Appendix A – Role of Negative Emissions Technologies

Virtually all of the 2°C scenarios within the IPCC's database include negative emissions technologies removing several hundred billion tonnes of carbon dioxide directly from the atmosphere across, and beyond, the century (Anderson, 2015). However, there is wide recognition that the efficacy and global rollout of such technologies are highly speculative, with a non-trivial risk of failing to deliver at, or even approaching, the scales typically assumed in the models.

Whilst the authors of this paper are supportive of funding further research, development and, potentially, deployment of NETs, the assumption that they will significantly extend the carbon budgets is a serious moral hazard (Anderson & Peters, 2016). Ultimately, if there is genuine action to mitigate emissions in line with a "likely" chance of staying below 2°C, and NETs do prove to be a viable and scalable option, then, in theory at least, an opportunity arises for holding the temperature rise to 1.5°C. By contrast, if action to mitigate for 2°C is undermined by the prospect of NETs, and such technologies subsequently prove not to be scalable, then we will have bequeathed a 3°C, 4°C or higher legacy. As is clear from the 2°C scenarios submitted to the IPCC, the inclusion of carbon capture and storage (CCS) and biomass energy with carbon capture and storage (BECCS) include considerably more fossil fuel combustion than those without them (Figure 1). It is evident, that mitigation advice to government is already being influenced by assumptions about NETs, and indeed the rapid uptake of CCS, neither of which shows any sign of approaching the scales of rollout in the models.

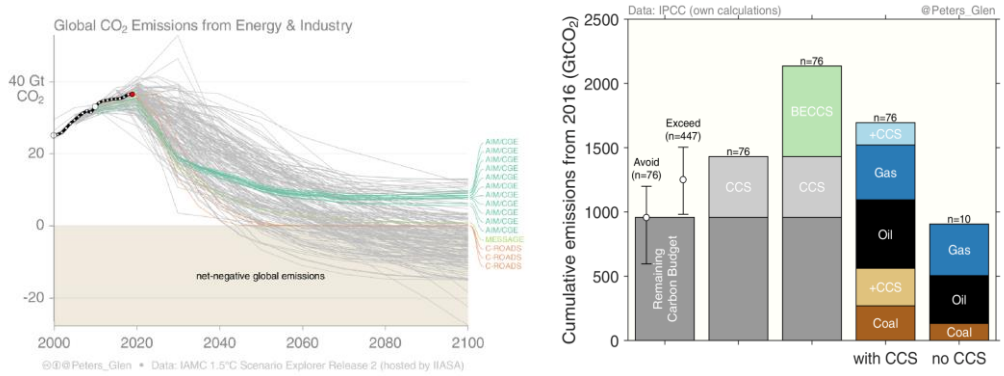

Figure 1 Emissions pathways based on the IPCC SR15 scenarios database, a) illustrate the extent of net-negative global emissions and very small number without CCS deployment (coloured lines) and b) how the inclusion of CCS and BECCS result in much more fossil fuel use (Reproduced from Peters & Sognnæs, 2019 CC-BY-NC-ND-4.0)

The coming together of the IPCC's carbon budgets with the Paris temperature commitments has catalysed considerable activity within the mitigation community. This is exemplified in Rockström et al. (2017) where they capture the spirit of the time in coining the *"carbon law"* as a heuristic guide to mitigation policy. However, they also embrace highly speculative BECCS, to extract many hundreds of billions of tonnes of carbon dioxide directly from the atmosphere across and beyond the 21st century. According to their analysis, untested BECCS is set to deliver the equivalent of 40-60% of today's total global energy use and a rate of removal of CO_2 greater than that currently absorbed by all the world's oceans.

Reliance on future technical options could provide interesting outliers to suites of more grounded mitigation scenarios. Instead, invoking BECCS (the NET of choice in virtually all models) as a technique for expanding the available carbon budget is ubiquitous across the IPCC's range of 2°C scenarios. This preference for future and highly speculative technologies over actual mitigation today emerges from the economic core of the 'integrated assessment models' (IAMs) that dominate the IPCC's mitigation work. By applying even a small discount rate, the

hypothetical costs of speculative technologies in the distant future consistently undercuts the real costs of meaningful mitigation today. Consequently, these models typically tune their outputs, implicitly, towards narratives that avoid mitigation not amenable to a technical fix.

