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# Biophysical and economic limits to negative $CO_2$ emissions

**Methods**

We describe the sources of information using in the analysis below; knowledge levels and uncertainties across the different NETs, and in terms of demand on land, water, nutrients, albedo, energy and costs differ greatly, but are sufficient to inform this comparative analysis. We have used all literature able to inform the analysis, irrespective of methodological approaches taken (e.g. attributional and consequential analyses are used as appropriate). Where possible, we have calculated impacts relative to counterfactual estimates (e.g. evaporative loss for BECCS and AR). Table S1 presents a summary of the data sources used to estimate per-t-C and global impact ranges, and provides a qualitative assessment of the relative confidence / uncertainty in the estimated ranges.

The net effect of NETs on radiative forcing depends on equilibrium effects in markets, and biophysical dynamic effects, subject only to general, or at least partial equilibrium models. Such models would *inter alia* specify changes in deployment of other technologies, as a result of NET deployment, and model the ensuing effects on water, land, nutrients, etc.[13,88,96]. The results of our study can be used as input values to global energy-system, climate and integrated assessment models that enable the investigation of dynamic effects.

***Impacts on land / GHG emissions, water, energy, nutrients, albedo and cost on a per-t-C removed from the atmosphere basis***

Estimates of impacts on land / GHG emissions, water, energy, nutrients, albedo and cost on a per-t-Ceq. removed from the atmosphere basis (as used shown in Figure 3) were derived as follows.

*Land / GHG emissions*: Annual net removals of carbon from the atmosphere per unit area (t Ceq./ ha/yr) were estimated as follows: DAC - Quantity of C removed per year by a reference DAC facility of 1 Mt $CO_2$ = 0.27 Mt C covering an area (including spacing and on-site compressor and regenerator)[15] of 150 ha; AR – assumes 500 $tCO_2$/ha = 136 tC/ha from forest regrowth over 40 years

**Table S1.** Data sources used to estimate per-t-C and global impact ranges of NETs. OC = own calculations; n/a = not applicable; Numbers refer to references from which data were drawn or used in own calculations; Colours are qualitative assessment of confidence / uncertainty in the estimated ranges where green = relatively high confidence / low uncertainty in the estimated range, red = relatively low confidence / high uncertainty in the estimated range, and orange = medium confidence / uncertainty in estimated range.

| NET | Per-t-C | | | | | | | Global estimates | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Negative emission | Land intensity | Energy | Water | Nutrients | Albedo | Cost | Negative emission | Land use | Energy | Water | Nutrients | Albedo | Cost |
| **BECCS** | OC, 58 | OC, 58 | OC, 15, 58, 118 | OC, 15, 56, 98, 113, 115, 116 | OC, 60, 88, 100, 101, 106 | 64 | 49, 57, 58, 70 | 10, 36, 45 | OC, 40, 42, 50, 53, 73 | OC, 10, 36, 45, 73, 88, 91 | OC, 51, 53 | OC; 53 | OC, 64 | 90 |
| **DAC** | 15 | 15 | 15 | 15, 84 | n/a | n/a | 15, 69 | OC, 15, 41 | OC | OC, 15 | 15, 84 | n/a | n/a | OC – qualitative |
| **EW** | 19 | 19 | 16, 59, 117, | 59 | n/a | n/a | 16, 59 | 71 | OC | OC, 59 | 59 | n/a | n/a | OC – qualitative |
| **AR** | OC, 97 | OC, 58, 98 | OC, 97 | OC, 56, 112 | OC, 88, 100 | 64, 66, 67, 68 | 49 | OC, 6, 7, 71 | OC, 40, 42, 50, 53 | n/a | OC, 40 | OC, 52, 53 | OC, 65 | OC - qualitative |

to maturity (assumes linear uptake), so mean annual accrual rate is 3.4 tC/ha/yr – for longer lasting AR, annual accrual rates drop (i.e. annual accrual rate over 80 years would be half of that over 40 years); For BE crops, negative emissions exclude fossil fuel displacement and are assumed to be mean of the range of carbon in biomass available for capture. Dedicated BE crop values are from Table S2 (mean of range for Miscanthus); Marginal crops - values from Table S2 (mean of the range for Sorghum); Crop residues - values from Table S2 (mean of the range for crop residues); Coppice - values from Table S2 (willow/poplar SRC); Pine - assumed same as annual increment for AR (see above); Tropical forests - tropical forests in humid areas assumed to have ~3x higher C accumulation than temperate forests following[97]; Boreal forests - boreal coniferous forests are assumed to have about half the carbon accumulation of temperate coniferous forests following[97]; EW of olivine value is the maximum value from[19]. Crop and forest BECCS sources are from[3,64,56,98-101]. Land use intensity (the area of land to produce one tCeq. of negative emissions) is plotted in Figure 3A.

