and red, respectively. Here, historical emissions are shaded out with the dark grey transparent rectangle, since all modeling started at 2005. Annual and cumulative emissions are measured in million tonnes carbon dioxide equivalents (Mt CO_2eq). Cumulative emissions for the EMRG and DDPP decarbonization pathways are the sum of annual emissions from 2018 to 2050 (inclusive).

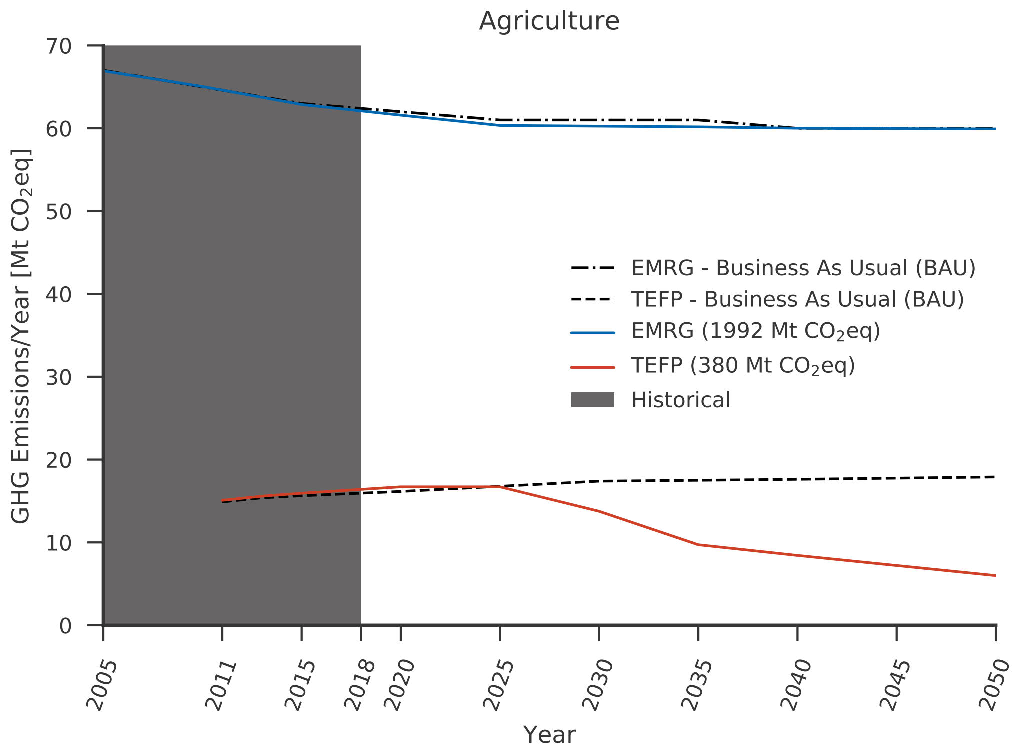


Figure S1.2 Decarbonization Pathway for agriculture sector. Note the difference in category definition, and that this sector has been aggregated into others, into its more primary inputs, in the DDPP project. Agriculture appears to be very inelastic (i.e. unresponsive) to mitigation measures and is therefore not discussed further in the report analysis.

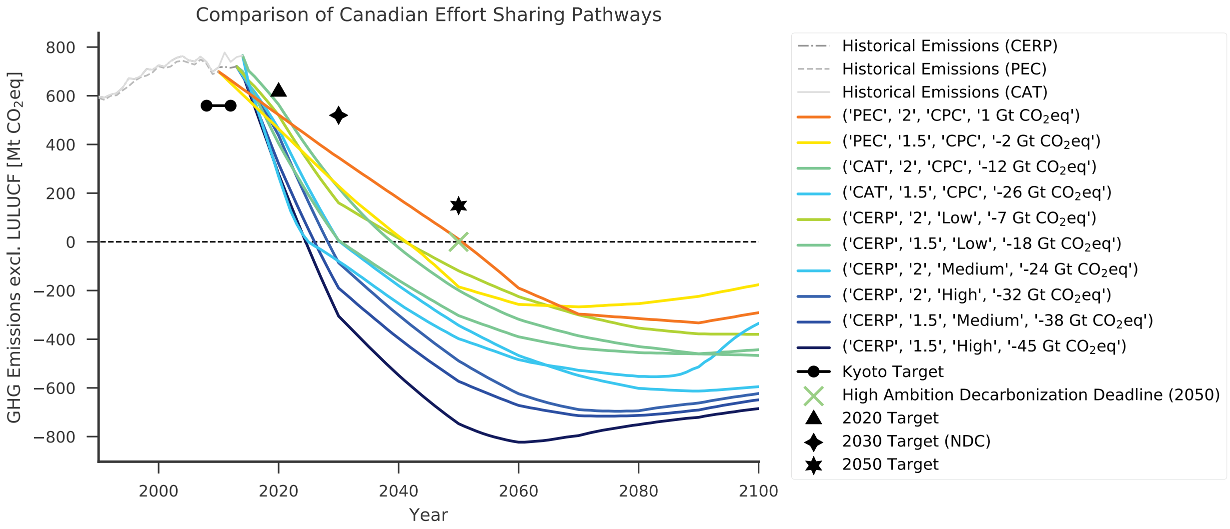


Figure S1.3 Comparison of select effort sharing pathways for Canada. The above figure contains effort sharing pathways, which share annual global emissions along a modeled trajectory to meet a specified temperature target. Annual emissions are in million tonnes carbon dioxide equivalents (CO2eq), and exclude emissions from Land Use, Land Use Change, and Forestry (LULUCF), in order to standardize the data for comparison. Three projects are shown: 1) Paris Equity Check (PEC, http://paris-equity-check.org/), 2) Climate Action Tracker (CAT, http://climateactiontracker.org/), and Climate Equity Reference Project (CERP, https://climateequityreference.org/). PEC generally gives the largest allocations to Canada, while CERP is most stringent. Cumulative emissions are shown in the legend in billion tonnes of carbon dioxide equivalents (Gt CO$_2$eq), and represent the Canada's share of world total remaining GHG emissions between 2018 and 2100.

			50%	**67%**
Resource sharing ($GtCO_2e$) Cumulative emissions 2020-2100	Grandfathering	1.5°C	8.8	4.5
		1.75°C	18.0	13.3
		2.0°C	27.2	22.0
	Equal per capita	1.5°C	2.6	1.3
		1.75°C	5.4	4.0
		2.0°C	8.1	6.6
	Cumulative per capita 1990	1.5°C	-12.0	-13.2
		1.75°C	-9.2	-10.6
		2.0°C	-6.5	-8.0
	Cumulative per capita 1960	1.5°C	-21.6	-22.9
		1.75°C	-18.9	-20.3
		2.0°C	-16.1	-17.7
Effort sharing ($GtCO_2e$) Cumulative emissions 2020-2100	CERf 1850|High Progressivity	1.5°C	-46.8	
		2.0°C		-33.9
	CERf 1950|Medium Progressivity	1.5°C	-38.9	
		2.0°C		-25.5
	CERf 1990|Low Progressivity	1.5°C	-19.6	
		2.0°C		-8.5
	CPC 1850	1.5°C	-29.9	
		2.0°C		-16.0
	CPC 1960	1.5°C	-18.8	
		2.0°C		-9.2
	CPC 1990	1.5°C	-8.8	
		2.0°C		-1.5
	EPC	1.5°C	3.0	
		2.0°C		7.9
	C&C 2030	1.5°C	5.4	
		2.0°C		10.0
	C&C 2050	1.5°C	8.5	
		2.0°C		13.1
	Grandfathering	1.5°C	13.9	
		2.0°C		24.5
	PEC | CAP	1.5°C	1.6	
		2.0°C		3.9
	PEC | EPC	1.5°C	5.4	
		2.0°C		9.6
	PEC | CPC 1990	1.5°C	-8.8	
		2.0°C		-5.5
	PEC | GDR	1.5°C	-11.3	
		2.0°C		-5.0
	PEC | CER	1.5°C	12.0	
		2.0°C		21.8

Table S1.1 Complete emissions shares

Paris Gaps				*Median*				
	Solutions Project	**DDPP**	**TEFP**	**ECCC | PCF additional measures**	**EMRG**	**ECCC | PCF**	**ECCC | projected**	**Mean**
High Equity	45.4	48.6	49.8	51.9	54.8	58.6	63.4	53.2
Medium Equity	15.1	18.3	19.5	21.6	24.5	28.3	33.1	22.9
Low Equity	-0.4	2.8	4.0	6.1	9.0	12.8	17.6	7.4

In $trillion			*Median*				
Solutions Project	**DDPP**	**TEFP**	**ECCC | PCF additional measures**	**EMRG**	**ECCC | PCF**	**ECCC | projected**	**Mean**
5.7	6.1	6.2	6.5	6.9	7.3	7.9	6.7
1.9	2.3	2.4	2.7	3.1	3.5	4.1	2.9
-0.1	0.3	0.5	0.8	1.1	1.6	2.2	0.9

Table S1.2 Complete Paris Gaps

8.2 Paper 2 supplementary material

Supplementary results

Table S2.1 summarizes cumulative emissions from gas extraction and end-use, from 2021 to midcentury and from 2026 — the proposed start date of the example project, *GNL Québec* — to midcentury. The project had an operating license of 25 years, and so the 2026 to 2050 period coincided with the tentative lifespan of the project.

		ECCC forecast then plateau	ECCC constant EF	CIRAIG (FE=1.2%)	CIRAIG (FE=2.7%)	CIRAIG (FE=3.7%)
Upstream	2021 to 2050	1.6	2.2	2.5	4.3	5.5
	2026 to 2050	1.3	1.9	2.2	3.7	4.7
Downstream	2021 to 2050	13.1	13.1	13.1	13.1	13.1
	2026 to 2050	11.1	11.1	11.1	11.1	11.1
Total	2021 to 2050	14.7	15.3	15.7	17.5	18.6
	2026 to 2050	12.4	13.0	13.3	14.8	15.8

Table S2.1 Cumulative GHG emissions related to Canadian gas extraction and combustion in billions of tonnes carbon dioxide equivalents (GtCO$_2$e). Upstream emissions include emissions during extraction, processing, and transport of gas, and liquefaction of LNG. Downstream emissions include combustion for gas, and gasification and transport of gasified LNG**.** Total emissions are the sum of upstream and downstream emissions. Calculated using forecasted extraction in the Canada Energy Regulator (CER) Canada's Energy Future 2020 evolving scenario. All amounts are the product of total volume of gas extracted over a set time period (in cubic metres, m^3) and the lifecycle emissions factor calculated by CIRAIG (2019) with their default fugitive emissions (FE) rate of 1.2%, the updated weighted average rate of the industry by Alvarez and colleagues (2018) of 2.7%, and the higher rate for unconventional gas as found by Howarth (2014) of 3.7%. Numbers rounded to nearest 0.1 Gt for clarity.

For comparison, Figure S2.1 summarizes cumulative emissions from both upstream and downstream processes for Canadian gas from 2021 to 2050, inclusive, according to the Canada's Energy Future evolving scenario. The lifecycle emissions from Canadian gas production (including extraction and auxiliary processes) over this period would amount to 10 GtCO$_2$, or 6% of the remaining 1.5°C carbon budget (67%) as most recently estimated by Matthews and colleagues[72]. When including methane (CH$_4$) over a 100-year time horizon, the cumulative lifecycle GHG emissions of Canadian gas grow to nearly 16GtCO$_2$e.

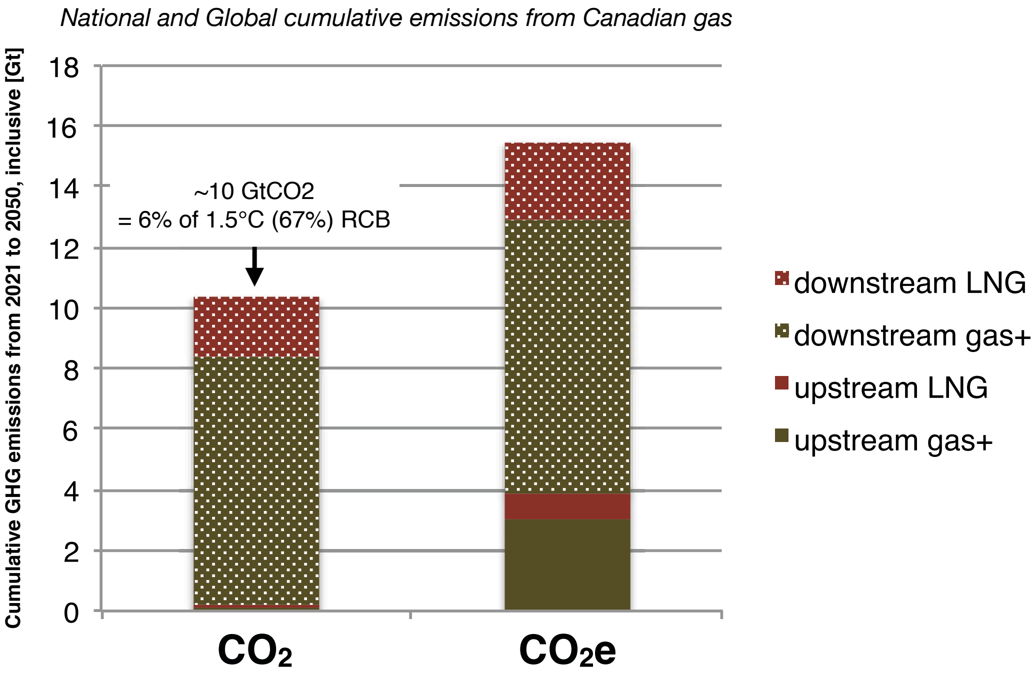


Figure S2.1 Cumulative GHG emissions related to Canadian gas extraction and combustion in billions of tonnes (Gt) carbon dioxide (CO_2) and CO_2 equivalents (CO_2e), from 2021 to 2050, inclusive. Estimates for CO_2-only use Canada's reported CO_2 emissions factor and CO_2e estimates use median estimate for emissions factors of ECCC reported emissions and LCA specific to gas for domestic use and LNG. Solid bars depict upstream and midstream emissions occurring within Canada, while dotted bars depict downstream emissions that occur inside and outside Canada. Note that LNG is solely an export product and so all downstream emissions from LNG combustion occur outside of Canada. Also note that CO_2 emissions can be compared to the remaining carbon budget (RCB). Aggregated GHG emissions are included for reference but should not be compared directly to a RCB.