Across the IAM scenarios this systemic preference for future and highly *uncertain* negative emissions extending carbon budgets is in contrast to the exclusion of those similarly *uncertain* positive carbon cycle feedbacks anticipated to reduce the available carbon budgets. Moving away from heavily discounted technical scenarios reliant on speculative technologies, opens up space to consider alternative routes for delivering rapid and deep mitigation. Such scenarios align more with the broad church of contextual political economy and even moral philosophy than the highly mathematical and non-contextual economics that dominates the IAMs.

Certainly, prolonged mitigation rates of over 10% per year will demand levels of political, social and technical innovation with few historical precedents (Hickel & Kallis, 2019). Nevertheless, if the Paris 2°C commitment is to transcend the rarefied world frequented by non-contextual economists and technophiles, it is such scales of whole-system innovation that is now called for.

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Appendix B – Cement

The difference in the cement intensity between societies with widespread and "mature" infrastructure and those rapidly constructing such infrastructure is evident when comparing, for example, the EU with China. For 2017, the former consumed around 330kg/capita of cement, with official estimates for the latter being over five times higher at nearer 1670kg/capita. Much higher figures still were evident during the boom years of some Middle East countries (Davidson, 2014), but other rapidly industrialising nations have had more moderate cement use with South Korea around 1010kg/capita, Vietnam 825kg/capita, and Malaysia 595kg/capita in 2017(US Geological Survey 2019, World Bank 2019).

At a global level, the volume of concrete use exceeds that of all other manufactured material, with the production of cement, a key ingredient, reaching 4.1 billion tonnes in 2017 (US Geological Survey, 2019). This production emitted around 8% of global carbon dioxide emissions, arising from both energy use and chemical processes (Lehne & Preston, 2018). In 2017 cement process emissions were 1.48 GtCO2 (Global Carbon Atlas, 2019), the equivalent of 4.3% of all emissions from direct global energy use. Even within the very conservative growth rates assumed in the International Energy Agency's (IEA) Cement Technology Roadmap vision aligned with their 2 degree Celsius scenario (2DS), cement production is set to continue to rise, reaching around 4.7 billion tonnes by 2050 (Table 2, IEA, 2018). This modest increase of 15% over 23 years equates to an annual average growth of around 0.4%, which is an order of magnitude lower than anything witnessed since the 1950s. Between 1950 and 2000, global cement production grew at 5.5% p.a., holding steady from 2000 to 2018 at 5.1%. Only since 2010 has any real period of reduced growth occurred, and even here it has still averaged 3.4% p.a. (US Geological Survey, 2014).

The IEA's 2DS scenario (IEA, 2018) is dependent on a major break from the historical precedent of cement as the core manufactured material in the industrialisation of rapidly 'developing' nations. Despite this, the scenario pushes technologies toward their currently understood limit, with process emissions remaining the stubborn residue. The assumption adopted here is that between 2050 and 2075 process emissions will be eliminated. This could come about through a combination of factors: from substitute feedstocks that eliminate process emissions and reductions in demand for cement as global infrastructure development matures, through to alternatives to cement becoming available, or carbon capture and storage (CCS) technologies deployed to remove process emissions at source.

Applying CCS to the rich CO2 stream from cement manufacture is a much simpler, cheaper and more efficient proposition than capturing CO2 from fossil fuel plants, where separation of CO2 from nitrogen in the flue gases along with upstream emissions of fuel extraction still impose a significant emissions burden, anticipated to be 100-200 gCO2/kWh (Gibon, T. et al., 2017). For cement, capturing process CO2 requires little more than separating the calcination of the limestone from the products of combustion providing the heat (~900 °C) for the calcination to occur. At the time of writing, a pilot plant designed to do exactly this is nearing completion in Belgium, and in terms of separation involves little more than an annular heat exchanger (Hills, T. et al., 2017).

Figure 1 is a modified version of the IEA 2DS scenario, with the process emissions eliminated by 2075.