In every case, the land use intensity increases as lower fertility land is used. Associated with the land-based NETs are carbon stock changes and greenhouse gas (GHG) emissions, which need to be accounted for when calculating the net GHG balance. Residues could be regarded as land neutral since they are a by-product and do not occupy land, but they are removed from cropland or forests which do have a land footprint. Even partial removal (30-40%) of crop and forest residue from land increases soil erosion hazard, soil carbon and nutrient losses[102], and similar impacts occur with forest residue removal[103], so care must be taken over residue removal rates, which can reduce the quantity of residue available for NETs considerably. Using organic waste (e.g. animal manure or residues from food processing that are otherwise used as soil amendment) presents similar constraints, although some energy conversion processes make it possible to return part of this organic matter to soils (e.g. anaerobic digestion[104]). Overall, the soil C sequestration forgone and nutrients exported by removing residues means that residue use as a feedstock is not GHG neutral (as the counterfactual would result in higher soil carbon stocks), but life-cycle GHG emissions are lower than for some BE crops. Edible feedstocks (i.e. which are used to produce most currently available biofuels) entail large $N_2O$ emissions related to inputs of fertilizer N, accounting for up to half of the life-cycle GHG emissions

**Table S2.** Contribution of different energy crops and residue types to reducing GHG emissions though use as BE feedstock[58,100,101,106]. The column "Carbon in biomass available for capture" (shown in bold) is used in the calculation of negative emissions potential of BECCS.

| Crop type | $N_2O$ emissions | Additional soil organic carbon (relative to annual food crops) | Additional below-ground biomass carbon | Temporary carbon storage in above-ground biomass | Carbon emission from indirect land-use change | Overall balance (as negative emissions) | **Carbon in biomass available for capture** | Total emission reduction including fossil fuel displacement and carbon capture | Total emission reduction including fossil fuel displacement and carbon capture (mean of range) |
|---|---|---|---|---|---|---|---|---|---|
| | *t Ceq./ha/yr* | *t Ceq./ha/yr* | *t Ceq./ha/yr* | *t Ceq./ha/yr* | *t Ceq./ha/yr* | *t Ceq./ha/yr* | ***t Ceq./ha/yr*** | *t Ceq./ha/yr* | *t Ceq./ha/yr* |
| Miscanthus | 0 | 0.68 | 0.35 - 0.46 | 0 | 0-0.29 | 0.75 – 1.15 | **5.83-8.59** | 7.54 – 15.68 | 11.61 |
| Switchgrass | 0 | 1.0 | 0.15 - 0.26 | 0 | 0-0.53 | 0.63 – 1.26 | **3.16-4.60** | 4.30 – 9.04 | 6.67 |
| Willow / Poplar SRC | 0 | 0.44 | 0.05 - 0.24 | 0-0.75 | 0-0.39 | 0.1 – 1.43 | **4.67** | 5.66 – 9.71 | 7.69 |
| Eucalyptus | 0 | 0.44 | 0.05 - 0.24 | 0-1.0 | 0-0.43 | 0.06 – 1.68 | **4.17-11.53** | 5.02 – 22.14 | 13.58 |
| Annual crops (e.g. sorghum) | 0.55 | -0.19 | 0 | 0 | 0.36 | -1.10 - -0.74 | **4.60-11.96** | 4.25 – 19.50 | 11.88 |
| Residues (agriculture) | 0.07 | -0.19 | 0 | 0 | 0 | -0.26 | **1.66-1.78** | 1.67 – 2.75 | 2.21 |
| Residues (forestry) | 0 | -0.06 | 0 | 0 | 0 | -0.05 | **0.60-1.05** | 0.65 – 1.80 | 1.23 |

of the end-products[105], in addition to their indirect emissions through land-use change effects. Lignocellulosic biomass crops (e.g. miscanthus, switchgrass, sweet sorghum) emit up to 10 times less $N_2O$ than food crops due to lower fertiliser N requirement, and have the potential to increase soil organic carbon if perennial[106], possibly resulting in a GHG sink were perennials to substitute for arable crops and little fertilizer were used. A major unknown is the global land-use change effects of purpose-grown BE crops given the possibility of land use change in one place driving conversion of land elsewhere[50,107-109]. Growing BE crops on marginal land could reduce indirect land-use change and associated GHG emissions, but productivity on this land is likely to be relatively low, leading to lower uptake / higher GHG emissions per MJ, compared to more productive land[110-111]. Table S2 shows the carbon and GHG emissions / removals associated with a range of energy crops and forest types, and the net negative emissions obtained including fossil-fuel offsets.