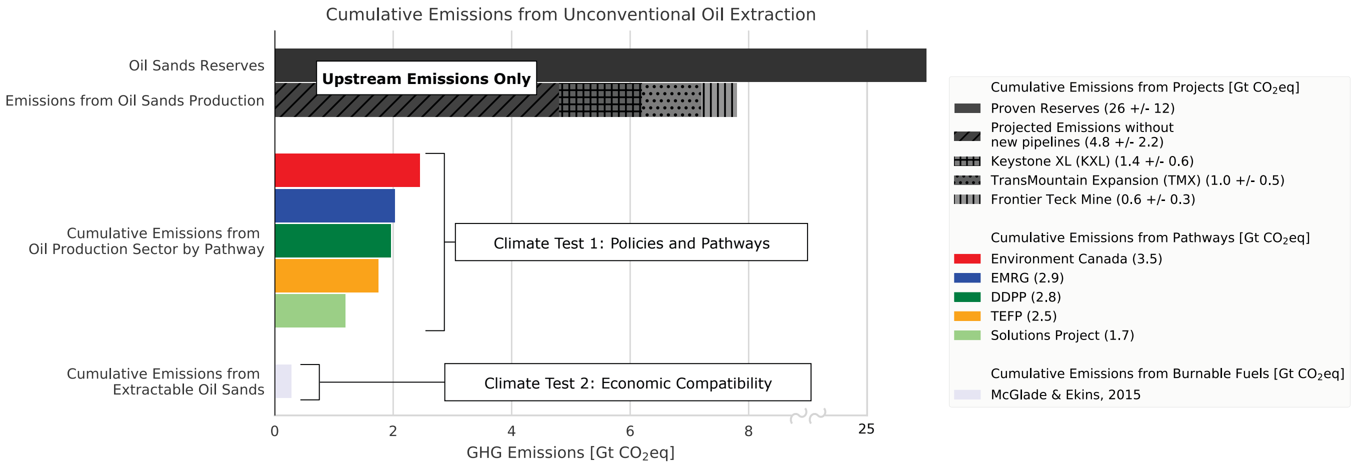


Figure S2.2 Illustrative climate tests for unconventional oil extraction in Canada. Dark grey bars represent cumulative emissions resulting from existing extraction and possible increases from additional transport capacity and new mines. Coloured bars represent cumulative emissions from the oil production sector for five decarbonization pathways (labeled “Climate Test 1”). The lower light-grey bar shows an estimated of the economically optimal emissions from Canadian oil sands for a 2°C climate scenario (labeled “Climate Test 2”). All values include upstream emissions only (i.e. excluding any potential increases in global emissions from the increase in consumption due to increased supply). Likewise, these emissions will occur domestically at the point of extraction, mostly in the province of Alberta. Note that projected emissions assume constant production and emissions intensity at present levels from now to 2050.

Figure S2.2 presents analogous analysis for Canada’s tar (or ‘oil’) sands. Due to space limitations in the manuscript, additional analysis of Canadian oil was omitted but can be expanded up for a future publication that builds on the established climate test framework.

Supplementary Discussion

Underlying assumptions in macroeconomic energy transition models

The two Canadian energy-emissions-economy models used here took differing approaches to reducing GHG emissions in Canada that reflected the modelers’ judgments regarding what was at the time politically tenable, technologically viable, and economically efficient. The EMRG model did not emphasize a high carbon price to promote emissions reductions, having asserted that a price high enough to drive Canadian decarbonization would be politically intractable, and preferred flexible regulations that would direct industries and households towards lower carbon activity. The Canadian DDPP model utilized a rising carbon price to incentivize cost-efficient mitigation, but still did not rely on one high enough to drive an energy transition alone, also having relied on additional policy measures like fossil fuel extraction subsidy phase outs to promote decarbonization. Both models performed similarly well at decarbonizing major sectors, including electricity, transport, and oil and gas extraction. Similarly, the models agreed that achieving major reductions to Canadian GHG emissions would require decarbonization of these sectors, and find that oil and gas extraction could be decarbonized substantially through electrification, efficiency measures and reductions in fugitive emissions during gas extraction, but production would still have to decline somewhat (even with highly optimistic technological innovation assumptions) if Canada were to reduce its annual GHG emissions to between 200 to 300 $MtCO_2e$ (approximately 70-60% below 2005 levels) by midcentury.

Both models' main scenarios presumed future low oil and gas prices, since sustained low oil and gas prices are to be expected during a global energy transition. Low prices would reduce demand for oil and gas as well as the financial incentive to decarbonize extraction. It follows that a low oil and gas price future would shift development priorities to other sectors, especially if additional policies supported a coinciding economic transition in Canada. We reiterate that neither model constrained GHG emissions to pathways or budgets consistent with a fixed amount of global heating, and so they cannot form the basis of a hard climate test that could determine which decisions are consistent with, for example, the goals of the Paris Agreement. Rather, they are used here to determine whether the decisions to build new fossil fuel infrastructure fit within the future emissions scenarios they have imagined, defined above as a soft climate test.

Accounting principles and their role in monitoring and enforcing GHG emissions reductions

Using territorial emissions for national emissions inventories (NEI) was most likely first a choice of simplicity and convenience, but now continues for both technical and political reasons. It is more straightforward to estimate a country's emissions as the product of bottom-up emissions factors and economic activity, for which data was readily available before comprehensive economic and GHG monitoring. Alternative accounting principles have been developed and now could complement existing territorial emissions to make international climate action more effective and equitable. (Steininger, Lininger, Meyer, Muñoz, & Schinko, 2015) Accounting for emissions at their point of fossil fuel extraction, referred to as extraction-based accounting (EBA), could be used to limit carbon leakage from fossil fuel exports. Like with the adoption of consumption-based emissions, which faces resistance from wealthy nations who benefit from the ability to displace emissions through trade, we expect strong opposition from fossil fuel producing nations against the widespread adoption of EBA. Additional GHG emissions monitoring using EBA could be adopted first by willing countries and more broadly through international agreement under the United Nations Framework Convention on Climate Change (UNFCCC). It could be made part of the rubric of a supply-side NDC program or a fossil fuel nonproliferation treaty (Section 1.2).

8.3 Paper 3 supplementary material

Supplementary Discussion

Justification for endogenization of labour in production and the distinction between the attribution of impact and responsibility

Economic activity is largely driven by the demand for final products. Simultaneously, employment provides the consumer income allowing for the purchase of these products. Economic activity depends on resource extraction (both renewable and non-renewable) and generates wastes such as GHG emissions. These inputs or outputs can be assigned to the economic sector where they first occur or, through the interlinked economy, to the consumer of the final goods and services. Note that there is no attempt here to assign blame for these impacts, only to attribute impacts in a manner consistent with a more holistic view of production, which may better represent the inter-sectoral relationships involved. In essence, we argue that it is conceptually incomplete to exclude the provision of labour from the production supply chain in an analysis of the environmental impacts generated by economic sectors, as is conventionally done. Our approach therefore can facilitate an understanding of the effects of promoting tertiarization and continuing to migrate towards service sector employment in the developed economies, absent concurrent changes in the qualitative and quantitative characteristics of aggregate demand.

Underlying drivers of sectoral change, industry-level analysis and discussion.

To identify the drivers of change between "open" and "closed" sectoral impact allocations, we examined trends in varying sectoral aggregations (Fig. S3.1,2) as well as individual industries. Globally, when examining mean values over the 2007 to 2011 period, increased impacts upon model closure are driven by the Service, Construction, and Manufacturing sectors (note that all sector names are capitalized). Collectively these sectors contain seven of the top ten growing industries. Service contain 61%, 57%, and 51% of the total increases of GHG emissions, land use, and water consumption, respectively; while 29%, 27%, and 31% occur in Construction; and 10%, 13%, and 15% occur in Manufactured Products.

Now we examine the underlying drivers of sectoral change by industry (industry names are in "quotations"). The change from open to closed accounts is denoted as $\Delta CO = CBA_{closed} - CBA_{open.}$ The largest shifts within the Service sector stem from "Public administration and defense, compulsory social security" (ΔCO^{GHG} = 5.0 $GtCO_2e$, $\Delta CO^{LandUse}$ = 13 Mkm^2, and $\Delta CO^{WaterConsumption}$ = 208 Gm^3); "Education" ($\Delta CO^{GHG} = 1.2$, $\Delta CO^{LU} = 3.7$, $\Delta CO^{WC} = 60$), and "Health and social work" ($\Delta CO^{GHG} = 1.1$, $\Delta CO^{LU} = 3.6$, $\Delta CO^{WC} = 52$). Significant increases are also attributable to "Computer and related activities" ($\Delta CO^{GHG} = 0.37$, $\Delta CO^{LU} = 0.86$, $\Delta CO^{WC} = 16$), and "Research and development" ($\Delta CO^{GHG} = 0.15$, $\Delta CO^{LU} = 0.49$, $\Delta CO^{WC} = 9.0$).

"Finance, insurance, and real estate" (FIRE) runs counter to the overall trend within the Services sector, with decreasing absolute impacts (Fig. S1A–C, G–I) and impact intensities (Fig. S3b, c, f) after model closure. This pattern could relate to high value per unit labor, rapid recent growth, complex processes related to financialization of the economy, and high proportional nonwage remuneration (e.g. stock options), all of which may negatively bias estimated impacts per unit output and merit further attention.

The largest decreases in GHG emissions upon closure in individual industries are found in the Shelter and Mobility sectors with “Coal-fired electricity” and “Petroleum refining” falling by 1.7 and 1.2 Gt $GtCO_2e$, respectively, accounting for 19% of the global decrease in emissions. For land use, the largest declines are found in specific industries within the Food, Shelter, and Services sectors: “Meat and dairy” ($\Delta CO^{LU} = -15$ Mkm^2) is by far the most over-accounted driver of land use, with “Forestry and logging” ($\Delta CO^{LU} = -8.0$ Mkm^2) second, and other food production and food-related services following (“Unclassified food processing” ($\Delta CO^{LU} = -4.6$ Mkm^2); “Cultivation of vegetables, Fruit and nuts” ($\Delta CO^{LU} = -1.7$ Mkm^2); and “Hotels and restaurants” ($\Delta CO^{LU} = -2.0$ Mkm^2) exhibiting the largest decreases after closure in their respective sectors). Finally, water consumption decreases most for industries within the Food and Service sectors, with “Unclassified food processing” ($\Delta CO^{WC} = -110$ Gm^3), “Cultivation of fruits, vegetables, and nuts” ($\Delta CO^{WC} = -95$ Gm^3); Cultivation and processing of staple crops like wheat ($\Delta CO^{WC} = -95$ Gm^3) and rice ($\Delta CO^{WC} = -86$ Gm^3), and other industries involving food preparation like the “Hotel and restaurant” industry ($\Delta CO^{WC} = -45$ Gm^3).

It is also worth noting that due to the internal heterogeneity of sectors, increased aggregation leads to higher levels of sectoral convergence when switching from open to closed CBA accounts. Notice the difference between figure 2 and figure S3.2, where sectoral classifications using fewer categories converge more than those with more granular breakdowns. More granular schemes, like the ISIC scheme, contain far fewer industries in certain sectors, which accentuates disparities far more, and does not result in sectoral convergence as depicted in the main analysis. That said, this does not undermine our findings, rather it adds more detailed insight into underlying drivers of environmental impacts. For example, in figure S3.2 (f), which uses the most disaggregated classification scheme (ISIC_granular), one can see how after closure, the main drivers of environmental degradation within Services reside in the research, technology, and public administration domains, while FIRE industries have lower impact per unit output. Ultimately, instead of the finding in the main text of sectoral convergence (or the indifferentiability of impacts between sectors), one can conclude that certain sectors that were once deemed low impact are now relatively high impact, when compared to other sectors after closure. For example, using the default classification scheme, the impact of food production (Food) and services (Services) was deemed the same per unit value, but when applying a more granular breakdown, we find most of the service sector (Other Services in the granular Consumption Category scheme, or L, M+N+O, and G+H in the ISIC and granular ISIC schemes) has a significantly higher impact per unit value than food production, after closure.

The shift from open to closed CBA models

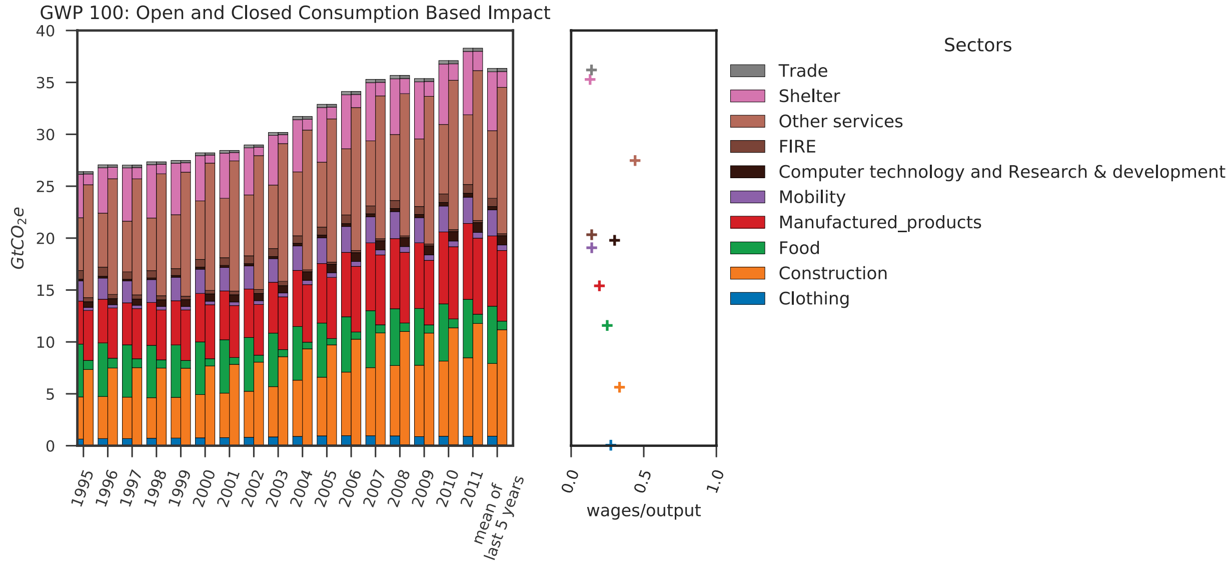
This shift to a closed-IO model (with respect to labour) is similar in nature to that which has been shown previously to result from a switch from production-based accounting (PBA) to consumption-based accounting (CBA), in which resources and impacts associated with the production of goods and services are allocated to the country of consumption rather than the country of production[65]. Introducing labour into the production supply chain reinforces the effect of switching to from PBA to CBA — environmental harm caused by consumptive activities in developed countries increases more relative to open-CBA accounts. This is due to the structure of developed countries economies, which typically have a larger share of tertiary industries and higher wages compared with developing economies. This implies that a substantial proportion of environmental impacts conventionally allocated to developing countries (according to open-CBA) are in fact driven by the indirect needs of industries in the developed world. In other words, open-CBA models do not account for differences in household consumption of labour embodied in internationally traded goods and services. For example, manufacturing a car in Canada requires steel and electronic component manufactured in China, and so the household consumption of Chinese labour who manufacture the steel and components (that are intermediary products ultimately assembled in Canada) are allocated to the industry based in Canada (in addition to the household consumption of Canadian labour, which is already counted as part of Canada's account in open-CBA models).