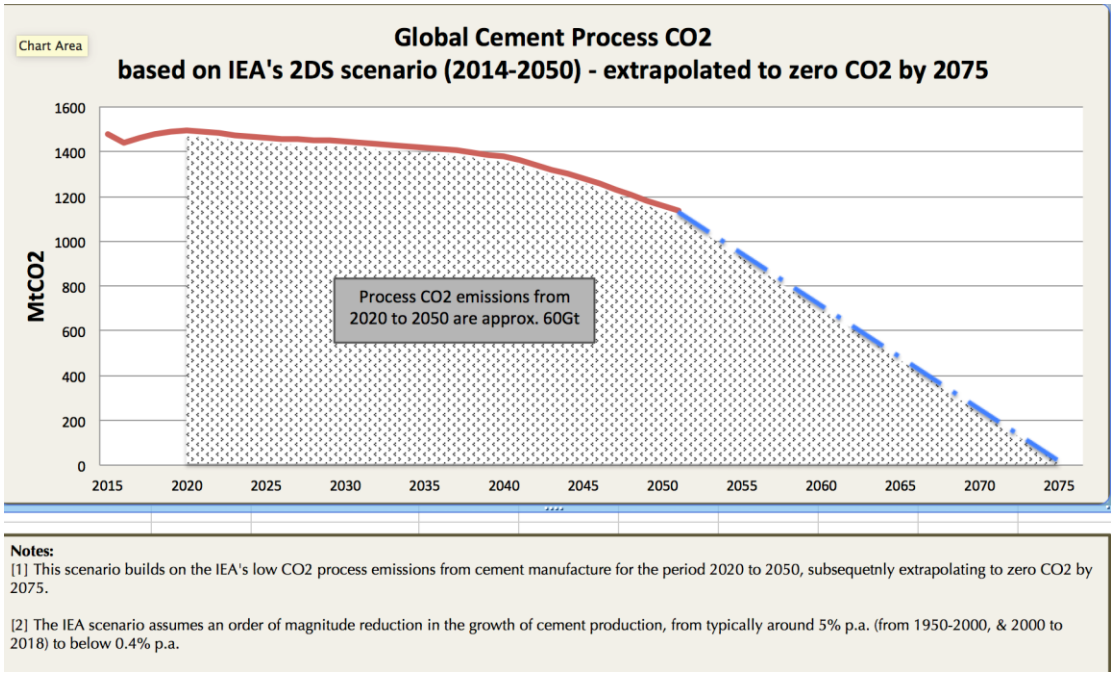

Figure 1 Global cement process carbon dioxide scenario

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Appendix C – Country Grouping

In the first pair of adjusted classifications, the 'developing' nations group (hereafter referred to as DG1) comprises the 'G77 and China' as well as all other non-Annex 1 nations with the exception of South Korea, Israel, Andorra and San Marino, all of whom have a Human Development Index (HDI) and a GDP per capita (PPP basis) very close to or above the Annex 1 mean. Ukraine is moved from its usual Annex 1 classification into DG1 as its HDI and PPP per capita are well below all other Annex 1 countries, and indeed well below many non-Annex 1 nations. This still leaves unclassified the eighteen nations not party to the UNFCCC. For completeness and based on a combined weighting of their HDI and PPP, nine of these are allocated to DG1 with the remaining nine to the 'developed' nations group (henceforth DD1). Between the eighteen nations not party to the UNFCCC, the emissions of Taiwan and Hong Kong dominate, and with both having high HDI and PPP values, are subsequently included within the DD1 grouping.

The second pair of classifications (DG2 and DD2) is identical to DG1 and DD1, but with one important distinction. The G77 grouping includes seven wealthy Middle East nations and Singapore, all with very high PPP values and relatively high HDIs. In the DG2/DD2 classification these countries are classified as 'developed country Parties' (i.e. belonging to DD2).

