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Designing Climate Change Mitigation Plans That Add Up

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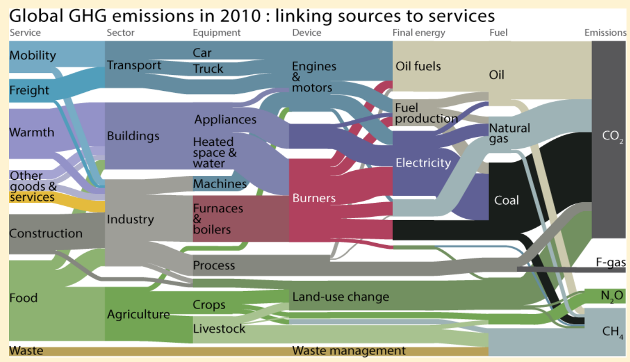
Supporting Information

ABSTRACT: Mitigation plans to combat climate change depend on the combined implementation of many abatement options, but the options interact. Published anthropogenic emissions inventories are disaggregated by gas, sector, country, or final energy form. This allows the assessment of novel energy supply options, but is insufficient for understanding how options for efficiency and demand reduction interact. A consistent framework for understanding the drivers of emissions is therefore developed, with a set of seven complete inventories reflecting all technical options for mitigation connected through lossless allocation matrices. The required data set is compiled and calculated from a wide range of industry, government, and academic reports. The framework is used to create a global Sankey diagram to relate human demand for services to anthropogenic emissions. The application of this framework is demonstrated through a prediction of per-capita emissions based on service demand in different countries, and through an example showing how the "technical potentials" of a set of separate mitigation options should be combined.



INTRODUCTION

The need for urgent large-scale action to counter climate change is well established, but anthropogenic emissions continue to rise ahead of the worst IPCC scenarios.[1] The political and economic difficulties of implementing change are widely discussed, but even agreeing on technical implementation plans remains problematic as the mitigation potential of particular options are often overstated and considered in isolation. In particular, attention to date has largely focused on energy supply, but increasingly, the difficulty of delivering such supplies at scale and in time is becoming clear. For example: MacKay[2] demonstrates that deployment of renewable energy in the UK is likely to be constrained by a available land; Smil[3] argues that "The speed of transition from a predominantly fossil-fuelled world to conversion of renewable flows is being grossly overestimated"; the International Energy Agency (IEA)[4] suggests that deployment of clean energy technologies and carbon capture and storage (CCS) is lagging behind critical projections. This lack of progress will cause a shift of attention toward demand-side options. However changes to demand, whether through efficiency measures, structural change, alternative service delivery, or changes in behavior, require wider changes in the energy and agricultural systems.

Mitigation options are evaluated through predictions of their effect on an inventory of emissions. An inventory of emissions is defined here as an additive decomposition of total annual anthropogenic emissions. To reveal the range of inventories in current use, Figure 1 shows how global anthropogenic greenhouse gas (GHG) emissions data is collected, estimated and reported at present.[5−13]

Energy related emissions are predicted from fuel use data, as reported to international statistical agencies by national agencies based on reports from companies in the main energy using sectors. Emissions from nonenergy related sources are estimated based on other "activity data" gathered by relevant international organisations. Primary data sources for nonenergy emissions include expert estimates and use of satellite imaging. GHG data sets often cross-reference one another to complement information omitted in their own data gathering and the Figure 1 shows how key data sets have different scopes.

Four parameters define the scopes of existing GHG emission data sets: (i) the range of GHGs included (CO_2, CH_4, N_2O, and three families of F-gases); (ii) the range of fuels included, or in case of nonenergy emissions, the range of other sources; (iii) the economic sectors that reported fuel use; (iv) the country in which emissions were released. Existing data sets therefore provide four possible GHG inventories, one for each of these parameters. These inventories can be used to determine priorities and assign responsibility, but cannot be used to design mitigation plans or evaluate demand-side changes, which depend on the interactions between different inventories.