Relation to Environmental Kuznets Curve and Sustainable Development Goals

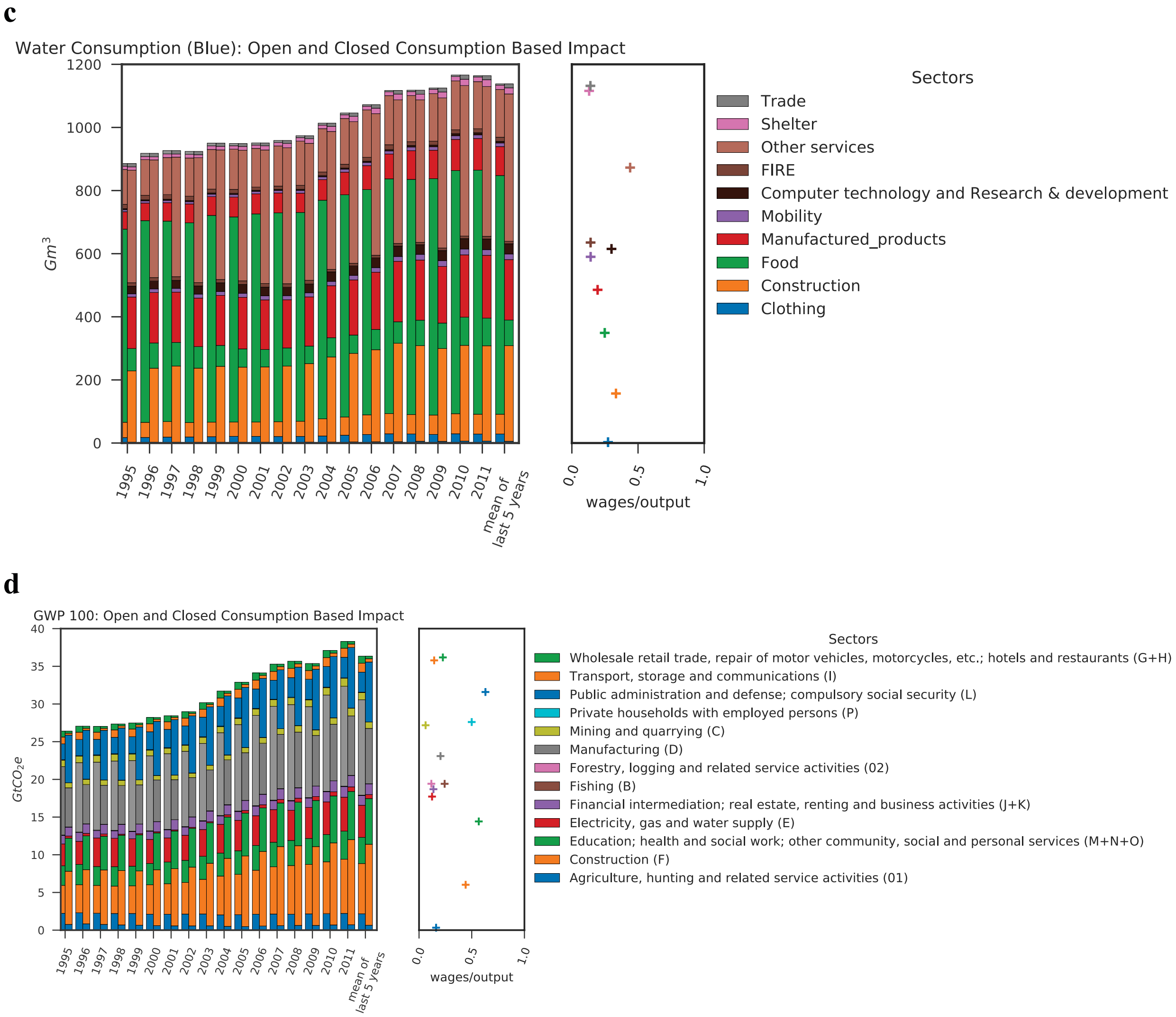
Our results pose a fundamental challenge to the notion that, all else being equal, economic tertiarization can provide a pathway to the decoupling of economic growth from environmental pressure. This idea is often invoked in the literature in the context of the more general Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental impacts for a nation typically follow an inverted U-shaped curve as they develop economically and become wealthier[221–223]. Despite coming under significant attack from researchers suggesting that the EKC concept may not be universal, empirically valid, or suitable for use in policy formulation[168,170,171,204,224–230] , the assumption that economic development can lead to an alleviation of environmental burdens remains firmly entrenched in the sustainable development discourse at the highest level. A notable example of this can be seen in the United Nations' Sustainable Development Goals (SDG), Goal 8, to "Promote inclusive and sustainable economic growth, employment and decent work for all." While we do not dispute that equitable access to employment is crucial to improve human well-being, our results do challenge the premise of this goal—according to the United Nations, "Sustainable economic growth will require societies to create the conditions that allow people to have quality jobs that stimulate the economy while not harming the environment."[186] In contrast to this assertion, higher wage employment facilitates higher levels of consumption, and our analysis shows clearly that increasing the proportion of highly-paid service sector employment will lead to an overall increase in environmental damages caused by economic activities unless fundamental changes emerge in areas such as resource extraction, reuse, and recycling; production techniques, and waste disposal. Additionally, this calls into question whether economic growth itself is sustainable, and if it is not, whether fulfilling the material basis for a dignified life for all is possible without growth.

Supplementary Figures

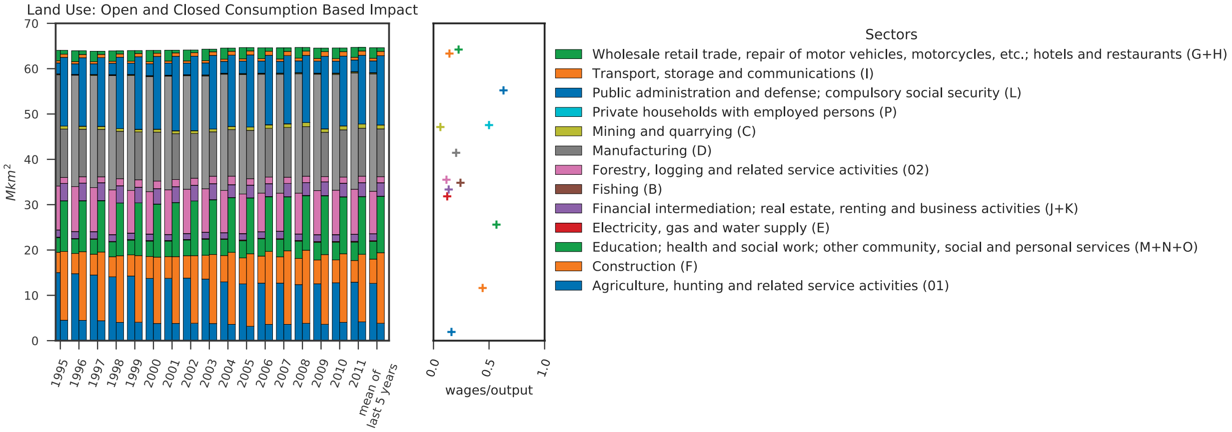
a



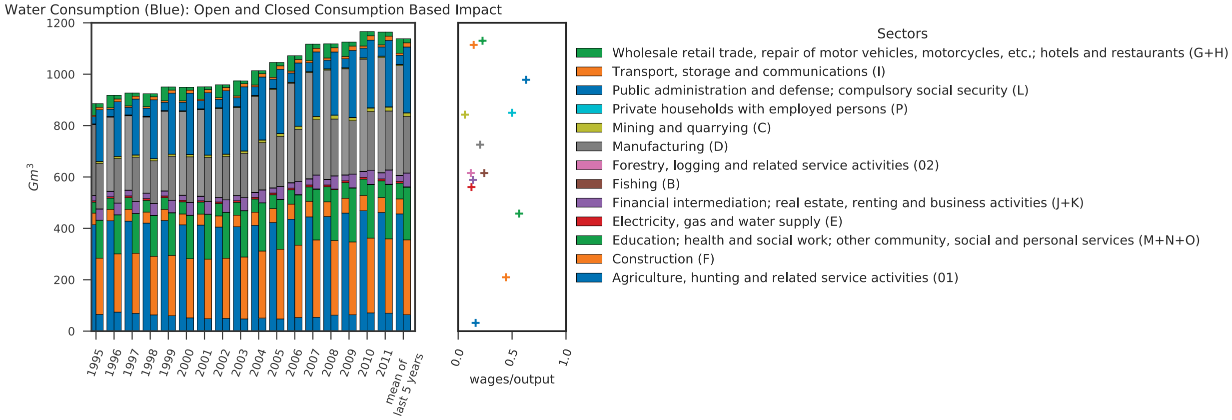
b


c
Water Consumption (Blue): Open and Closed Consumption Based Impact
1200
1000
800
600
400
200
0
Gm^3
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
mean of last 5 years
0.0
0.5
1.0
wages/output
Sectors
Trade
Shelter
Other services
FIRE
Computer technology and Research & development
Mobility
Manufactured_products
Food
Construction
Clothing
d
GWP 100: Open and Closed Consumption Based Impact
40
35
30
25
20
15
10
5
0
$GtCO_2e$
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
mean of last 5 years
0.0
0.5
1.0
wages/output
Sectors
Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)
Transport, storage and communications (I)
Public administration and defense; compulsory social security (L)
Private households with employed persons (P)
Mining and quarrying (C)
Manufacturing (D)
Forestry, logging and related service activities (02)
Fishing (B)
Financial intermediation; real estate, renting and business activities (J+K)
Electricity, gas and water supply (E)
Education; health and social work; other community, social and personal services (M+N+O)
Construction (F)
Agriculture, hunting and related service activities (01)

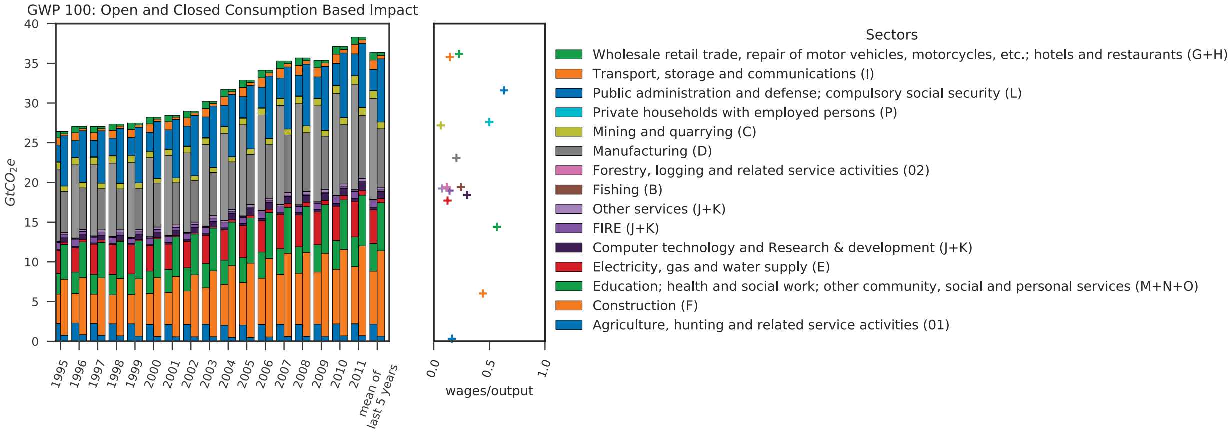
e


Land Use: Open and Closed Consumption Based Impact
Mkm²
0
10
20
30
40
50
60
70
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
mean of last 5 years
0.0
0.5
1.0
wages/output
Sectors
Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)
Transport, storage and communications (I)
Public administration and defense; compulsory social security (L)
Private households with employed persons (P)
Mining and quarrying (C)
Manufacturing (D)
Forestry, logging and related service activities (02)
Fishing (B)
Financial intermediation; real estate, renting and business activities (J+K)
Electricity, gas and water supply (E)
Education; health and social work; other community, social and personal services (M+N+O)
Construction (F)
Agriculture, hunting and related service activities (01)

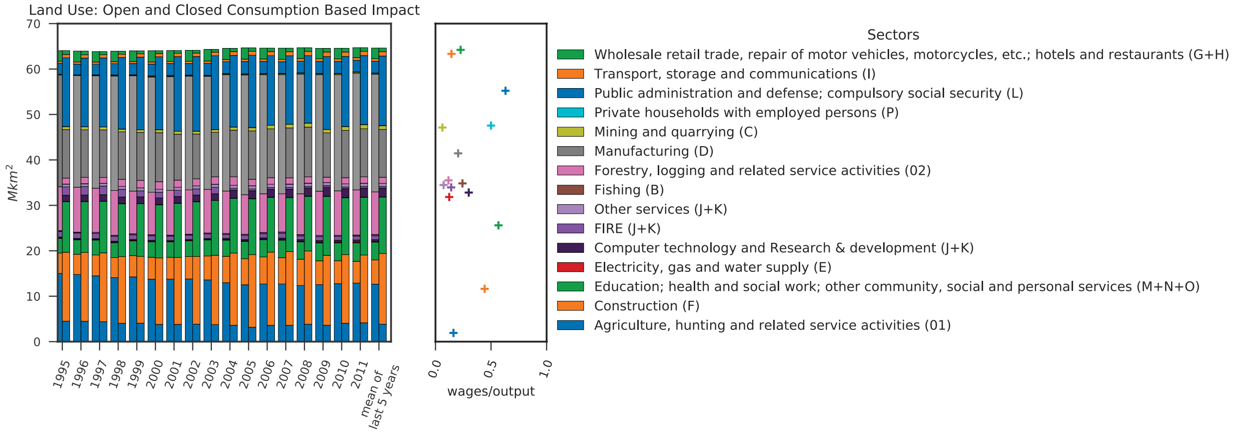
f


Water Consumption (Blue): Open and Closed Consumption Based Impact
Gm³
0
200
400
600
800
1000
1200
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
mean of last 5 years
0.0
0.5
1.0
wages/output
Sectors
Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)
Transport, storage and communications (I)
Public administration and defense; compulsory social security (L)
Private households with employed persons (P)
Mining and quarrying (C)
Manufacturing (D)
Forestry, logging and related service activities (02)
Fishing (B)
Financial intermediation; real estate, renting and business activities (J+K)
Electricity, gas and water supply (E)
Education; health and social work; other community, social and personal services (M+N+O)
Construction (F)
Agriculture, hunting and related service activities (01)