Table 1 lists all countries of the world that have carbon emissions data available (based on the Global Carbon Project, 2018) as well as their classification as either developed (DD) or developing (DG) country Parties. There are eight countries that are classified as developing in the first pair of adjusted classifications and developed in the second, hence belonging to DG1 as well as DD2. The adjusted classifications mirror UNFCCC protocol, with the exception of those few countries whose GDP per capita (PPP basis), as the principal indicator, and level of development (as measured in HDI), as a secondary indicator, merit their re-classification. Classifications based on UNFCCC terminology (Annex-1 & Non-Annex 1; G77+China; and LDC) are also listed in Table 1, as are each country's GDP per Capita (PPP basis) and HDI.

Table 1: Country classifications as developing (DG) and developed (DD) country Parties.

	Developing or Developed	**UNFCCC classification**	**G77+ China**	**LDC**	**GDP per capita 2017, PPP (current international $)**	**Source if not World Bank (2019)**	**HDI 2017**	**Source if not UNDP (2019)**
Belarus	DD	Annex 1			18837		0,808	
Bulgaria	DD	Annex 1			20948		0,813	
Russian Federation	DD	Annex 1			25533		0,816	
Croatia	DD	Annex 1			26288		0,831	
Turkey	DD	Annex 1			26519		0,791	
Romania	DD	Annex 1			26657		0,811	
Greece	DD	Annex 1			27602		0,87	
Hungary	DD	Annex 1			28108		0,838	
Latvia	DD	Annex 1			28199		0,847	
Poland	DD	Annex 1			29122		0,865	
Slovak Republic	DD	Annex 1			31616		0,855	

Portugal	DD	Annex 1			31673		0,847	
Estonia	DD	Annex 1			31742		0,871	
Lithuania	DD	Annex 1			32998		0,858	
Cyprus	DD	Annex 1			34503		0,869	
Slovenia	DD	Annex 1			34868		0,896	
Czech Republic	DD	Annex 1			36327		0,888	
Spain	DD	Annex 1			37998		0,891	
Israel	DD	Non-Annex 1			38262		0,903	
Korea, Rep.	DD	Non-Annex 1			38335		0,903	
Italy	DD	Annex 1			39427		0,88	
Malta	DD	Annex 1			41034		0,878	
New Zealand	DD	Annex 1			41109		0,917	
France	DD	Annex 1			42850		0,901	
United Kingdom	DD	Annex 1			43269		0,922	
Japan	DD	Annex 1			43279		0,909	
Finland	DD	Annex 1			44866		0,92	
Canada	DD	Annex 1			46705		0,926	
Belgium	DD	Annex 1			47840		0,916	
Australia	DD	Annex 1			48460		0,939	
Sweden	DD	Annex 1			50208		0,933	
Germany	DD	Annex 1			50639		0,936	
Denmark	DD	Annex 1			51364		0,929	
Austria	DD	Annex 1			52398		0,908	
Netherlands	DD	Annex 1			52503		0,931	
Iceland	DD	Annex 1			53153		0,935	
Andorra	DD	Non-Annex 1			54576	(1) 2015 value	0,858	
United States	DD	Annex 1			59532		0,924	
Norway	DD	Annex 1			61414		0,953	
San Marino	DD	Non-Annex 1			63414		0,961	6)
Switzerland	DD	Annex 1			64712		0,944	
Ireland	DD	Annex 1			75648		0,938	
Luxembourg	DD	Annex 1			103745		0,904	
Monaco	DD	Annex 1			123579	(1) 2015 value	0,956	6)
Liechtenstein	DD	Annex 1			189176	(1) 2009 value	0,916	
Somalia	DG	Non-Annex 1	G77	LDC	547	(2) 2010 value	0,364	6)
Central African Republic	DG	Non-Annex 1	G77	LDC	726		0,367	
Burundi	DG	Non-Annex 1	G77	LDC	734		0,417	
Congo, Dem. Rep.	DG	Non-Annex 1	G77	LDC	887		0,457	
Niger	DG	Non-Annex 1	G77	LDC	1017		0,354	
Malawi	DG	Non-Annex 1	G77	LDC	1202		0,477	
Mozambique	DG	Non-Annex 1	G77	LDC	1248		0,437	
Liberia	DG	Non-Annex 1	G77	LDC	1283		0,435	
Sierra Leone	DG	Non-Annex 1	G77	LDC	1527		0,419	