Interactions between three of these inventories (two different economic sector classifications and GHGs) have previously been connected in an informative Sankey diagram created by the World Resources Institute (WRI).[10] However, the design of

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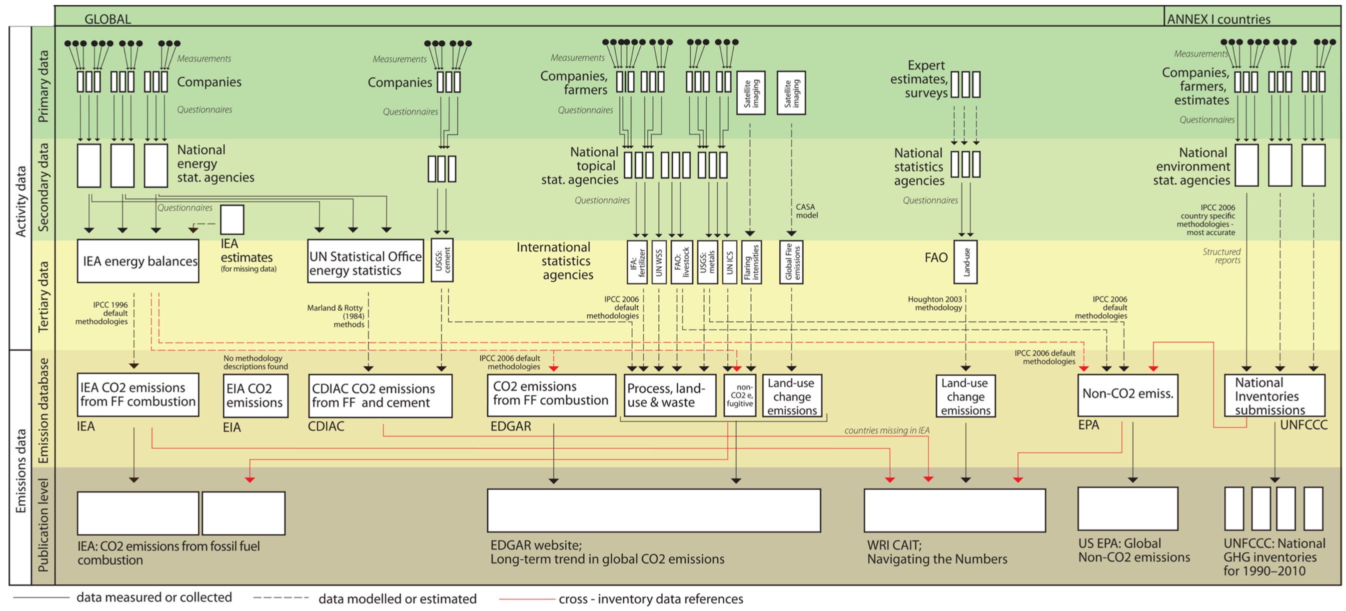

Figure 1. The accumulation of emissions data into global inventories.

this diagram, which is constrained by the structure of existing emissions inventories, reveals options only by economic sector. This usefully clarifies one form of responsibility, but the development and evaluation of comprehensive mitigation plans requires also that inventories be organized, structured, and connected to reflect service demand, technology choice and performance, fuel selection, land-use, and management decisions.

Without this structuring, a number of problems can arise:

- The drivers of demand for the activities that lead to anthropogenic emissions are related to final services (such as warmth, commuting or food) which in turn arise from the use of equipment. Without a consistent inventory of emissions associated with these services, predictions of the relative importance of different demand reduction options may be confusing or inaccurate. For example: cities are responsible for approximately 70% of GHG emissions;[14] 17–32% of GHG emissions are related to the production of food;[15] the use of buildings accounts for 33% of GHG emissions.[16] Although, each of these statistics is true, the allocation of emissions to final services can be completed in such a way that a specific issue seems more important.
- A mitigation plan comprises many actions whose combined effect can only be predicted within a consistent framework. This may not happen if direct, indirect, fugitive, and non-CO_2 emissions are incorrectly separated; changes at a product level are scaled incorrectly to national or global levels; the effect of a combination of actions is anticipated to be the sum of their effects if applied separately. For example, marginal abatement curves may fail to consider interactions, use inconsistent baselines and lead to double counting,[17] and the difficulty of defining boundaries for life cycle assessment studies leads to both double-counting and the omission of emissions.[18]
- The manner in which emissions inventories are structured determines which technical opportunities and potentials for mitigation they can reveal. For example, technical efficiency studies can only be made with an inventory of energy-using devices, and demand reduction can only be evaluated relative to final services. A study of integrated models used to anticipate transition pathways and future equilibria arising from different energy or carbon related price signals reports that at least six different approaches are in use for assessing technical mitigation opportunities.[19]
- Misinformation about mitigation options which influences public perception, business and policy decision making, could be reduced by a consistent presentation of all emissions. For example, efforts aimed at promoting compact fluorescent light bulbs while prominent in public consciousness, have little overall impact on global emissions.[20]