*Water*: Annual water use per-t-C removed from the atmosphere ($m^3$/tCeq./yr) values were estimated as follows: DAC – minimum, maximum and average water use values are from estimates of evaporative loss in amine DAC units given in[84]; AR – provides total interception and transpiration water loss for broadleaves (low value of range) and conifers (high value of range)[112] calculated assuming annual rainfall of 1000mm and annual increments given in the land / GHG emissions panel. All water use estimates subtract the water use under previous land use to provide a net change in water use. For all of the following BE sources, annual water use for growing the crop was added to water for cooling the plant and CCS technology. The CCS component of BECCS is also relatively water intensive. Extra water is needed for the scrubbers that remove $CO_2$ from the air compared to a power plant without CCS. Additional water is also typically needed for the energy penalty of the carbon-capture system, in particular the energy needed to power the CCS. This parasitic load reduces a plant's capacity by ~20-25%[113]. Another analysis[114] estimated that a comprehensive implementation of CCS in 2030 could raise freshwater withdrawals by 2–3% and consumption by as much as 52–55% in the United States. Though there is a range of potential water use characteristics for CCS plants[115], the CCS component of BECCS is assumed to have the same water requirements as a coal CCS plant[15]. Annual water use for plant growth was calculated as follows: BE crops – annual water use assumed as per broadleaved trees above; Marginal crops - annual water use value for sorghum from[116]; Crop residues - annual water use value for wheat from[116] assuming water use attributed to the residues as well as the grain; Coppice – annual water use assumed the same as broadleaved forest; Pine – annual water use assumed the same as coniferous forest; Tropical forest - annual water use assumed the same as broadleaved forest; Boreal forest - annual water use assumed the same as coniferous forest – all forests are assumed to be unirrigated. For EW of olivine, one molecule of water is required for each molecule of $CO_2$ removed, so each tCeq. would require 1.5 $m^3$ water. Expressing additional water use as a proportion of runoff in a region would give a more accurate picture of the threat to water resources at a given location, but without a spatially disaggregated analysis this is not feasible, so global assessments relative to total freshwater use are presented.

*Energy*: Energy production or energy input requirement per-t-C removed from the atmosphere (GJ/tCeq./yr) were estimated as follows: DAC – minimum of the range is the combined minimum thermodynamic energy for capture plus minimum theoretical compression energy, and maximum of the range assumes 40% conversion efficiency for heat and electricity with all values from page 40 of[15]; EW minimum energy requirements are calculated from open-pit mining energy consumption[117], and olivine $CO_2$ capture potential[16]; with total energy requirement estimates from[57]; AR requires low energy input (for site preparation only) and has no energy output. Energy end uses for BECCS vary, but here we calculate for power generation (using the median value reported in[3], i.e. conversion technologies representative of the 2000-2010 time period worldwide), where the carbon can be captured for storage. For all of the following BE sources, energy use for CCS technology for a BECCS plant has the same energy requirements as a coal CCS plant from page 25 of[15], and CCS energy use is subtracted from the energy generated from combustion of the BE feedstock (GJ/tC), with assumed energy penalties of 20-25% (Table S2[118]). BE crops – ranges for oil given by values for Brazilian Soybean (low) and Asian oil palm (high), ranges for starch/sugar ethanol given by European wheat (low) and Brazilian sugarcane (high), ranges for lignocellulose given by North American switchgrass (low) and European Miscanthus (high) – all from [58]; Marginal crops – range for oil given by Indian Jatropha (low) and Jatropha from Thailand (high) from[58]; Crop residues - range for lignocellulose given by Sorghum stover (low) and corn stover (high) from[58]; Coppice – range given by the range for coppice for Europe from[58]; Pine – annual increment for pine is ~half of increment for coppice so energy output is assumed to be half of coppice; Tropical forest – has ~3x higher C accumulation than temperate forests following Table 3A.5 of[97] so energy output assumed to be 3x pine; Boreal forest - assumed to have about half the carbon accumulation of temperate coniferous forests following Table 3A.5 of[97] so energy output assumed to be half that of pine.