Madagascar	DG	Non-Annex 1	G77	LDC	1555		0,519	
Eritrea	DG	Non-Annex 1	G77	LDC	1585	(3)	0,44	
South Sudan	DG	Non-Annex 1	G77	LDC	1590	(3)	0,388	
Togo	DG	Non-Annex 1	G77	LDC	1660		0,503	
Gambia, The	DG	Non-Annex 1	G77	LDC	1696		0,46	
Korea, Dem. People's Rep.	DG	Non-Annex 1	G77		1700	(1) 2015 value	0,733	(6)
Guinea-Bissau	DG	Non-Annex 1	G77	LDC	1700		0,455	
Haiti	DG	Non-Annex 1	G77	LDC	1815		0,498	
Burkina Faso	DG	Non-Annex 1	G77	LDC	1862		0,423	
Uganda	DG	Non-Annex 1	G77	LDC	1864		0,516	
Ethiopia	DG	Non-Annex 1	G77	LDC	1899		0,463	
Chad	DG	Non-Annex 1	G77	LDC	1941		0,404	
Afghanistan	DG	Non-Annex 1	G77	LDC	1972		0,498	
Rwanda	DG	Non-Annex 1	G77	LDC	2039		0,524	
Kiribati	DG	Non-Annex 1	G77	LDC	2180		0,612	
Mali	DG	Non-Annex 1	G77	LDC	2214		0,427	
Guinea	DG	Non-Annex 1	G77	LDC	2242		0,459	
Benin	DG	Non-Annex 1	G77	LDC	2272		0,515	
Solomon Islands	DG	Non-Annex 1	G77	LDC	2422		0,546	
Zimbabwe	DG	Non-Annex 1	G77		2429		0,535	
State of Palestine	DG	Non-Annex 1	G77		2465	(2) 2005 value	0,686	
Yemen, Rep.	DG	Non-Annex 1	G77	LDC	2601		0,452	
Nepal	DG	Non-Annex 1	G77	LDC	2697		0,574	
Comoros	DG	Non-Annex 1	G77	LDC	2745		0,503	
Syrian Arab Republic	DG	Non-Annex 1	G77		2900	(1) 2015 value	0,536	
Lesotho	DG	Non-Annex 1	G77	LDC	2926		0,52	
Tanzania	DG	Non-Annex 1	G77	LDC	2946		0,538	
Tajikistan	DG	Non-Annex 1	G77		3195		0,65	
Vanuatu	DG	Non-Annex 1	G77	LDC	3208		0,603	
Kenya	DG	Non-Annex 1	G77		3285		0,59	
Sao Tome and Principe	DG	Non-Annex 1	G77	LDC	3351		0,589	
Senegal	DG	Non-Annex 1	G77	LDC	3450		0,505	
Djibouti	DG	Non-Annex 1	G77	LDC	3567	(3)	0,476	
Micronesia, Fed. Sts.	DG	Non-Annex 1	G77		3693		0,627	
Cameroon	DG	Non-Annex 1	G77		3715		0,556	
Kyrgyz Republic	DG	Non-Annex 1			3726		0,672	
Bangladesh	DG	Non-Annex 1	G77	LDC	3869		0,608	
Tuvalu	DG	Non-Annex 1		LDC	3925		0,711	(6)
Cote d'Ivoire	DG	Non-Annex 1	G77		3936		0,492	
Mauritania	DG	Non-Annex 1	G77	LDC	3950		0,52	
Cambodia	DG	Non-Annex 1	G77	LDC	4009		0,582	
Zambia	DG	Non-Annex 1	G77	LDC	4024		0,588	