This paper seeks to address these problems by developing and presenting a comprehensive picture of global anthropogenic GHG emissions, including the required transformations between a sufficient set of inventories, to allow the design of credible mitigation plans. The resulting data structure will be used to demonstrate how the limitations of existing approaches may be overcome.

■ MATERIALS AND METHODS

Demand for the activities that lead to anthropogenic emissions arises out of a need for a variety of services, driven in turn by population and wealth. The services arising from energy are provided by economic sectors (businesses) and technically delivered through use of equipment, which contains a powered device that converts a "final" form of energy to low-grade heat in exchange for service provision. The final energy is created by the energy industry from a fuel, whose combustion leads to emissions. (Some industrial processes also lead to "process emissions" related to chemical reactions.) The services arising from agriculture and other land-use are also provided by sectors (including subsistence agriculture) and delivered from an allocated area of land. The way in which this land is managed

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drives the release of emissions, either directly (for example by forest clearing) or via biological processes. Thus

$$\begin{matrix}\text{energy}\\ \text{service}\end{matrix} \rightarrow \text{sector} \rightarrow \text{equipment} \rightarrow \text{device} \rightarrow \begin{matrix}\text{final}\\ \text{energy}\end{matrix} \rightarrow \text{fuel} \rightarrow \text{emissions} \quad (1)$$

$$\begin{matrix}\text{land}\\ \text{service}\end{matrix} \rightarrow \text{sector} \rightarrow \begin{matrix}\text{land}\\ \text{use}\end{matrix} \rightarrow \begin{matrix}\text{land}\\ \text{management}\end{matrix} \rightarrow \text{processes} \rightarrow \text{emissions} \quad (2)$$

Each stage of the chains in [1 + 2] defines a complete inventory of emissions (e.g., $\mathbf{V}_a$), which should reflect decision making through an appropriate level of disaggregation. Adjacent inventories (e.g., $\mathbf{V}_b$) must therefore be connected by transformations ($\mathbf{V}_b = [\mathbf{A}]\cdot\mathbf{V}_a$) which fully reallocate the same total emissions, so the rows of **A** sum to unity. Existing data do not match the inventories required in [1 + 2], and the necessary transformation matrices have not previously been created.

The most current and detailed data on global energy-related CO_2 emissions is provided by the IEA for 2010,[6] and is organized by fuels and sectors. In parallel, the EDGAR v.4.2 2010FT data set[8] includes, in addition, inventories for GHGs omitted from the IEA data set (CH_4, N_2O and F-gases) and also fugitive and transformation emissions. However the level of disaggregation of data into fuels and sectors is not as detailed as in the IEA data set. Supporting Information (SI) Table S1 combines the IEA and EDGAR data sets and allocates these to each of the IEA sectors. The result is then reorganized in SI Table S2 into the sector inventory proposed here, which equates to the second stage of chain [1]. Judgement is required to select the size of each inventory to reveal useful detail without creating unhelpful complexity, and this analysis has aimed to define approximately fifteen elements per inventory while minimizing the "other" category.

The transformation matrices from sectors to equipment, devices and final energy are closely related to those used by Cullen and Allwood[20] to allocate responsibility for energy use. The matrices are provided as SI Tables S3−S7 with detailed footnotes showing how each allocation ratio was derived from 16 sources[5,6,8,11,20−32] using triangulation from multiple sources where possible. In some cases, regional or national data, often from developed countries, have been scaled up where global figures were unavailable. The data sources used to create the allocations in SI Tables S6−S7 included emissions by final energy and by gas, which have been used as part of the triangulation.