g

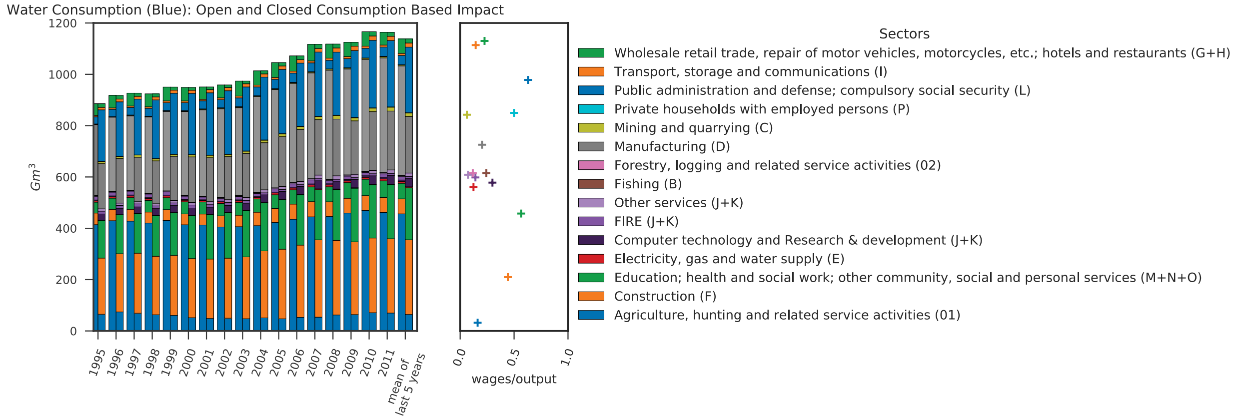

GWP 100: Open and Closed Consumption Based Impact
GtCO₂e
0
5
10
15
20
25
30
35
40
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
mean of last 5 years
0.0
0.5
1.0
wages/output
Sectors
Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)
Transport, storage and communications (I)
Public administration and defense; compulsory social security (L)
Private households with employed persons (P)
Mining and quarrying (C)
Manufacturing (D)
Forestry, logging and related service activities (02)
Fishing (B)
Other services (J+K)
FIRE (J+K)
Computer technology and Research & development (J+K)
Electricity, gas and water supply (E)
Education; health and social work; other community, social and personal services (M+N+O)
Construction (F)
Agriculture, hunting and related service activities (01)

h



Land Use: Open and Closed Consumption Based Impact

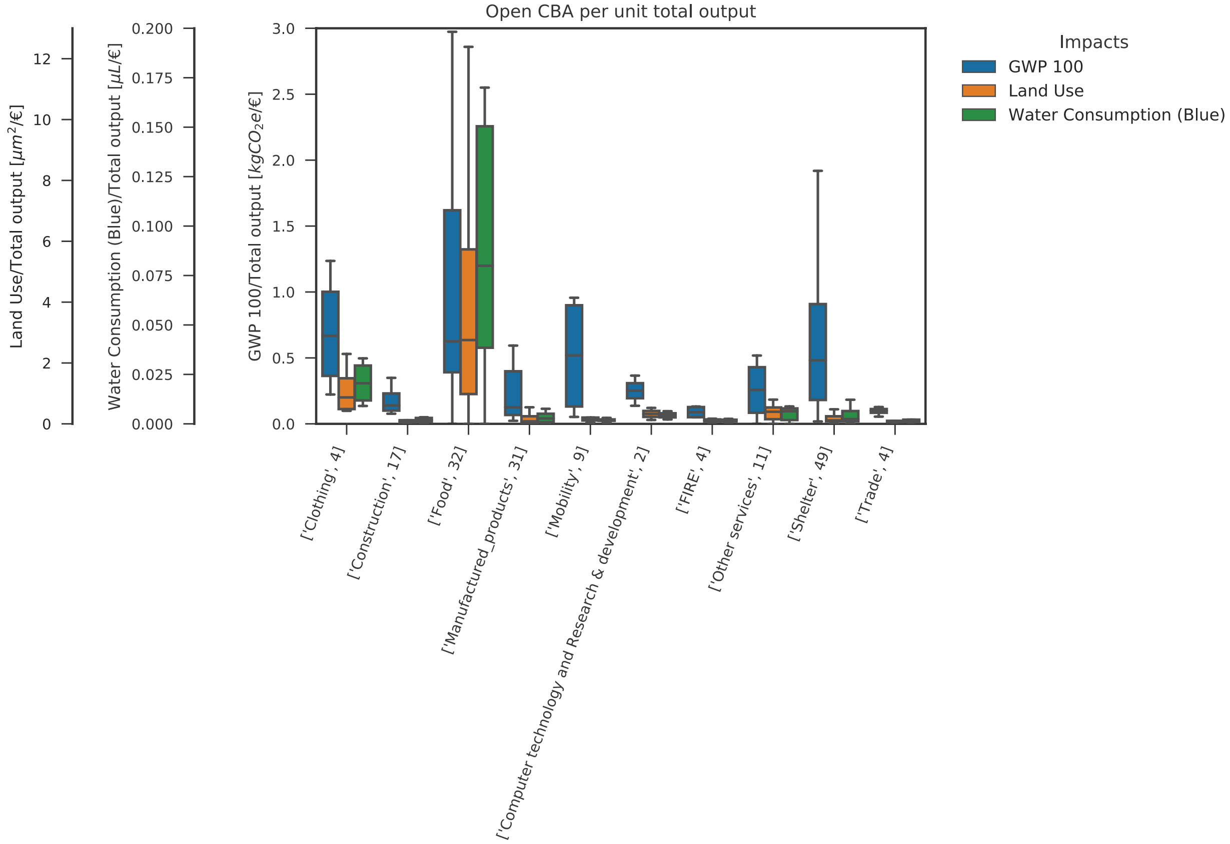
i



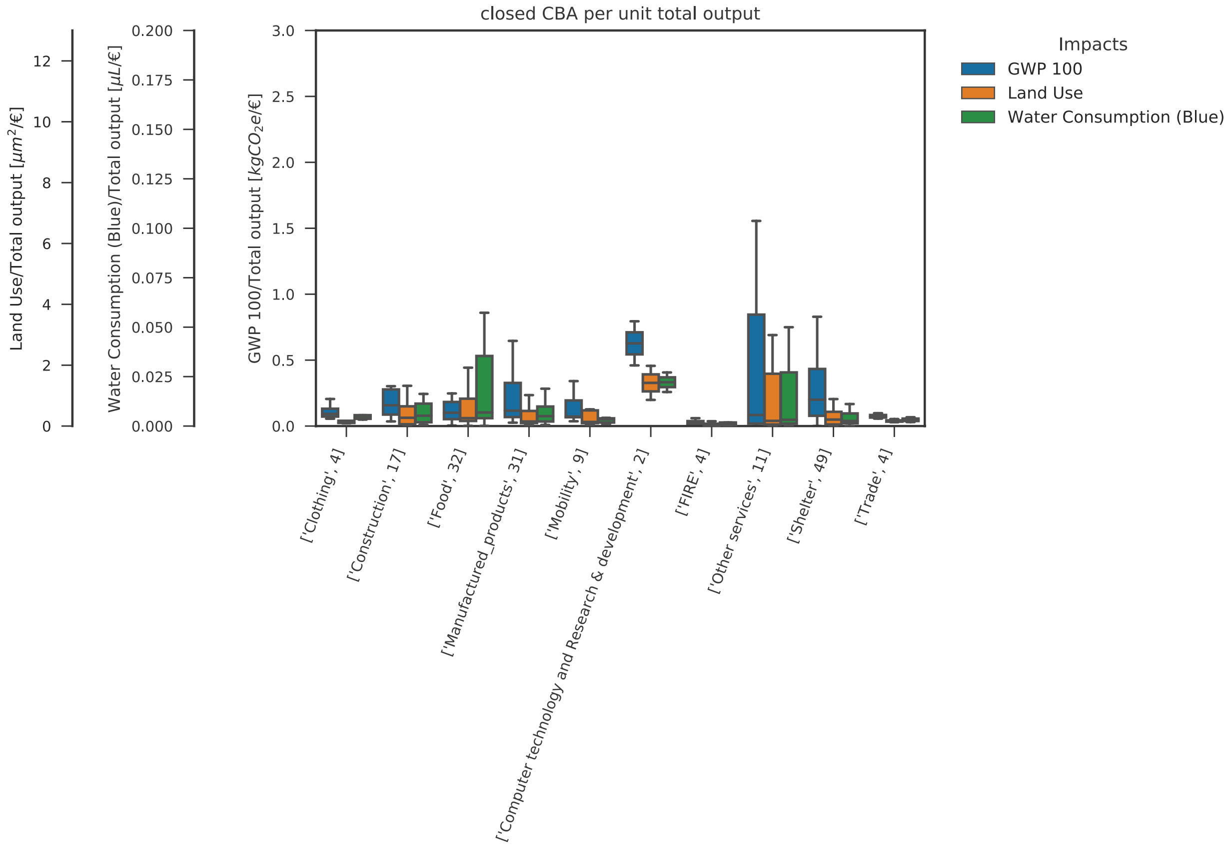
Water Consumption (Blue): Open and Closed Consumption Based Impact

Figure S3.1 Timeseries (like in Fig. 5.1) with alternative industry categorizations and levels of aggregation, with "open" (left bar) and "closed" (right bar) consumption-based accounts for Consumption Categories (as in Fig.1), with Services disaggregated into Finance, Real Estate, and Insurance (FIRE), Computer technology and research & development, and Other services (containing the remaining industries in the original Services category) for a. GHG emissions, b. land use, and c. water consumption; e–f. Plots for same three environmental impacts for ISIC classification scheme; g–i. Plots for same three environmental impacts for ISIC classification scheme with the "Financial intermediation; real estate, renting and business activities (J+K)" sector disaggregated into same three subcategories (as in a–c).

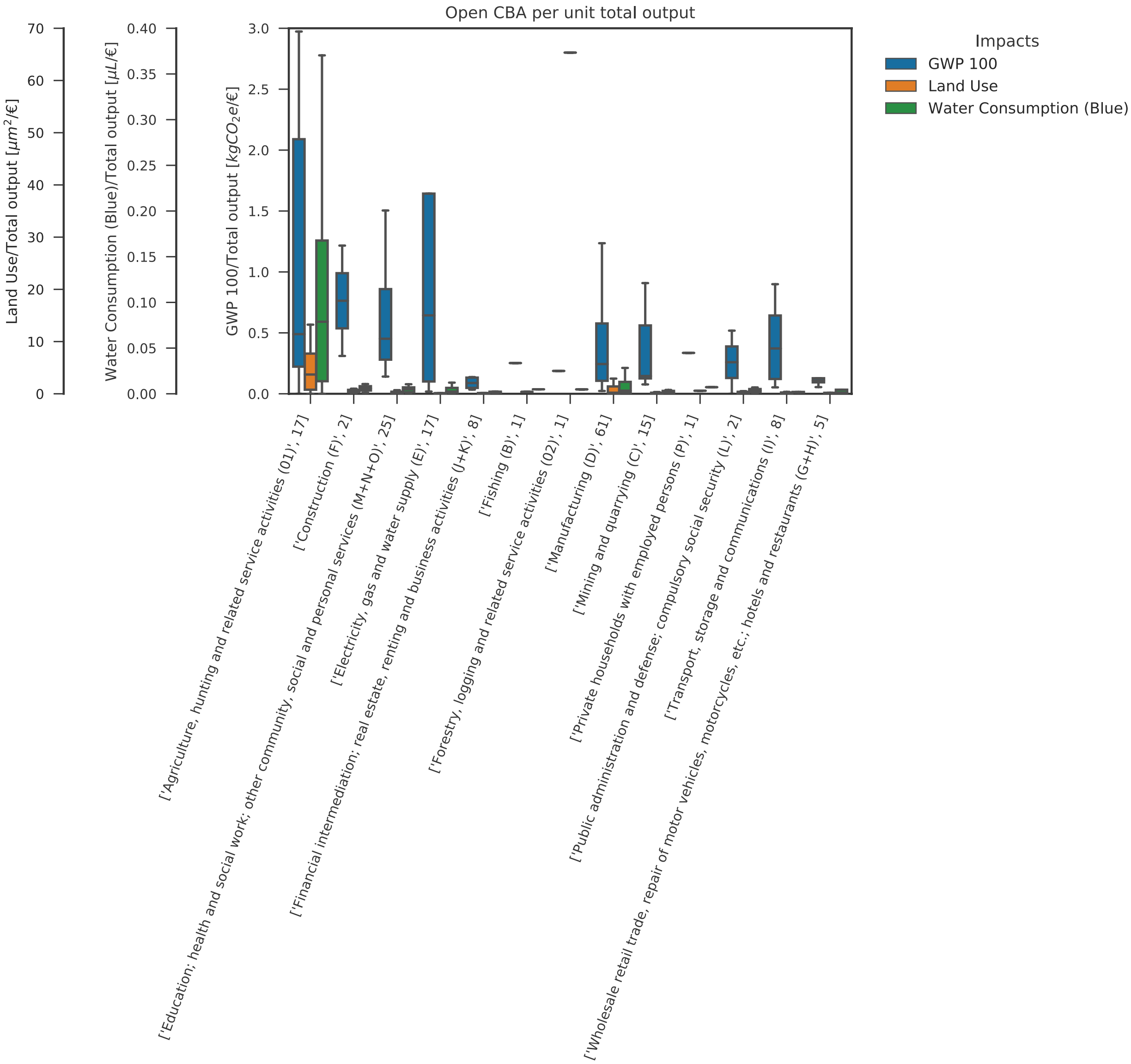
a


Open CBA per unit total output
Land Use/Total output [μm^2/€]
0
2
4
6
8
10
12
Water Consumption (Blue)/Total output [μL/€]
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
GWP 100/Total output [$kgCO_2e$/€]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
['Clothing', 4]
['Construction', 17]
['Food', 32]
['Manufactured_products', 31]
['Mobility', 9]
['Computer technology and Research & development', 2]
['FIRE', 4]
['Other services', 11]
['Shelter', 49]
['Trade', 4]
Impacts
GWP 100
Land Use
Water Consumption (Blue)