Papua New Guinea	DG	Non-Annex 1	G77		4199		0,544	
Marshall Islands	DG	Non-Annex 1	G77		4238		0,708	
Ghana	DG	Non-Annex 1	G77		4492		0,592	
Sudan	DG	Non-Annex 1	G77	LDC	4904		0,502	
Honduras	DG	Non-Annex 1	G77		4986		0,617	
Congo, Rep.	DG	Non-Annex 1	G77		5443		0,606	
Pakistan	DG	Non-Annex 1	G77		5527		0,562	
Moldova	DG	Non-Annex 1			5698		0,7	
Nieu	DG	Non-Annex 1			5800	(4) 2004 value	0,794	(6)
Nicaragua	DG	Non-Annex 1	G77		5842		0,658	
Nigeria	DG	Non-Annex 1	G77		5875		0,532	
Tonga	DG	Non-Annex 1	G77		5957		0,726	
Myanmar	DG	Non-Annex 1	G77	LDC	6161		0,578	
Samoa	DG	Non-Annex 1	G77		6627		0,713	
Angola	DG	Non-Annex 1	G77	LDC	6644		0,581	
Vietnam	DG	Non-Annex 1	G77		6776		0,694	
Uzbekistan	DG	Non-Annex 1			6865		0,71	
Cabo Verde	DG	Non-Annex 1	G77		6898		0,654	
Lao PDR	DG	Non-Annex 1	G77	LDC	7023		0,601	
India	DG	Non-Annex 1	G77		7059		0,64	
Timor-Leste	DG	Non-Annex 1	G77	LDC	7213		0,625	
Bolivia	DG	Non-Annex 1	G77		7560		0,693	
El Salvador	DG	Non-Annex 1	G77		8006		0,674	
Guatemala	DG	Non-Annex 1	G77		8150		0,65	
Guyana	DG	Non-Annex 1	G77		8163		0,654	
Morocco	DG	Non-Annex 1	G77		8217		0,667	
Philippines	DG	Non-Annex 1	G77		8343		0,699	
Belize	DG	Non-Annex 1	G77		8507		0,708	
Eswatini	DG	Non-Annex 1	G77		8641		0,588	
Ukraine	DG	Annex 1			8667		0,751	
Jamaica	DG	Non-Annex 1	G77		9046		0,732	
Jordan	DG	Non-Annex 1	G77		9153		0,735	
Bhutan	DG	Non-Annex 1	G77	LDC	9372		0,612	
Fiji	DG	Non-Annex 1	G77		9555		0,741	
Armenia	DG	Non-Annex 1			9647		0,755	
Dominica	DG	Non-Annex 1	G77		10016		0,715	
Namibia	DG	Non-Annex 1	G77		10449		0,647	
Georgia	DG	Non-Annex 1			10683		0,78	
Egypt, Arab Rep.	DG	Non-Annex 1	G77		11584		0,696	
Ecuador	DG	Non-Annex 1	G77		11587		0,752	
St. Vincent & the Grenadines	DG	Non-Annex 1	G77		11744		0,723	
Tunisia	DG	Non-Annex 1	G77		11911		0,735	
Indonesia	DG	Non-Annex 1	G77		12284		0,694	