The structure of the chains is linear, but this requires decisions about some coupled connections in the data, as shown in the following three examples: (i) electricity generation requires a conversion of energy that takes place in a device and equipment—in coal burners, oil burners, and gas turbines—but these are not shown on the diagram; (ii) steel for manufacturing trucks was allocated to freight service, but freight (for delivery of iron ore) was not allocated to steel; (iii) biofuel use should be counted as part of both land and energy systems, but to avoid double counting, the responsibility of biofuels for land-use change and fertilizer use was traced through its use in equipment and devices in the energy system and then connected to the source of its emissions in the land-use system.

SI Tables S1−S7 include rows showing "emissions in energy from nonfossil fuel sources", which are related to land-use or industrial processing, and explained in more detail in SI Tables S8−S10, derived from nine sources,[8,33−36,38−41] as described below.

Nonenergy related emissions from industrial production include the release of CO_2 during calcination of limestone for lime and cement production, non-CO_2 emissions in nonferrous metals production, oxidation of hydrocarbons when not used for energy purposes and F-gas leakages. Allocation of these emissions to sectors is shown in SI Table S8, based on EDGAR[8] and U.S. Geological Survey lime statistics.[33]

The most consistent 2010 emissions data source related to nonenergy GHG emissions is the EDGAR data set.[8] U.S. Environmental Protection Agency[13] also offers a source of data for non-CO_2 emissions in agriculture and other sectors, sourced where possible from national submissions of emission data sets to UNFCCC. However, the most recent data is for 2005 and excludes several of the nonenergy CO_2 emissions covered by EDGAR. SI Table S9 therefore shows the transformation of EDGAR data into the land-management inventory of this analysis. EDGAR uses a proxy for land-use change emissions, based on satellite-derived fire data sets. This allows reporting of estimates for recent years, but falls short of capturing the full complexities of land-use change, better represented in estimates by Houghton.[12] SI Tables S9−S13 define the allocation matrices to transform land system emissions from the EDGAR data set into land- management, land-use, sector emissions, biological processes where appropriate and final emissions. These tables draw on data from six sources,[34−36,39−42] with one-hundred year global warming potentials from the fourth IPCC Assessment Report used to calculate emission equivalents.[43]

Three different approaches were compared to estimate land-use change emissions associated with biofuel use. First, the use of indirect land-use change emissions implied by Edwards et al.,[37] in conjunction with the expansion of biofuel production between years 2009 and 2012, based on IEA data[5] gives the highest estimate of 0.7 $PgCO_2$. Second, the calculation of direct combustion emissions from biofuels with no discount for short cycling (biogenic) carbon, as previously suggested by Haberl et al.,[38] gives an estimate of 0.15 $PgCO_2$. Finally, a similar estimate is obtained if the total land-use change emissions are divided between total global agriculture land-uses. Therefore, 0.15 $PgCO_2$ was taken as the mean estimate.

The selection of final services is based on a well-established body of research that attempts to measure energy and carbon emissions per unit output of final service. Described as physical-thermodynamic indicators by Patterson[44] and specific energy consumption (SEC) in the inverse form by Phylipsen et al.,[45] the approach requires the final service to be measurable in physical units, such as tonnes of steel or kilometres of travel. Schenk and Moll[46] argue that the use of physical units leads to a better understanding of energy demand, although in practice the availability of data often leads to the specification of final services in a mix of physical and monetary units, as proposed by Farla and Blok[47] and Schipper et al.[48] In contrast, the UK Carbon Trust[49] attributes UK carbon emissions from fuels to services through six "carbon accounts", ending with a set of "high level consumer needs" which includes categories such as "recreation and leisure" which are difficult to measure in physical units.

In this paper, final services are selected to mark the start of each chain [1 + 2] and each service can be quantified using physical units. The emissions invested to create industrial materials and food are treated as embodied and allocated onto