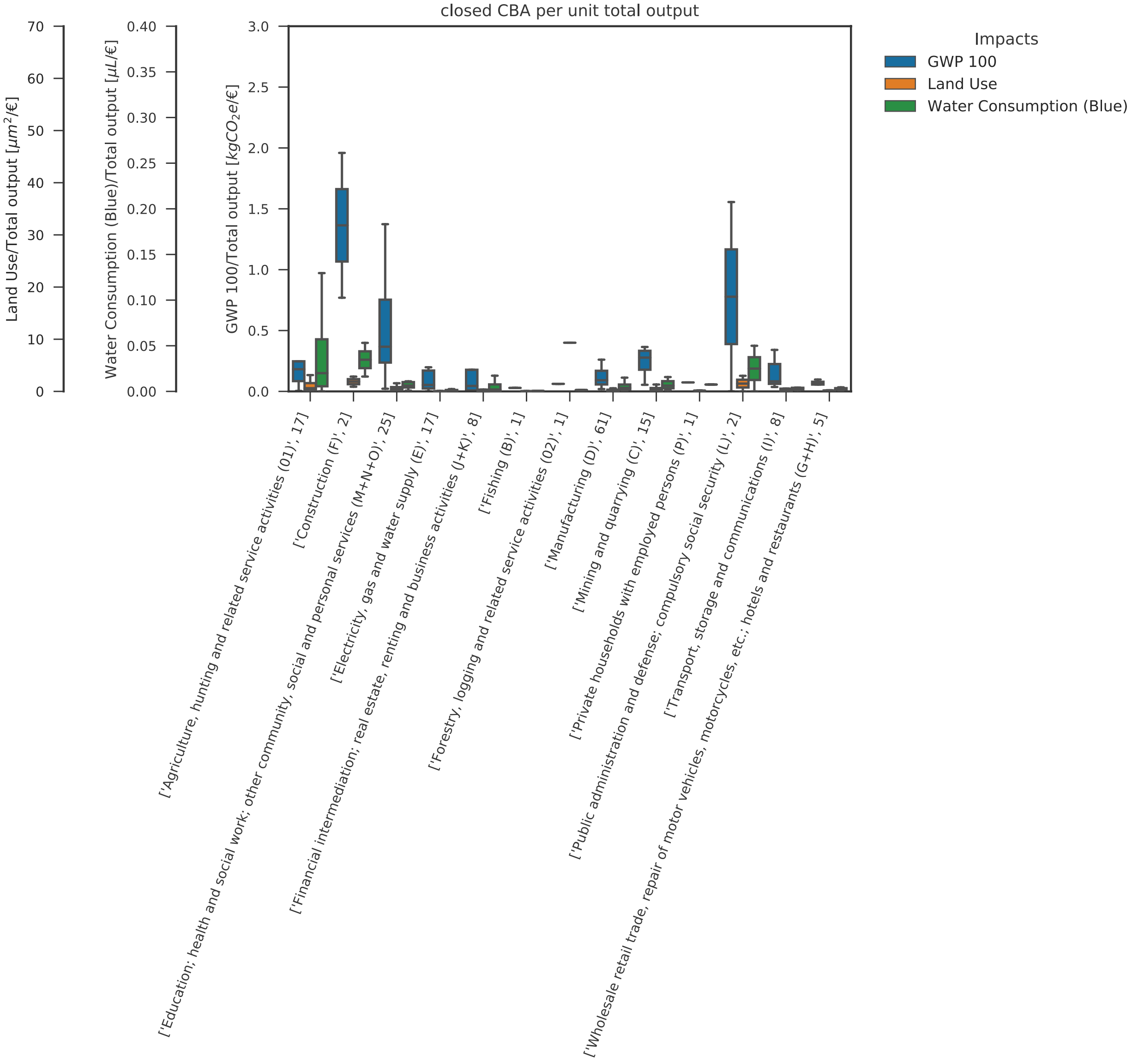
b


closed CBA per unit total output
Land Use/Total output [μm^2/€]
0
2
4
6
8
10
12
Water Consumption (Blue)/Total output [μL/€]
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
GWP 100/Total output [$kgCO_2e$/€]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
['Clothing', 4]
['Construction', 17]
['Food', 32]
['Manufactured_products', 31]
['Mobility', 9]
['Computer technology and Research & development', 2]
['FIRE', 4]
['Other services', 11]
['Shelter', 49]
['Trade', 4]
Impacts
GWP 100
Land Use
Water Consumption (Blue)

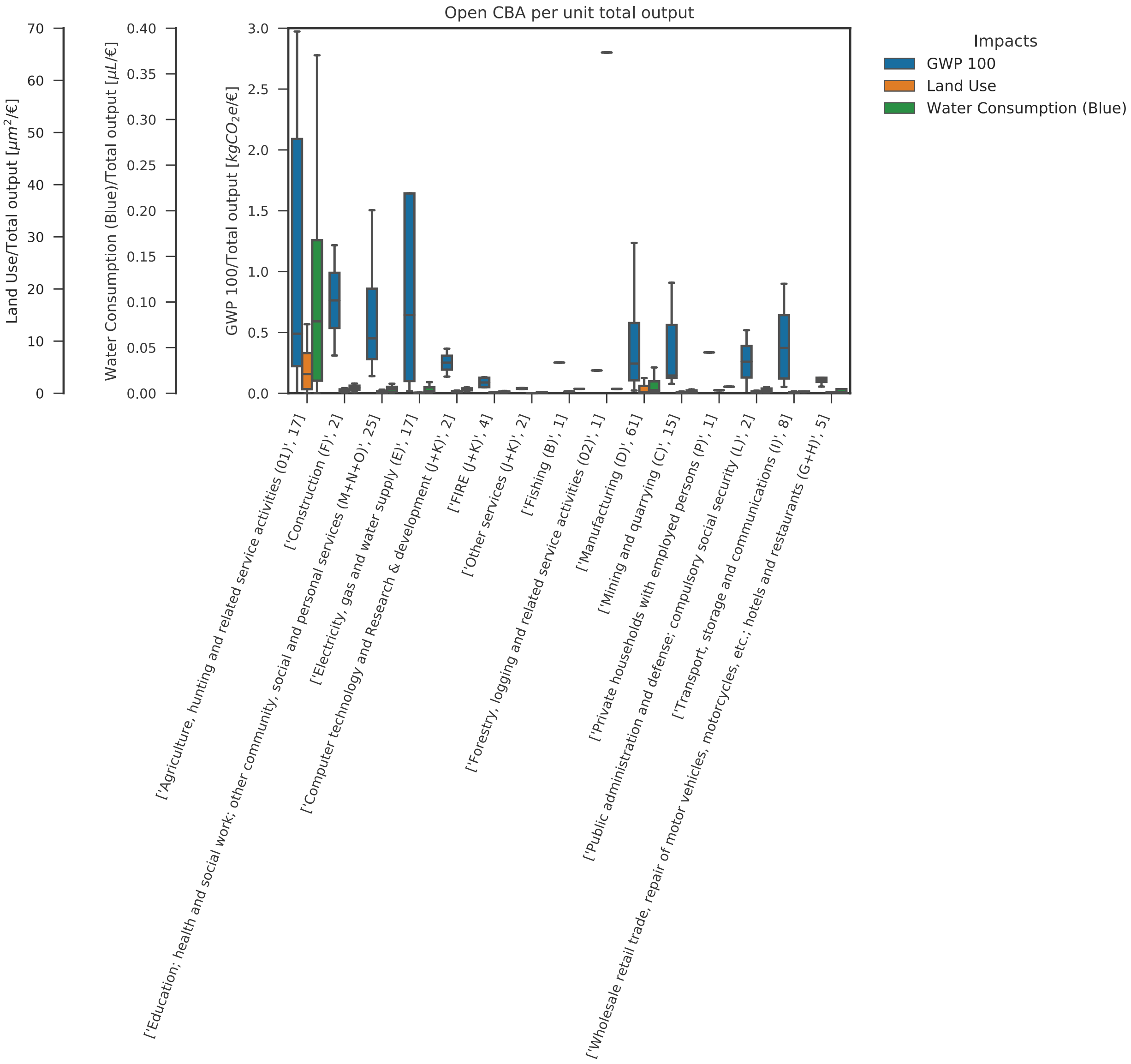
c


Open CBA per unit total output
Land Use/Total output [μm^2/€]
0
10
20
30
40
50
60
70
Water Consumption (Blue)/Total output [μL/€]
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
GWP 100/Total output [$kgCO_2e$/€]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
['Agriculture, hunting and related service activities (01)', 17]
['Construction (F)', 2]
['Education; health and social work; other community, social and personal services (M+N+O)', 25]
['Electricity, gas and water supply (E)', 17]
['Financial intermediation; real estate, renting and business activities (J+K)', 8]
['Fishing (B)', 1]
['Forestry, logging and related service activities (02)', 1]
['Manufacturing (D)', 61]
['Mining and quarrying (C)', 15]
['Private households with employed persons (P)', 1]
['Public administration and defense; compulsory social security (L)', 2]
['Transport, storage and communications (I)', 8]
['Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)', 5]
Impacts
GWP 100
Land Use
Water Consumption (Blue)

d


closed CBA per unit total output
Land Use/Total output [μm^2/€]
70
60
50
40
30
20
10
0
Water Consumption (Blue)/Total output [μL/€]
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
GWP 100/Total output [$kgCO_2e$/€]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Impacts
GWP 100
Land Use
Water Consumption (Blue)
['Agriculture, hunting and related service activities (01)', 17]
['Construction (F)', 2]
['Education; health and social work; other community, social and personal services (M+N+O)', 25]
['Electricity, gas and water supply (E)', 17]
['Financial intermediation; real estate, renting and business activities (J+K)', 8]
['Fishing (B)', 1]
['Forestry, logging and related service activities (02)', 1]
['Manufacturing (D)', 61]
['Mining and quarrying (C)', 15]
['Private households with employed persons (P)', 1]
['Public administration and defense; compulsory social security (L)', 2]
['Transport, storage and communications (I)', 8]
['Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)', 5]

e


Open CBA per unit total output
Land Use/Total output [μm^2/€]
70
60
50
40
30
20
10
0
Water Consumption (Blue)/Total output [μL/€]
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
GWP 100/Total output [$kgCO_2e$/€]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Impacts
GWP 100
Land Use
Water Consumption (Blue)
['Agriculture, hunting and related service activities (01)', 17]
['Construction (F)', 2]
['Education; health and social work; other community, social and personal services (M+N+O)', 25]
['Electricity, gas and water supply (E)', 17]
['Computer technology and Research & development (J+K)', 2]
['FIRE (J+K)', 4]
['Other services (J+K)', 2]
['Fishing (B)', 1]
['Forestry, logging and related service activities (02)', 1]
['Manufacturing (D)', 61]
['Mining and quarrying (C)', 15]
['Private households with employed persons (P)', 1]
['Public administration and defense; compulsory social security (L)', 2]
['Transport, storage and communications (I)', 8]
['Wholesale retail trade, repair of motor vehicles, motorcycles, etc.; hotels and restaurants (G+H)', 5]