*Nutrients*: Nutrient content (here represented by nitrogen content: kg N kg $C^{-1}$) is not applicable to DAC or EW technologies. For forests and energy crops, all values are from[88,101]. Most modern lignocellulosic energy crops require no annual application of N fertiliser (though a small amount is sometimes used in the establishment phase[60] – but usually much less than applied to cropland and pastureland that is replaced). Further, the ratio of $N_2O$ emissions to fertilizer N inputs is much lower for perennial BE crops than it is for cropland and grassland[106]. A recent study on growing wheat after growing unfertilized miscanthus for 20 years showed very little depletion of soil N[119].

*Albedo*: DAC and EW assumed to have no impact on albedo. All values for albedo change (unit-less) are for surface albedo. These values for forests and BE feedstocks are from[56,64] and assume change from grassland. Values for broadleaves (aspen) used for BE crops, coppice and tropical forest, and values for conifers are used for pine and boreal forests. The range for AR uses values for broadleaves (high) and conifers (low). Values including and excluding snow cover are presented.

*Costs:* Costs per unit of carbon removed from the atmosphere ($ $tC^{-1}$) of DAC are from page 14 of[15]. Costs of enhanced weathering of olivine come from[16,57]. Costs for BECCS are the range from 6 IAMs[49] and the range reflects the type and energy end-use of BECCS and regional variability. These $/tC values are shown in Figure 3 but are not used for upscaling to total global costs (see below).

***Implementation of NETs***

Levels of implementation of NETs consistent with a <2°C target (i.e. with concentration levels of 430–480 ppm $CO_2$-eq. in 2100) were assumed; for BECCS this is 3.3 GtCeq./yr in 2100 (Table

S3[10,36,45]). For DAC, though the maximum level of deployment could yield ~10 GtCeq./yr removals[41] in 2100, for comparison with BECCS we assume the level of implementation of DAC that also delivers 3.3 GtCeq./yr negative emissions in 2100. For other NETs which are not able to meet the same level of removals, we use values compiled from an analysis of the recent literature to give mean and maximum implementation levels. The area under AR is not given in the AMPERE[10,45] and LIMITS[36] studies, so AR impacts were estimated for areas calculated using the mean AR accrual rate of 3.4 tCeq./ha/yr (Fig. 3A), at implementation levels in 2100 estimated to give removals in 2100 of around 1.1 GtCeq./yr, with a maximum value of 3.3 GtCeq./yr (from[6,7,71]). EW estimates are mean and maximum carbon removal from ocean liming and addition of crushed olivine to the ocean, and "other" is for EW by soil loading[71] giving mean removals of 0.2 Pg C $yr^{-1}$ by 2100 and maximum values of 1 Pg $yr^{-1}$.

***Bottom-up estimation of global impacts and limits to supply of NETs***

Bottom-up estimates of global impacts and limits to supply of NETs were estimated by multiplying the per-t-C impact estimates of impact (see Figure 3) by the total levels of implementation of each NET expressed as GtCeq./yr or Mha/yr in 2100, described above. Since costs cannot be scaled using per-t-C impacts, investment needs were used instead as described in *Investment needs* below.

*Investment needs*: Investments into BECCS technologies provide an additional indicator for assessing the scale and speed of BECCS deployment over the next several decades. Table S4 summarizes investment estimates[90] from six global integrated assessment models that assessed 2°C scenarios within the context of the LIMITS model inter-comparison (one of the studies contributing to the study summarised in Table S4). Owing to unique assumptions in the models, there are considerable differences in capital requirements for biomass electricity generation with CCS and biofuels production with CCS by 2030 and 2050. In fact, some models prefer a single route to negative emissions while completely foregoing another. On average across the models, some $36.2 and $29.4 billion/yr worth of investment is seen as optimal by 2030 for scaling up biomass electricity and biofuels production technologies worldwide. By 2050, these investment levels grow to $138.3 and

$122.6 billion/yr, respectively. In the near term (2030), BECCS investments appear to be split fairly evenly between today's industrialized and developing countries, whereas in the mid-term (2050) the IAMs indicate that the bulk of the investment dollars will likely need to flow to the developing world. That does not imply, however, that developing countries will be responsible for bearing the full costs of these negative emissions efforts. In particular, by mid-century, China, the United States and the countries of Latin America and Southeast Asia are projected to invest heavily in BECCS technologies.