Table 1. Flows of Emissions Included in Each of the Final Services

final service	included emission sources	physical units (annual flows)
travel	passenger transport for holiday, visiting family, shopping, sport; associated material production (steel, aluminum, plastics) and manufacturing of cars	16×10^{12} passenger kilometres
commuting	passenger transport for work, business and education; associated material production (steel, aluminum, plastics) and manufacturing of cars	6×10^{12} passenger kilometres
freight	freight transport fuel use; material production (steel, aluminum, plastics) and manufacturing of trucks and ships	47×10^{12} tonne kilometres
washing	hot water detergents, cosmetics and pharmaceuticals, incl. some packaging; energy use in washing machines and dishwashers; manufacturing of washing machines and dishwashers	1.5×10^{12} m^3K (hot water) 2.8×10^{18} Nm (mechanical work)
thermal comfort	heated and cooled space	30×10^{15} m^3K (hot/cold air)
illumination	energy used by light devices	480×10^{18} lm.s
communication	energy in use and manufacturing of electronics; writing and printing paper	1.80×10^{21} bytes
textiles	textile industry energy use; production of polymer fibres; fertilizer for cotton (energy and N_2O emissions)	71×10^6 tonnes (fiber)
industrial equipment	production of some steel and aluminum; energy use by the industrial machines production sector	1.9×10^6 tonne (steel/aluminum)
construction of buildings and infrastructure	production of steel, aluminum and chemicals for construction and furniture uses; cement production; energy use in construction and quarrying industries; energy use in the wood industry incl. land-use change emissions; emissions from vegetation clearing for settlements	15×10^9 $m^3MPA^{2/3}$
food	energy use for cooking; energy cost of fertilizer production (part of the chemical industry); energy use in the food processing industry; energy use in chemical, aluminum and paper industries associated with food and drink packaging; energy use on farms (tractors, irrigation systems); N_2O emissions from fertilizer use; CH_4 from rice, livestock and manure management; land-use change for agriculture	30×10^{18} J (food)
waste	CH_4 emissions from waste and wastewater	840×10^6 tonnes

final services, as is land-use change. SI Table S14 defines this allocation based on seven sources,[50−56] mostly trade associations, such as World Steel Association, and statistical agencies, who report production volumes or market shares. The inventory of Final Services is disaggregated into the categories defined in Table 1, which includes an estimate of current global service demand quantified in physical units, based on 6 sources.[20,39,54,57−59] SI Tables S15−S18 describe the disaggregated categories for all the inventories across chains [1 + 2].[60,61]

RESULTS AND DISCUSSION

The inventories and transformations defined by the structure of the chains [1 + 2] have been used to create the Sankey Diagram of Figure 2, which demonstrates how service demand on the left eventually drives emissions on the right, via a combination of business activity, technical systems, energy or land selection and conversion. The lines on the diagram are clustered into groups frequently used in policy analysis with color used to emphasize key relationships.

The diagram draws attention both to scales of responsibility and opportunities for improvement. The combination of energy, process and land-related emissions emphasizes the significance of Food Production and Construction as drivers of global GHG emissions, among which cement, livestock, rice paddy fields, and fertilizer make notably large contributions. (Emissions associated with fertilizer arise both from its energy-intensive production within the chemical industry and from N_2O release from its application shown in the land-management inventory.)

The figure demonstrates that improving the efficiency of electricity generation would be an effective technical innovation, however this has already had considerable attention, while the demand for energy in buildings and the production of a few basic materials both cause greater emissions, and could be addressed without innovation by under-deployed solutions for building envelopes[62] and material efficiency.[63] Treating industrial materials as services gives some indication of the relative effects of use and embodied emissions, although the use-phase emissions relate to a total stock of products, not just one year's additions to stock. Emissions allocated to several of the sectors in Figure 2 are higher than in some previous reports, due to the inclusion of indirect emissions associated with upstream fuel conversions, fugitive emissions, and industrial processing. The new data structure presents emissions inventories data in a way which is similar to the inner structure of some energy system models and integrated assessment models. These models frequently include energy transformations from fuels to devices, sectors, and energy demands. The diagram of Figure 2 shows these transformations in a fully transparent way.

To demonstrate the application of the new data structure, Figure 3 compares estimated per-capita emissions of global average, U.S. and Chinese consumers based on their demand for the physical units of service in Table 1. The left-hand bar of Figure 3 is identical to the left side of Figure 2, scaled only by global population. Data from 21 references[5,6,20,21,26,27,39,54,57,59,64−72] were used to estimate per capita service demand in the U.S., China, and the world in SI Table S19. Final service demands for travel, illumination, communication, food, and waste were calculated using either directly recorded country-based emissions or country-based emissions intensities, whereas country-level data for final energy use was used to calculate thermal comfort and washing. For industrial activities the analysis is more complicated because emissions embodied in products must be reallocated when products are traded between countries. Trade data shows that for cement production, food processing, chemicals, paper, other industry and new settlements, production is mostly indigenous (i.e., emissions occur in the country where these products are consumed) so the trade issue is avoided. For steel, aluminum, textiles, and food, we correct for international trade by using country-based emissions intensities for indigenous production consumed within the country and an average global emissions intensity for imported products, before reallocating these materials to final service demand in SI Table S20. The physical trade statistics used do not account for trade in final products made of steel, aluminum and plastics, an area where further research is required. Figure 3 predicts that emissions per person in the U.S. are more than two-and-a-half times those in China. Travel services and services delivered in buildings (such as washing and thermal comfort) drive most of the additional