f

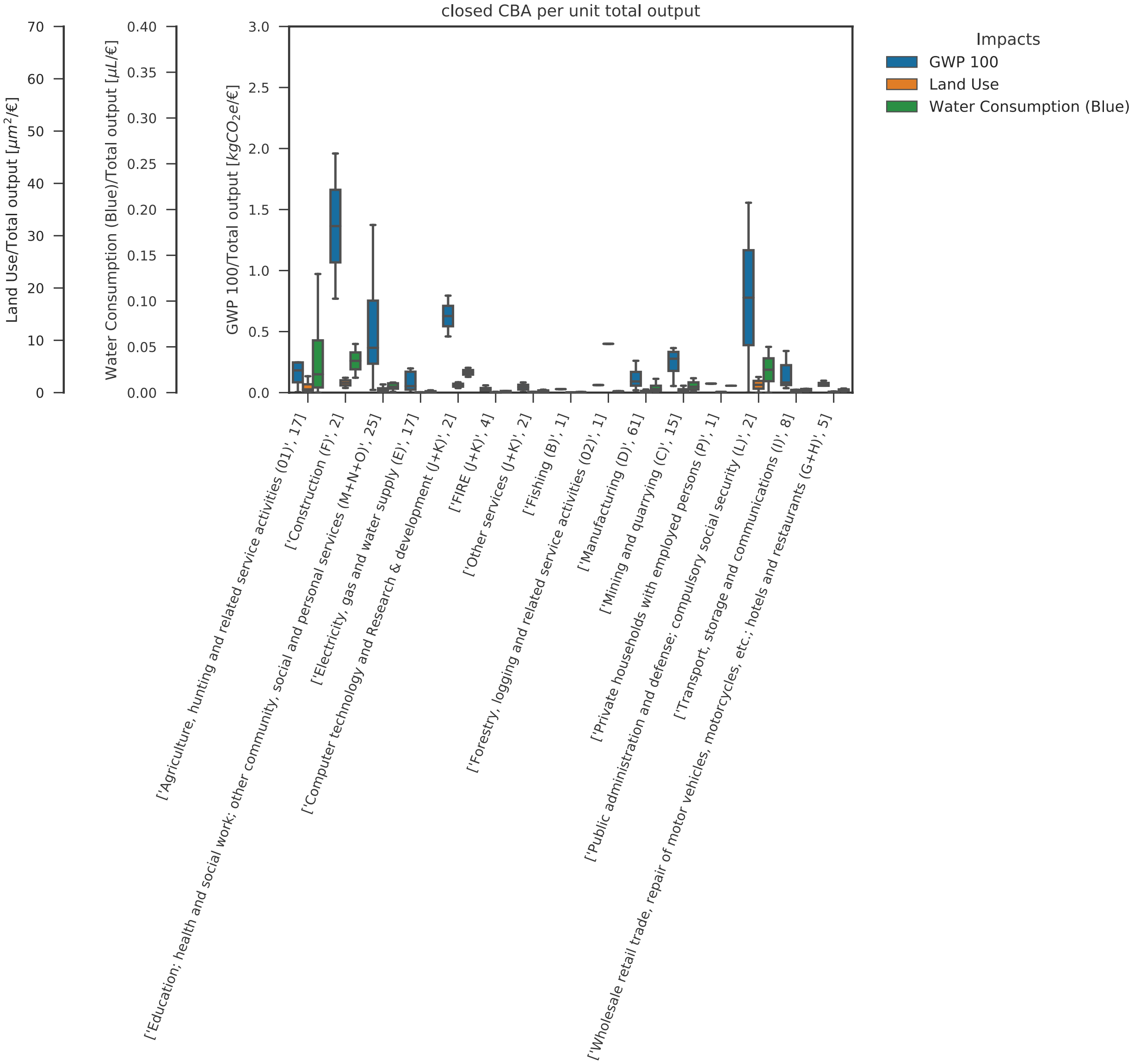
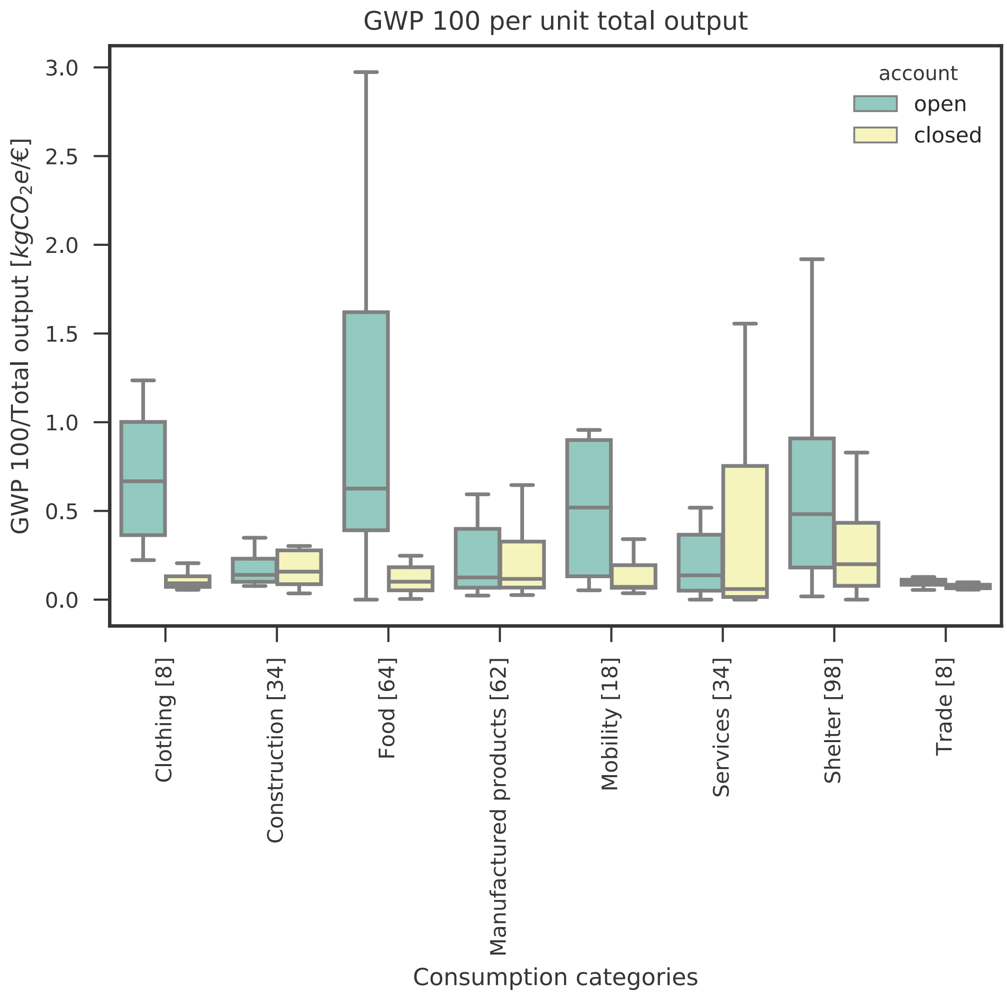
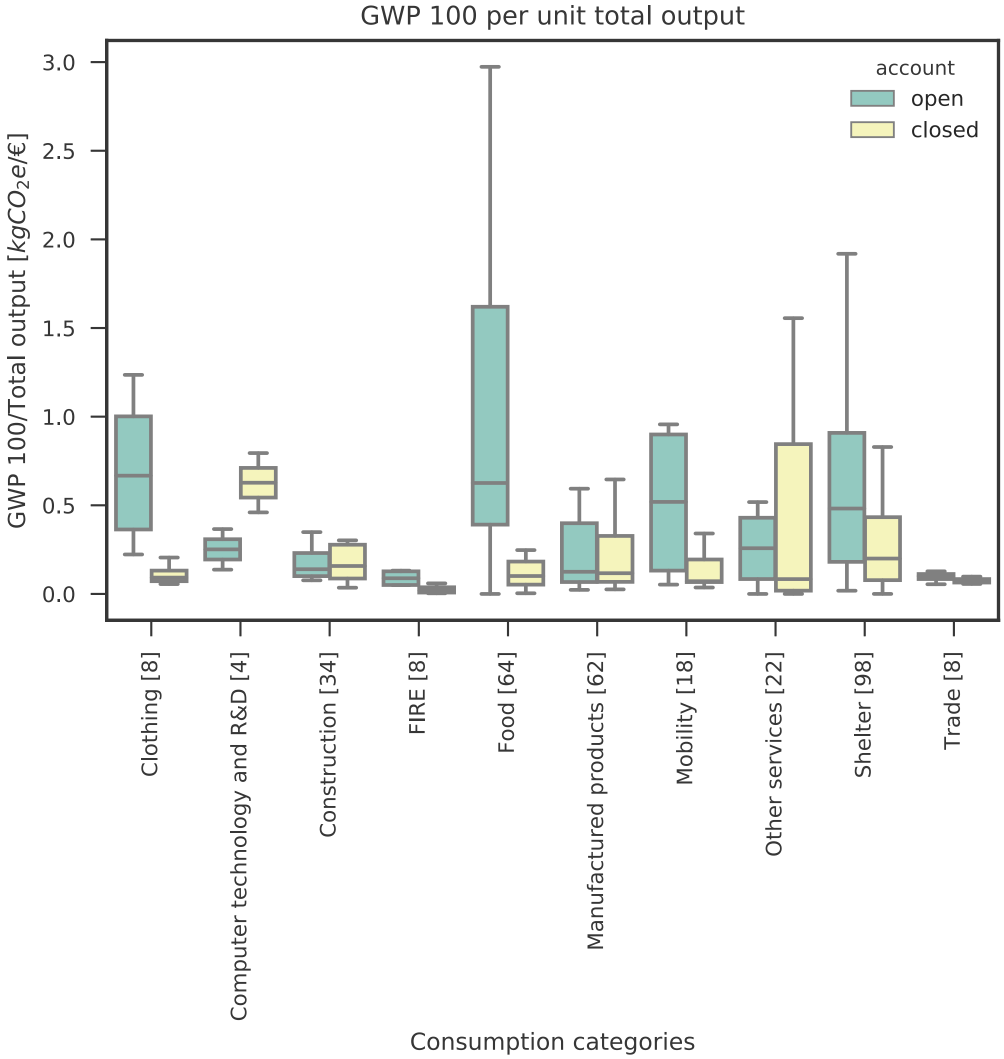


Fig. S3.2 Box plots (like in Fig. 2) with alternative industry categorizations and levels of aggregation, with a. open-CBA and b. closed-CBA for Consumption Categories (as in Fig. 5.2), with Services disaggregated into Finance, Real Estate, and Insurance (FIRE), Computer technology and research & development, and Other services (containing the remaining industries in the original Services category; see Supplementary Data for a table of all industries and classifications); c. open-CBA and d. closed-CBA for ISIC classification scheme; and e. open-CBA and f. closed-CBA for ISIC classifications with the "Financial intermediation; real estate, renting and business activities (J+K)" sector disaggregated into same three subcategories (as in a and b). Whiskers show maximum and minimum values within 1.5 IQR of the 75th and 25th percentiles. Outliers have been omitted to improve legibility.

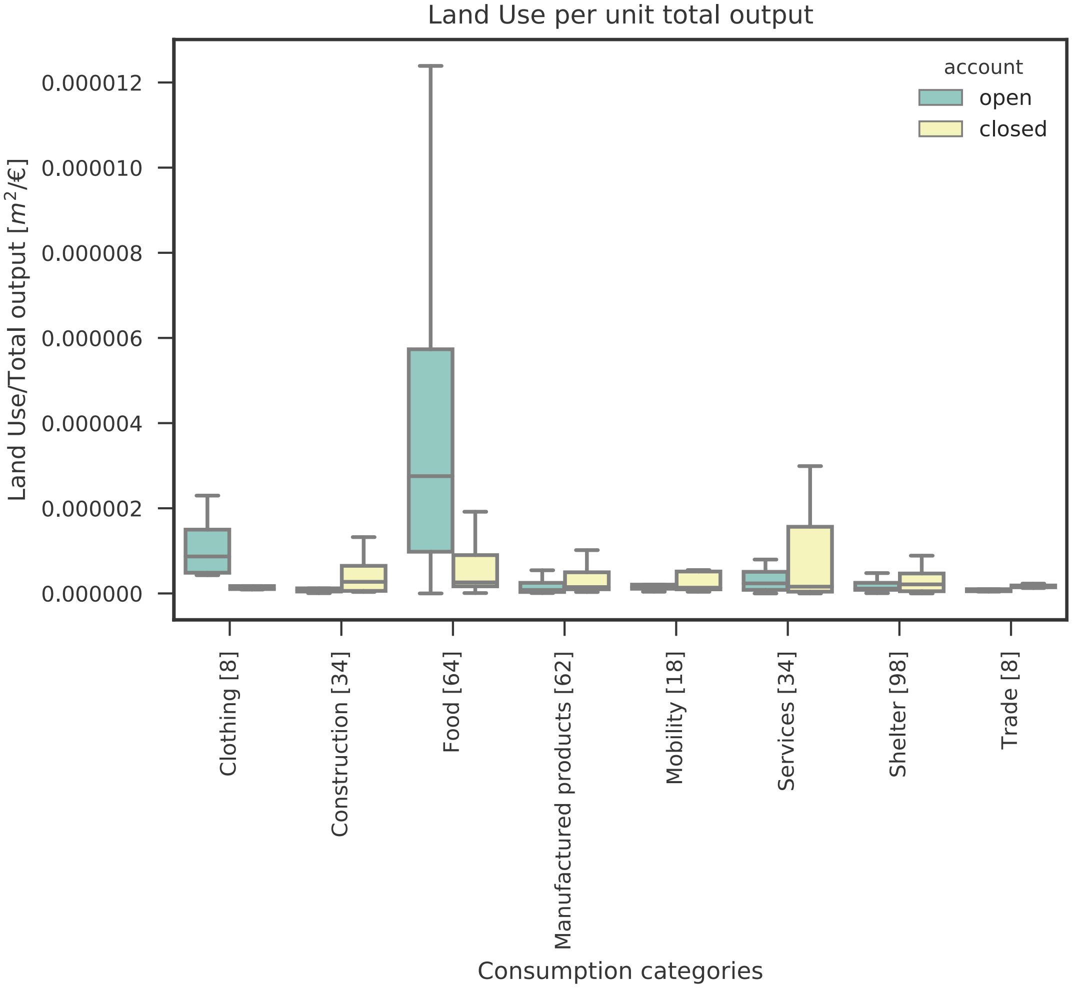
a


GWP 100 per unit total output
GWP 100/Total output [$kgCO_2e/€$]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
account
open
closed
Clothing [8]
Construction [34]
Food [64]
Manufactured products [62]
Mobility [18]
Services [34]
Shelter [98]
Trade [8]
Consumption categories

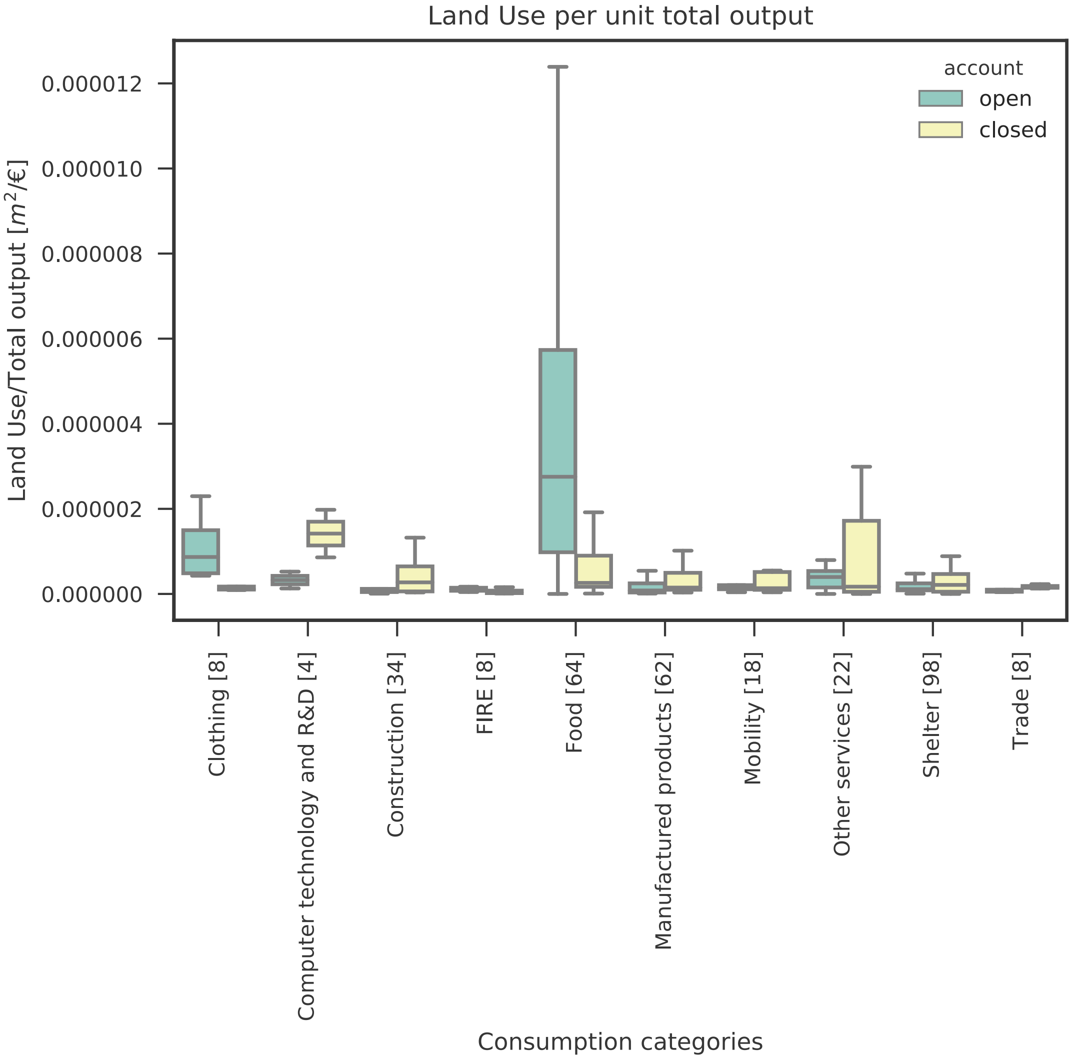
b


GWP 100 per unit total output
GWP 100/Total output [$kgCO_2e$/€]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
account
open
closed
Clothing [8]
Computer technology and R&D [4]
Construction [34]
FIRE [8]
Food [64]
Manufactured products [62]
Mobility [18]
Other services [22]
Shelter [98]
Trade [8]
Consumption categories