Venezuela, RB	DG	Non-Annex 1	G77		12514	(3)	0,761	
Sri Lanka	DG	Non-Annex 1	G77		12835		0,77	
Mongolia	DG	Non-Annex 1	G77		12918		0,741	
Albania	DG	Non-Annex 1			12943		0,785	
Cuba	DG	Non-Annex 1	G77		13028	(1) 2016 value	0,777	
Paraguay	DG	Non-Annex 1	G77		13082		0,702	
Bosnia and Herzegovina	DG	Non-Annex 1	G77		13108		0,768	
Peru	DG	Non-Annex 1	G77		13434		0,75	
South Africa	DG	Non-Annex 1	G77		13498		0,699	
St. Lucia	DG	Non-Annex 1	G77		13956		0,747	
Nauru	DG	Non-Annex 1	G77		14158		0,721	(6)
Colombia	DG	Non-Annex 1	G77		14473		0,747	
Lebanon	DG	Non-Annex 1	G77		14482		0,757	
Palau	DG	Non-Annex 1			14823		0,798	
Grenada	DG	Non-Annex 1	G77		15124		0,772	
Suriname	DG	Non-Annex 1	G77		15159		0,72	
Algeria	DG	Non-Annex 1	G77		15260		0,754	
Macedonia, FYR	DG	Non-Annex 1			15290		0,757	
Serbia	DG	Non-Annex 1			15429		0,787	
Brazil	DG	Non-Annex 1	G77		15484		0,759	
Dominican Republic	DG	Non-Annex 1	G77		16030		0,736	
Maldives	DG	Non-Annex 1	G77		16653		0,717	
Cook Islands	DG	Non-Annex 1			16700	(1) 2016 value	0,829	(6)
China	DG	Non-Annex 1	G77		16807		0,752	
Iraq	DG	Non-Annex 1	G77		16899		0,685	
Botswana	DG	Non-Annex 1	G77		16988		0,717	
Costa Rica	DG	Non-Annex 1	G77		17074		0,794	
Azerbaijan	DG	Non-Annex 1			17398		0,757	
Thailand	DG	Non-Annex 1	G77		17872		0,755	
Turkmenistan	DG	Non-Annex 1	G77		17993		0,706	
Gabon	DG	Non-Annex 1	G77		18075		0,702	
Mexico	DG	Non-Annex 1			18273		0,774	
Barbados	DG	Non-Annex 1	G77		18520		0,8	
Montenegro	DG	Non-Annex 1			19352		0,814	
Libya	DG	Non-Annex 1	G77		19631		0,706	
Argentina	DG	Non-Annex 1	G77		20785		0,825	
Iran, Islamic Rep.	DG	Non-Annex 1	G77		20841		0,798	
Mauritius	DG	Non-Annex 1	G77		22309		0,79	
Uruguay	DG	Non-Annex 1	G77		22562		0,804	
Antigua and Barbuda	DG	Non-Annex 1	G77		23472		0,78	
Equatorial Guinea	DG	Non-Annex 1	G77		24387		0,591	
Panama	DG	Non-Annex 1	G77		24469		0,789	
Chile	DG	Non-Annex 1	G77		24635		0,843	

Kazakhstan	DG	Non-Annex 1			26435		0,8	
St. Kitts and Nevis	DG	Non-Annex 1	G77		28576		0,778	
Seychelles	DG	Non-Annex 1	G77		29265		0,797	
Malaysia	DG	Non-Annex 1	G77		29449		0,802	
Bahamas, The	DG	Non-Annex 1	G77		30430		0,807	
Trinidad and Tobago	DG	Non-Annex 1	G77		31578		0,784	
Oman	DG1 & DD2	Non-Annex 1	G77		41675		0,821	
Bahrain	DG1 & DD2	Non-Annex 1	G77		47527		0,846	
Saudi Arabia	DG1 & DD2	Non-Annex 1	G77		53779		0,853	
Kuwait	DG1 & DD2	Non-Annex 1	G77		71943		0,803	
United Arab Emirates	DG1 & DD2	Non-Annex 1	G77		73878		0,863	
Brunei Darussalam	DG1 & DD2	Non-Annex 1	G77		78836		0,853	
Singapore	DG1 & DD2	Non-Annex 1	G77		93905		0,932	
Qatar	DG1 & DD2	Non-Annex 1	G77		128374		0,856	
Not Parties to UNFCCC								
Wallis and Futuna Islands	DG				5320	(1) 2004 value	0,763	(7)
St. Helena	DG				8822	(1) 2009 value	0,797	(6)
Anguilla	DG				13334	(1) 2008 value	0,865	(6)
French Polynesia	DG				18000	(1) 2015 value	0,737	(6)
Bonaire, St. Eustatius & Saba	DG				20000	(5)	-	-
Curacao	DG				20827	(1) 2004 value	-	-
New Caledonia	DG				32063	(1) 2015 value	0,789	(7)
Turks and Caicos Islands	DG				32732	(1) 2007 value	0,873	(6)
British Virgin Islands	DD				34200	(1)	0,945	(6)
Monsserat	DG				36696	(1) 2011 value	0,821	(6)
Aruba	DD				39409		0,908	(6)
Faroe Islands	DD				43434	(1) 2014 value	0,95	(6)
Greenland	DD				44221	(1) 2015 value	0,839	(8)
Taiwan	DD				50500	(1)	0,907	2017 value
Hong Kong SAR, China	DD				61540		0,933	2017 value
St. Pierre and Miquelon	DD				61874	(1) 2006 value	0,762	(7)
Bermuda	DD				102687	(1) 2016 value	0,981	(6)
Macao SAR, China	DD				115123		0,909	(9)

2017 PPP Data

All PPP data from World Bank unless otherwise noted.