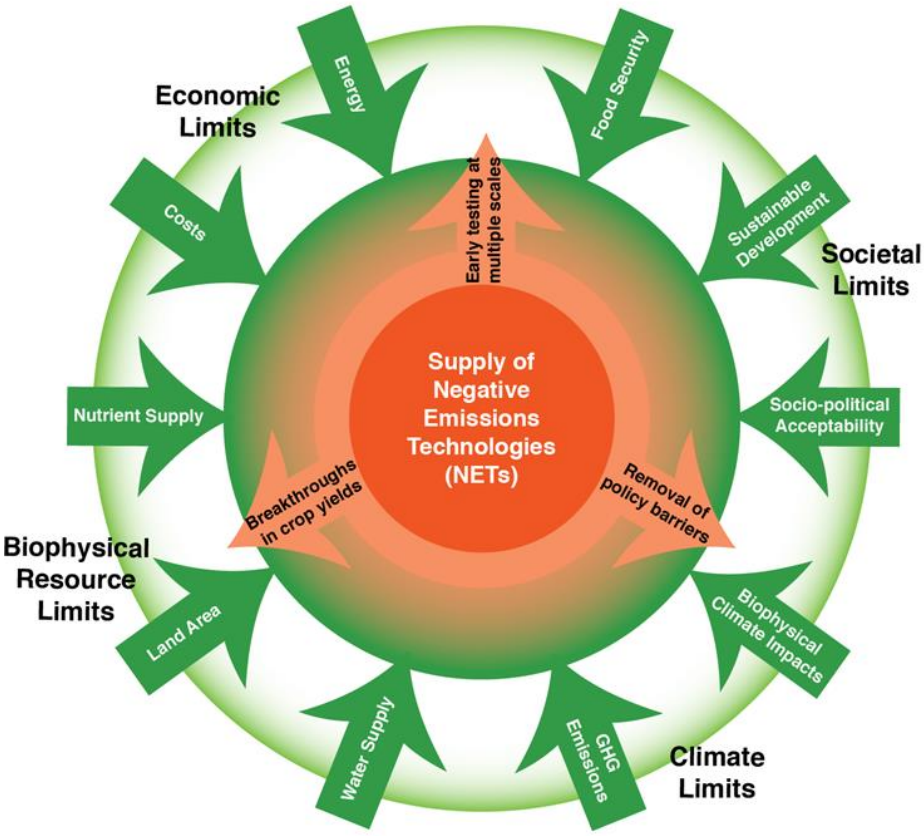


**Figure S1.** Summary of drivers of and limits to the supply of NETs. Outward-pointing arrows represent activities that may increase the availability of NETs. Inward-pointing arrows represent key biophysical, economic, societal and climate-related limits to the global supply of NETs.

**Table S3.** BECCS deployment levels in climate change mitigation scenarios from the AMPERE (available at: https://tntcat.iiasa.ac.at/AMPEREDB/)[10,45] and LIMITS (available at: https://tntcat.iiasa.ac.at/LIMITSDB/)[36] modelling comparison exercises. Only scenarios that apply the full unconstrained mitigation portfolio of the underlying models are shown (default technology assumptions). Policy scenarios include various short-term (i.e. including delayed action) and long-term climate targets as well as staged accession to an international climate agreement. The highest BECCS deployments are all produced by a single model (GCAM), which has the largest flexibility to compensate near term emissions by negative emissions in the second half of the century. BECCS deployment (1,4) is reported in negative values as carbon emissions are removed from the atmosphere. Gross emissions (2,6) could only be separated for carbon emissions from fossil fuel combustion and industry, but not for carbon emissions from land use which can include negative emissions from vegetation regrowth and afforestation. Therefore, net positive land use carbon emissions are included in gross emissions. All values converted from GtCO2 to GtC and are rounded to two significant digits.