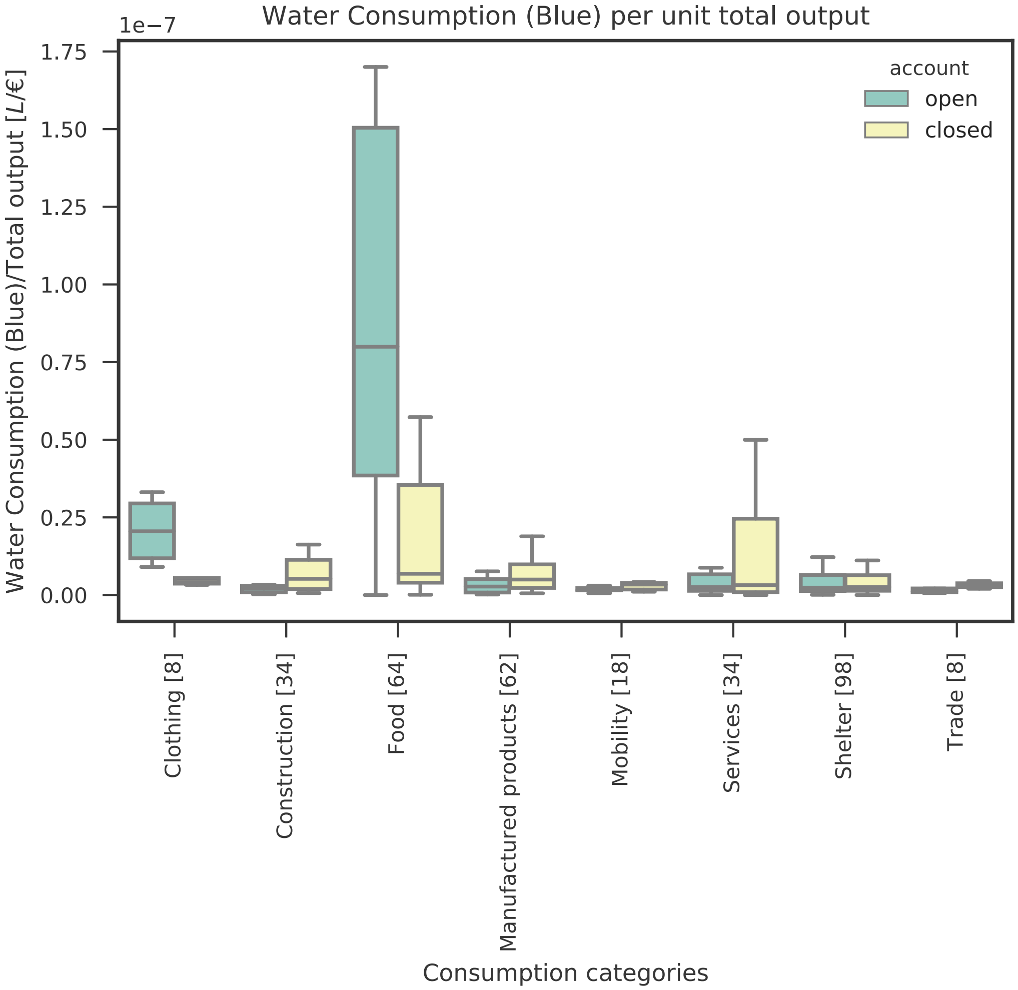
c


Land Use per unit total output
Land Use/Total output [m^2/€]
0.000012
0.000010
0.000008
0.000006
0.000004
0.000002
0.000000
account
open
closed
Clothing [8]
Construction [34]
Food [64]
Manufactured products [62]
Mobility [18]
Services [34]
Shelter [98]
Trade [8]
Consumption categories

d


Land Use per unit total output
account
open
closed
Land Use/Total output [m^2/€]
0.000012
0.000010
0.000008
0.000006
0.000004
0.000002
0.000000
Clothing [8]
Computer technology and R&D [4]
Construction [34]
FIRE [8]
Food [64]
Manufactured products [62]
Mobility [18]
Other services [22]
Shelter [98]
Trade [8]
Consumption categories

e


Water Consumption (Blue) per unit total output
1e−7
Water Consumption (Blue)/Total output [L/€]
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
account
open
closed
Clothing [8]
Construction [34]
Food [64]
Manufactured products [62]
Mobility [18]
Services [34]
Shelter [98]
Trade [8]
Consumption categories

f

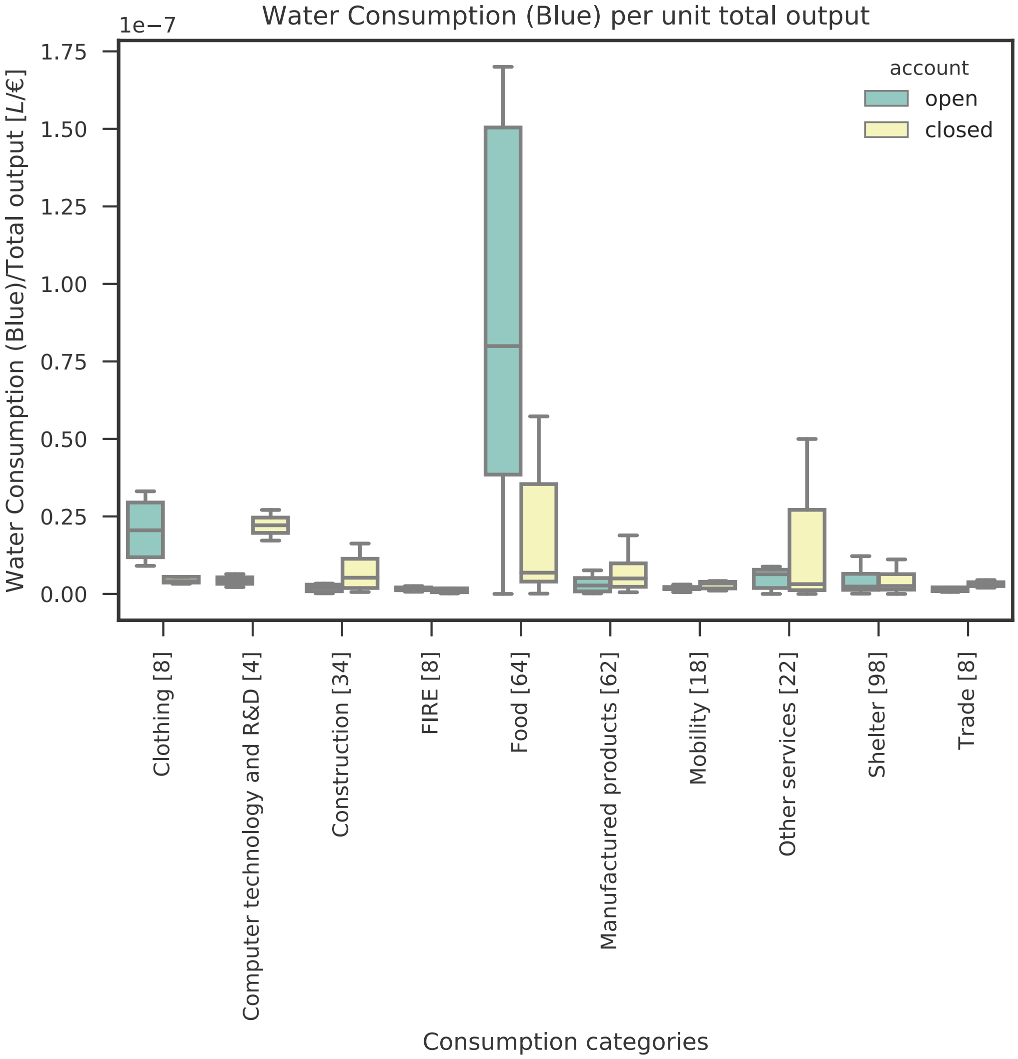
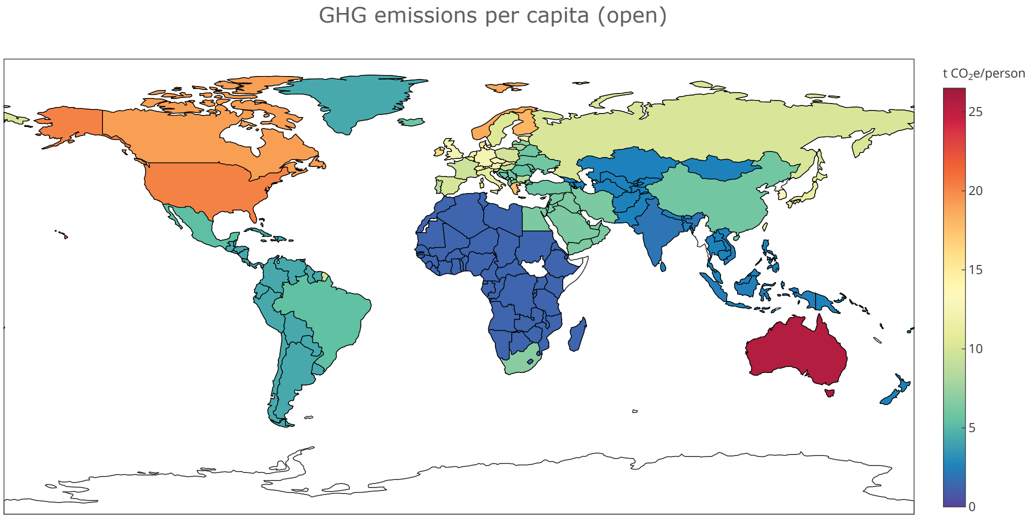
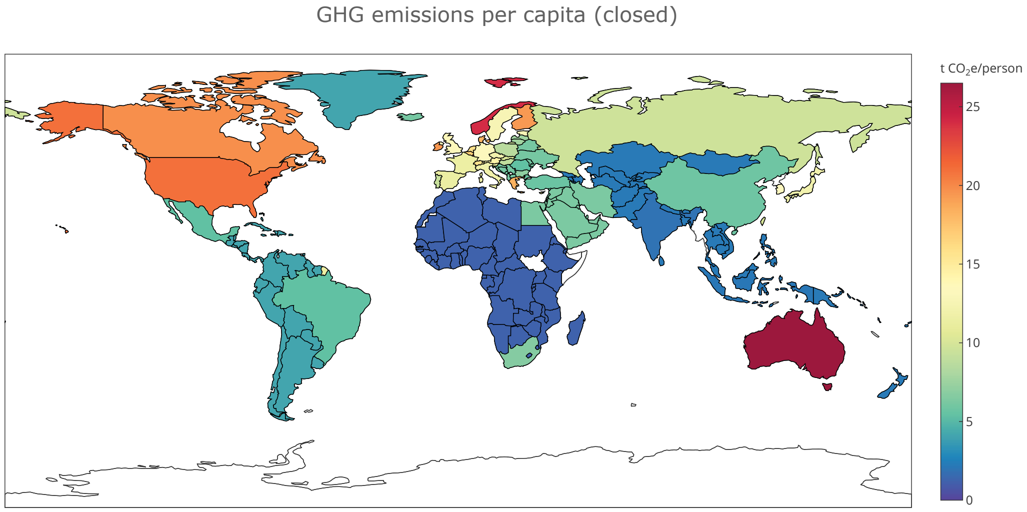


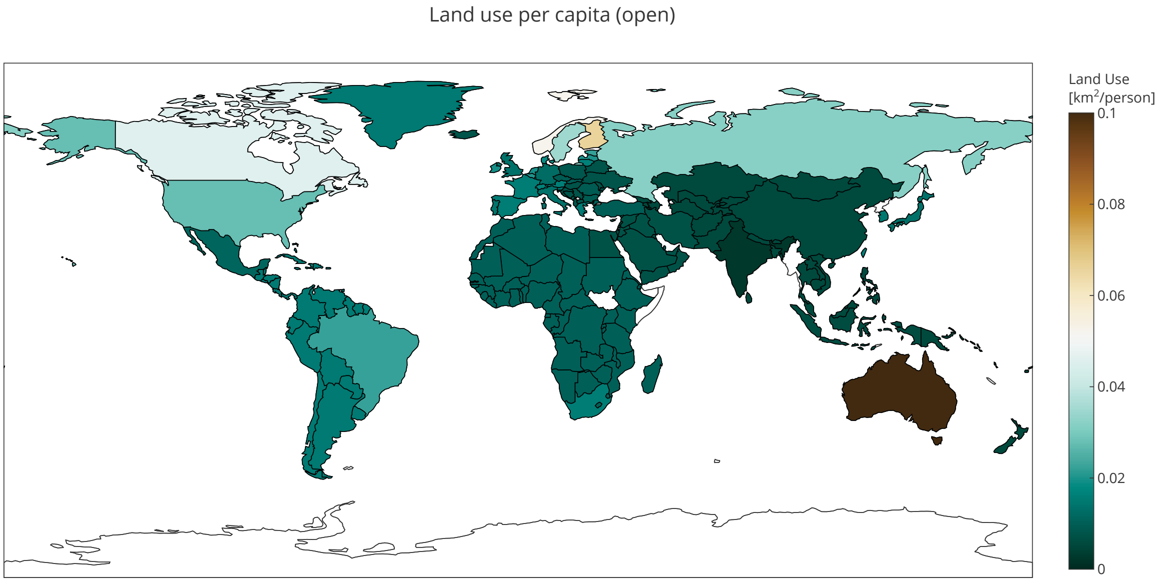
Figure S3.3 Box plots with open and closed models for each impact for Consumption Categories with Services and disaggregated Services. Using the same data as presented in Figs. 2 and S2, now displayed with open and closed models as adjacent box plots for each impact. Sample sizes are included in square brackets. Whiskers show maximum and minimum values within 1.5 IQR of the 75th and 25th percentiles. Outliers have been omitted for legibility.