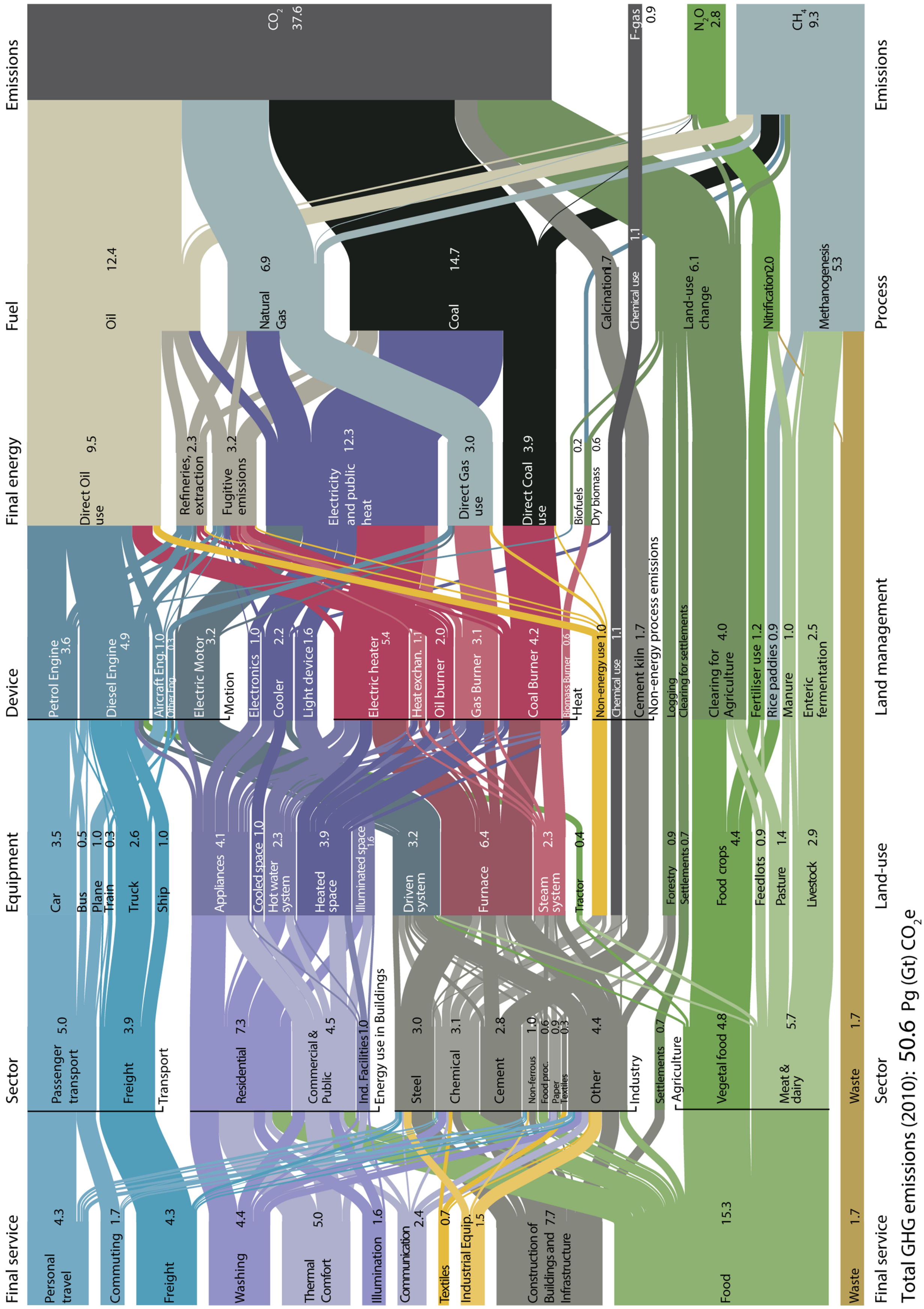

Figure 2. The proposed data structure represented as a Sankey diagram for all anthropogenic global GHG emissions in 2010.