| | | **Carbon emissions in 2100** | | | **Cumulative carbon emissions 2010-2100** | | |
|---|---|---|---|---|---|---|---|
| $CO_2$eq concentration in 2100 | *n* | BECCS deployment: amount of carbon removed (GtC/yr) (1) | Gross emissions (GtC/yr) (2) | Net total emissions (GtC/yr) (3) | BECCS deployment: amount of carbon removed (GtC) (4) | Gross emissions (GtC) (5) | Net total emissions (GtC) (6) |
| 430-480 | 44 | -3.3 (-5.9, -1.9) | 1.8 (0.54, 2.3) | -2.6 (-5.9, -0.4) | -150 (-230, -100) | 430 (390, 600) | 280 (180, 320) |
| 480-530 | 61 | -4.1 (-15, -2.4) | 2 (0.74, 3.3) | -2.7 (-16, 0.13) | -170 (-350, -87) | 520 (480, 680) | 320 (280, 460) |
| 530-650 | 54 | -3.4 (-15, 0) | 3.3 (1.8, 4.6) | -1.1 (-16, 3.8) | -130 (-360, 0) | 700 (620, 820) | 560 (320, 690) |

**Table S4.** Annual energy investments for BECCS technologies in 2030 and 2050 in a scenario consistent with staying below 2° C temperature rise. Data source: six global IAMs used in the LIMITS model inter-comparison (LIMITS-RefPol-450 scenario[90]). Average values across models are shown for each region, with full model ranges in parentheses. Investments into biofuels production with CCS and hydrogen production w/ CCS were not explicitly reported by modelling teams in the LIMITS exercise. Values for the former can be back-calculated, however, by multiplying total investments into biofuels production (both with and without CCS) and the share of total biofuels production that is equipped with CCS. While not exact, this estimation works quite well because the unit-level investment cost of a given biofuels production facility with CCS is only slightly greater than one without CCS. Totals may not add exactly due to rounding and averaging and because of a heterogeneous "REST_WORLD" region that is not shown here. For regional definitions, see[90].

| **Investments into BECCS in a Scenario Consistent with 2° C** | | | | |
|---|---|---|---|---|
| | **Biomass Electricity with CCS** | | **Biofuels Production with CCS** | |
| *units: billion US$2005/yr* | 2030 | 2050 | 2030 | 2050 |
| **AFRICA** | 1.2 (0 – 4.7) | 17.2 (0 – 67.2) | 0.5 (0 – 1.6) | 8.1 (0 – 24.0) |
| **CHINA+** | 2.9 (0 – 10.1) | 30.5 (0 – 166.5) | 6.4 (0 – 30.2) | 16.4 (0 – 73.2) |
| **EUROPE** | 3.8 (0 – 8.3) | 12.4 (0 – 32.5) | 3.6 (0 – 13.8) | 9.4 (0 – 41.8) |
| **INDIA+** | 4.5 (0 – 12.5) | 10.4 (0 – 37.8) | 4.6 (0 – 21.2) | 6.9 (0 – 30.0) |
| **LATIN_AM** | 1.7 (0 – 2.9) | 15.8 (0 – 32.5) | 2.4 (0 – 11.0) | 17.5 (0 – 70.2) |
| **MIDDLE_EAST** | 0.3 (0 – 1.1) | 2.6 (0 – 12.1) | 0.7 (0 – 1.9) | 20.4 (0 – 100.4) |
| **NORTH_AM** | 5.9 (0 – 21.6) | 15.9 (0 – 39.9) | 5.9 (0 – 28.8) | 18.6 (0 – 74.9) |
| **PAC_OECD** | 0.7 (0 – 2.2) | 3.9 (0 – 10.2) | 0.4 (0 – 1.8) | 4.4 (0 – 11.4) |
| **REF_ECON** | 2.8 (0 – 9.1) | 10.9 (0 – 20.5) | 2.1 (0 – 9.0) | 3.2 (0 – 10.7) |
| **REST_ASIA** | 5.6 (0 – 23.5) | 11.9 (0 – 44.2) | 2.1 (0 – 9.5) | 10.4 (0 – 41.9) |
| **Developing** | 16.2 (0 – 43.5) | 88.3 (0 – 287.7) | 16.6 (0 – 75.4) | 79.7 (0 – 339.8) |
| **Industrialized** | 20.0 (0 – 79.4) | 50.0 (0 – 101.7) | 12.7 (0 – 55.1) | 43.0 (0 – 169.5) |
| **World** | 36.2 (0 – 122.9) | 138.3 (0 – 389.4) | 29.4 (0 – 130.5) | 122.6 (0 – 509.2) |

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