GHG emissions per capita (open)
t CO₂e/person
25
20
15
10
5
0

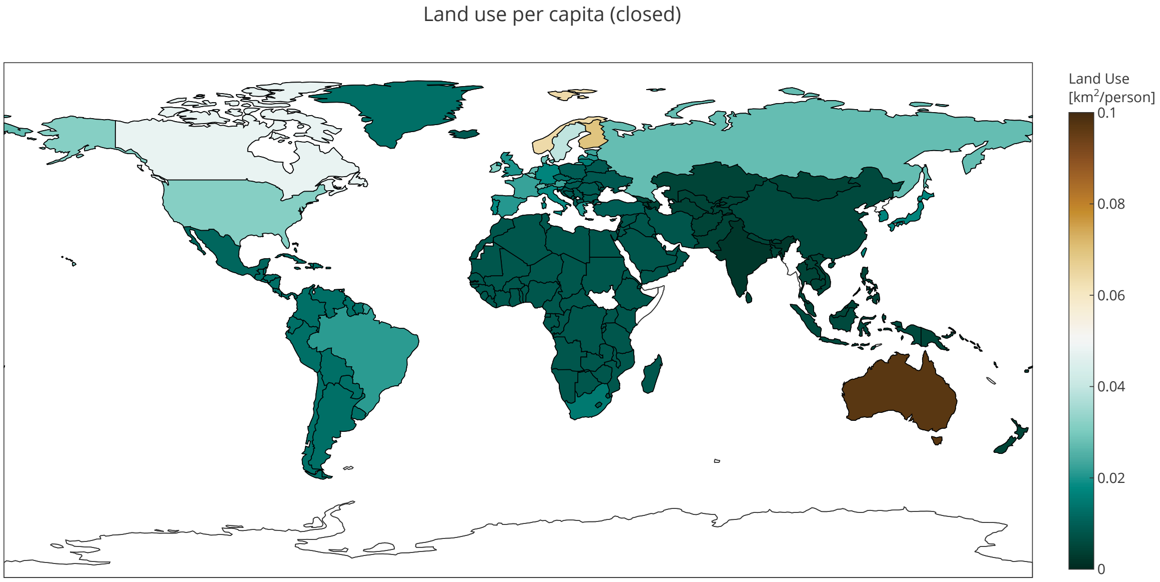
a


GHG emissions per capita (closed)
t CO₂e/person
25
20
15
10
5
0

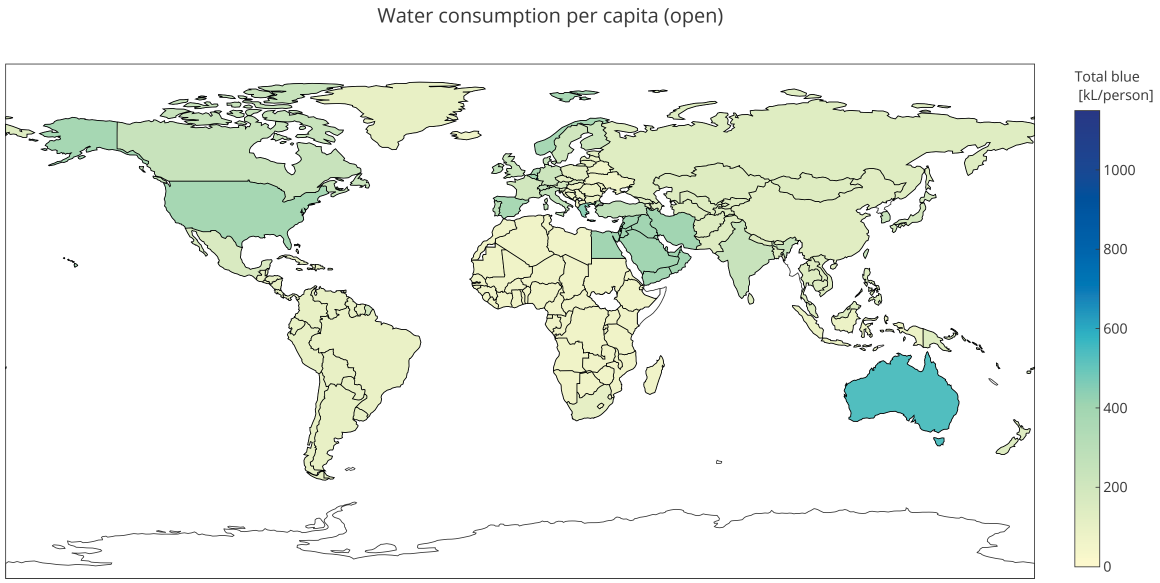
b


Land use per capita (open)
Land Use
[km2/person]
0.1
0.08
0.06
0.04
0.02
0

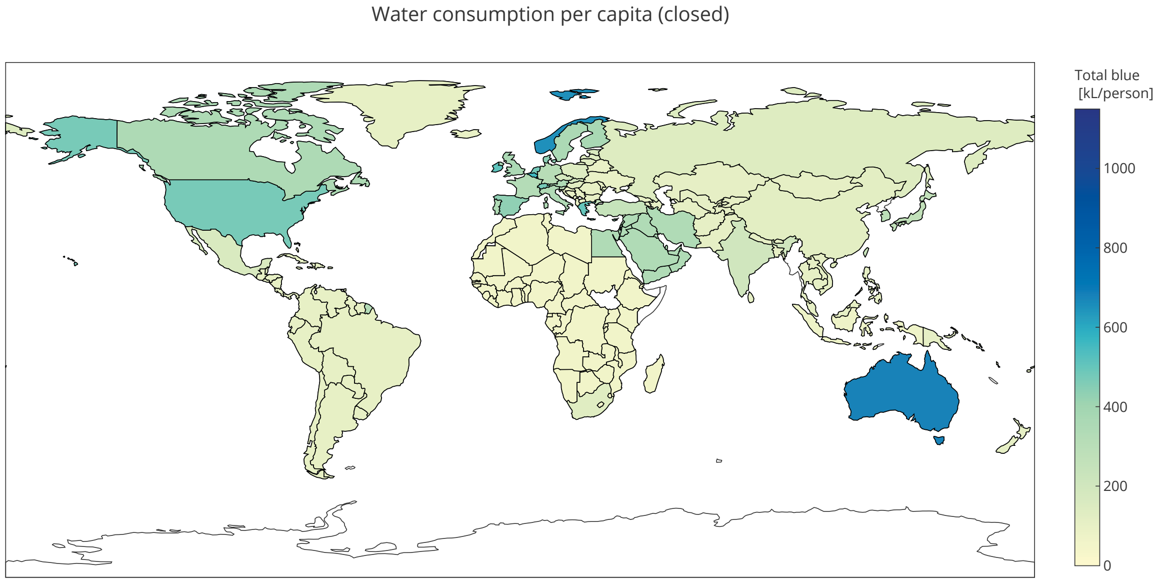
c


Land use per capita (closed)
Land Use
[km2/person]
0.1
0.08
0.06
0.04
0.02
0

d



e



f

Fig. S3.4 Choropleths for open and closed model per capita impacts, for GHG emissions (a, b), land use (c, d), and water consumption (e, f).

Supplementary Methods

Detailed explanation of closing the model

This section explains in detail the approach of endogenizing labour in an environmentally extended multi-regional input–output (EE-MRIO) model, referred to as "closing" the model with respect to labour.

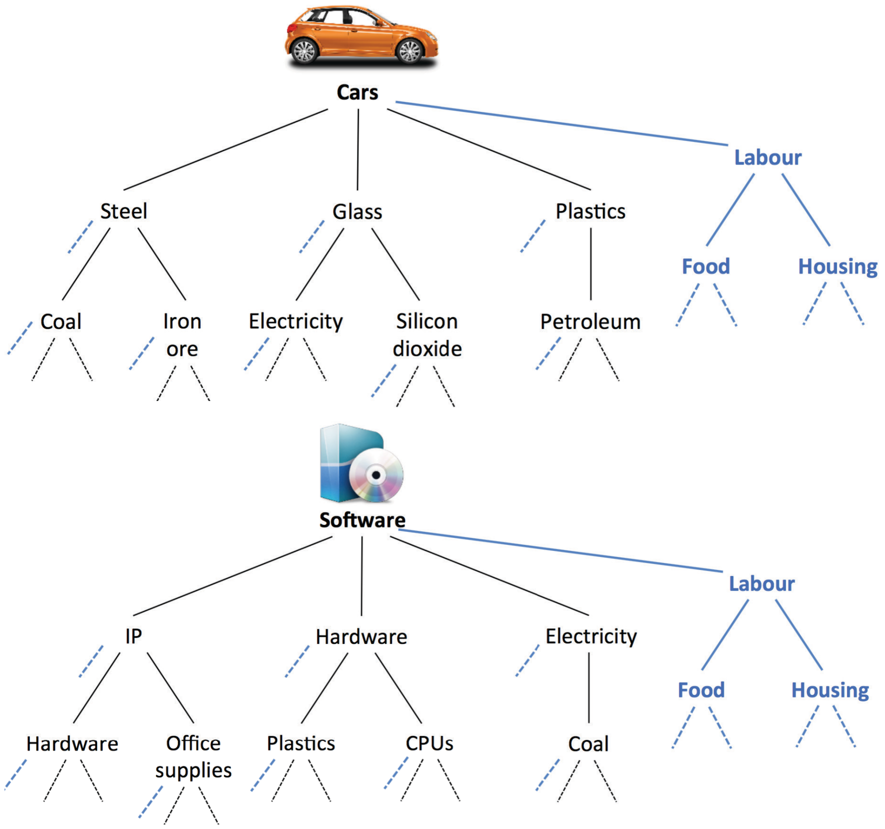


Figure S3.5 Simplified diagram showing the addition of labour to the supply chain for two example industries.

Conceptually, closing the model with respect to labour means treating labour as an input to production and part of global supply chains. For example, car manufacturing (Fig. S3.5) typically requires material inputs of steel, glass, and plastic components, among other inputs. Each of these inputs has their own subsequent inputs. Input–Output (IO) analysis allows for the integration of the entirety of the supply chain, though labour is not conventionally included in IO analysis. Here we add labour as its own input for each industry with its own chain of attendant inputs. After this modification, normal demand-pull manipulations utilizing the Leontief inverse matrix result in consumption-based accounts for the total output of each industry.

Here we outline our modifications of the base MRIO model to close it with respect to labour (formally represented in the model as employed persons). Note that the composition of household consumption in each country is treated as homogeneous (as with all MRIO). Also note that we have selected the EXIOBASE industry-by-industry (*ixi*) account in place of the product-by-product (*pxp*) version (the former classifies transactions by industry of origin and destination, and the latter in terms of goods and services).

		buying sector				
selling sector	1	$\cdots$	j	$\cdots$	n	*Households* (Consumers)
1	z_{11}	$\cdots$	z_{1j}	$\cdots$	z_{1n}	$z_{1,n+1}$
$\vdots$	$\vdots$		$\vdots$		$\vdots$	$\vdots$
i	z_{i1}	$\cdots$	z_{ij}	$\cdots$	z_{in}	$z_{i,n+1}$
$\vdots$			$\vdots$		$\vdots$	$\vdots$
n	z_{n1}	$\cdots$	z_{nj}	$\cdots$	z_{nn}	$Z_{n,n+1}$
Households (Labour)	$z_{n+1,1}$	$\cdots$	$z_{n+1,j}$	$\cdots$	$z_{n+1,n}$	$z_{n+1,n+1}$

Figure S3.6 Input–output table of inter-industry flows with households endogenous (adapted from ref.[197]).

Figure S3.6 shows a single region IO table with an expanded transaction matrix. The *n+1* row contains the wages paid to each sector while the *n+1* column contains the final demand of households (where *n* is the number of countries *x* industries). The total output vector and technical coefficient matrix are calculated in the normal way after the closing the transaction matrix *Z* (refer to ref.[197] for a detailed explanation of closed-IO manipulations).

The final demand matrix *Y*, contains final demands for households, government, non-government institutions, etc. We remove the final demand for households and append this to *Z*, making household consumption endogenous to the model. Wages are taken from the MRIO factor inputs data and split into row vectors where wages along the block diagonal represent the compensation of employees of each industry within a country. Wages off the block diagonal are set to zero by default (Fig. S3.7). Values in the *n+1*, *n+1* entries are removed (set to zero) to avoid double counting (these exchanges are already represented in *Z* as compensation of labour of private households).

$$\begin{matrix}
z^{11}_{11} & \cdots & z^{11}_{1n} & z^{11}_{1,n+1} & z^{12}_{11} & \cdots & z^{12}_{1n} & z^{12}_{1,n+1} \\
\vdots & & \vdots & \vdots & \vdots & & \vdots & \vdots \\
z^{11}_{n1} & \cdots & z^{11}_{nn} & z^{11}_{n,n+1} & z^{12}_{n1} & \cdots & z^{12}_{nn} & z^{12}_{n,n+1} \\
z^{11}_{n+1,1} & \cdots & z^{11}_{n+1,n} & z^{11}_{n+1,n+1} & z^{12}_{n+1,1} & \cdots & z^{12}_{n+1,n} & z^{12}_{n+1,n+1} \\
z^{21}_{11} & \cdots & z^{21}_{1n} & z^{21}_{1,n+1} & z^{22}_{11} & \cdots & z^{22}_{1n} & z^{22}_{1,n+1} \\
\vdots & & \vdots & \vdots & \vdots & & \vdots & \vdots \\
z^{21}_{n1} & \cdots & z^{21}_{nn} & z^{21}_{n,n+1} & z^{22}_{n1} & \cdots & z^{22}_{nn} & z^{22}_{n,n+1} \\
z^{21}_{n+1,1} & \cdots & z^{21}_{n+1,n} & z^{21}_{n+1,n+1} & z^{22}_{n+1,1} & \cdots & z^{22}_{n+1,n} & z^{22}_{n+1,n+1}
\end{matrix}$$

Figure S3.7 Multiregional input–output table for two countries.

The superscript index in Fig. S3.7 indicates the countries in question, specifically indicating the trade flows between countries. Countries along the block diagonal (*i=j*) represent intra-national flows while off-diagonal countries represent international flows. For example, superscript index *21* contains the flows from country *1* to *2*.

$$\begin{matrix}
z^{11}_{11} & \cdots & z^{11}_{1n} & z^{11}_{1,n+1} & z^{12}_{11} & \cdots & z^{12}_{1n} & z^{12}_{1,n+1} \\
\vdots & & \vdots & \vdots & \vdots & & \vdots & \vdots \\
z^{11}_{n1} & \cdots & z^{11}_{nn} & z^{11}_{n,n+1} & z^{12}_{n1} & \cdots & z^{12}_{nn} & z^{12}_{n,n+1} \\
z^{11}_{n+1,1} & \cdots & z^{11}_{n+1,n} & 0 & 0 & \cdots & 0 & 0 \\
z^{21}_{11} & \cdots & z^{21}_{1n} & z^{21}_{1,n+1} & z^{22}_{11} & \cdots & z^{22}_{1n} & z^{22}_{1,n+1} \\
\vdots & & \vdots & \vdots & \vdots & & \vdots & \vdots \\
z^{21}_{n1} & \cdots & z^{21}_{nn} & z^{21}_{n,n+1} & z^{22}_{n1} & \cdots & z^{22}_{nn} & z^{22}_{n,n+1} \\
0 & \cdots & 0 & 0 & z^{22}_{n+1,1} & \cdots & z^{22}_{n+1,n} & 0
\end{matrix}$$

Figure S3.8 Multiregional input–output table for two countries, with superfluous entries removed and set to zero.

Note that wages in the *n+1* rows of each country in Fig. S3.8 are only defined and contain non-zero entries along the block diagonal. This convention signifies that wages are only paid domestically to employees, and any international payments to employees would be represented as domestic payment. The *n+1* row entries off the block diagonal are therefore set to zero.