World Bank https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD (Accessed March 10, 2019)

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2017 HDI Data

All HDI data from UNDP unless otherwise noted.

UNDP
http://hdr.undp.org/sites/default/files/2018_human_development_statistical_update.pdf.
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Appendix D – Swedish Pathway Details

Emissions covered under the EU Effort Sharing Regulation (ESR) approximate to all territorial emissions except those from energy-intensive industry, power and heat generation, all aviation and international shipping. The sub-goals of the Swedish climate policy framework addressing ESR emissions state that, compared to 1990 levels, territorial greenhouse gas emissions are to be 40% lower in 2020, 63% lower in 2030 and 75% lower in 2040. The climate policy framework further states that national transport emissions (not including domestic aviation) should be 70% lower than 2010 emissions by 2030 which corresponds to 69% lower than 1990 levels.

In their annual report from 2019 the Swedish Climate Policy Council conclude that Sweden's existing policies are failing to deliver the annual mitigation rates aligned with the targets set by the climate policy framework; emission reductions have been under 1% per annum for 2015-2017, rather than the 5-8% required (Klimatpolitiska rådet, 2019). The report further concludes that the annual report on progress by the government only partly fulfils the requirements for reporting, as set out by the climate law.

The current mandate of the Council is to assess whether the government's policies are in line with the Swedish long-term targets, not if these targets in themselves are in line with Paris and the latest scientific understanding of climate change. However, an assessment of the grounds and models on which the government builds its policies on is included in the mandate, opening up potential scope for the council to make a broader and more thorough assessment.

In the aligned pathway presented in the main body of the paper, linear emission pathways between the targets are assumed, following reports by the Swedish Climate Policy Council (Klimatpolitiska rådet, 2018 & 2019) and the most recent background report from the Environmental Protection Agency (Naturvårdsverket, 2019) informing the government's ongoing work of establishing a climate policy strategy. While steeper pathways with annual emission reductions are included in several reports by the Environmental Protection Agency (Naturvårdsverket, 2018 & 2019), and mentioned as an option in the latest report from the Climate Policy Council (Klimatpolitiska rådet, 2019), linear emissions pathways still dominate advice to government and are hence those assumed here.

For aviation, the Swedish Transport Administration's headline growth scenario assumes an 82% increase in passengers by 2040 (cf. 2015) (Trafikverket, 2016). Cumulative aviation emissions up until 2050 are approximated using an assumed annual sector growth rate of 2.4% and a fuel efficiency increase of 2% per annum in line with the International Aviation Transport Association's (IATA) target of 50% reductions in emissions by 2050 (cf. 2005). If Larsson et al.'s (2019) method is followed and emissions from domestic flights subtracted (based on data from the Swedish Environmental Protection Agency), total CO_2 emissions from Swedish residents' international air travel can be estimated to be 4,9 Mt CO_2 in 2017, growing to 5,8 Mt CO_2 in 2030. This is around 75% and 100% higher than CO_2 emissions from a bunker fuel basis that is included in the pathway in this paper, for 2017 and 2030 respectively.

For shipping, a linear mitigation path is assumed from 2020, reaching 50% reduction by 2050 (cf. 2008) in line with the International Maritime Organisation's (IMO) target. The Swedish Transport Administration's headline scenario suggests a 90% growth in the sector between 2012 and 2040. The Swedish Shipowners Association has adopted a goal of carbon neutrality by 2050 (Svensk Sjöfart, 2015), with recent discussions about moving it to 2045. However, with the prognosed sector growth above, extrapolated to 2050, this would require an increased carbon efficiency of 8% per annum or more. The IMO target combined with the same sector growth, implies an increased carbon efficiency of around 4% per annum in 2020, reaching 6% per annum in 2050, which are considered to be more likely rates of delivery.

The cement pathway is in line with ongoing multi-stakeholder discussions on mitigating industrial process-emissions in line with the Swedish net-zero 2045 target. (Svemin, 2018, Figure 8). For cement, this is assumed to be mainly through the development and deployment of carbon capture and storage (CCS) and carbon capture and use (CCU).

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