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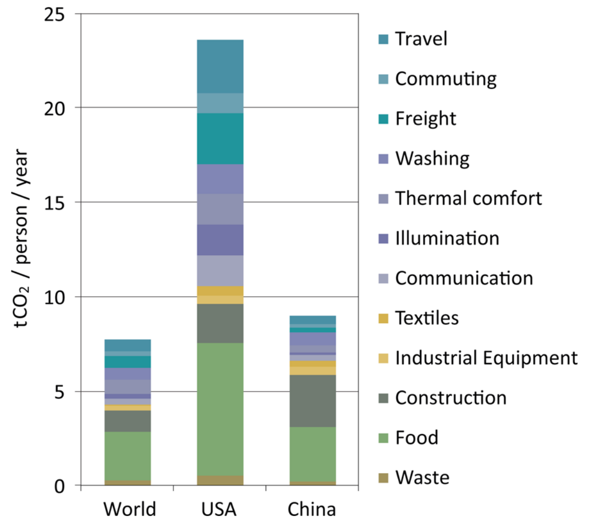

Figure 3. Per capita emissions in different countries derived from physical service demand.

emissions in the U.S., whereas Chinese per capita demand for steel and cement currently exceeds that of the U.S. Using this approach provides a physical-based alternative to input-output based methods used for allocating responsibility to consumption at a national level, where the conversion from monetary to physical units can lead to errors.[73]

A mitigation plan comprises many actions whose combined effect can only be predicted within a consistent framework, but this is not always achieved. For example, the technical options that make up a marginal abatement curve are typically only considered in isolation, leading to overestimates of the abatement potential, and the focus on individual products in life cycle assessment requires definition of an arbitrary boundary around the impacts associated with a single product.

The structure of Figure 2 allows resolution of these problems. To demonstrate this, Figure 4A is an extract from Figure 2, reporting the emissions associated with commuting. Table S21 presents five illustrative options to mitigate these emissions: (i) car sharing, (ii) a switch to train, (iii) car light-weighting, (iv) technology switch to diesel, and (v) engine improvements. Each of these illustrative options has the potential to reduce 20% of car commuting emissions if applied alone (with the exception of technology switch to diesel, where the potential is 12%). These individual potentials are smaller if compared to overall commuting emissions due to issues associated with embodied emissions and trade-offs. For example, if passengers take the train instead of driving, the emissions from trains will rise.

Figure 4 shows how the underlying interactions between these options affect the combined mitigation potential. Applying all the abatement options from SI Table S21 gives a combined mitigation potential of 51%, much less than a simple sum of individual potentials. A demonstration of a combined mitigation potential in SI Table S21 requires an arbitrary order of implementation, while Figure 4A and B better illustrates the dynamic relationships and trade-offs between mitigation options—as one option is implemented the baseline for all the other emission changes. If multiple options are considered, it is not possible to define the technical mitigation potential of any option separately, as it is conditional on a particular state of the system. By combining direct and indirect emissions and always considering the total set of global emissions, the structure of Figure 2 provides a self-consistent allocation of emissions to the chosen set of final services. It could therefore be interpreted as a set of high-level life cycle analyses without double-counting or omissions due to imperfect selection of the boundaries of analysis.

Designing and evaluating emissions mitigation plans remains an art as well as a science. There are two key sources of uncertainty in the data used in this analysis. As Figure 1 shows, all national or international emissions data are estimates not measurements. Some ranges of uncertainties for these estimates are provided in the literature[9,43,74] giving high confidence (±5%) in estimates of CO_2 emissions from fossil fuels and cement production but high uncertainty for emissions from land-use change (±70%).[43] These estimated uncertainties have been applied in Table 2, to make confidence predictions for the estimates of emissions associated with final services in this analysis. A second source of uncertainty relates to allocations of emissions from one inventory to another. Typically, these uncertainties are larger for inventories with fewer available data,

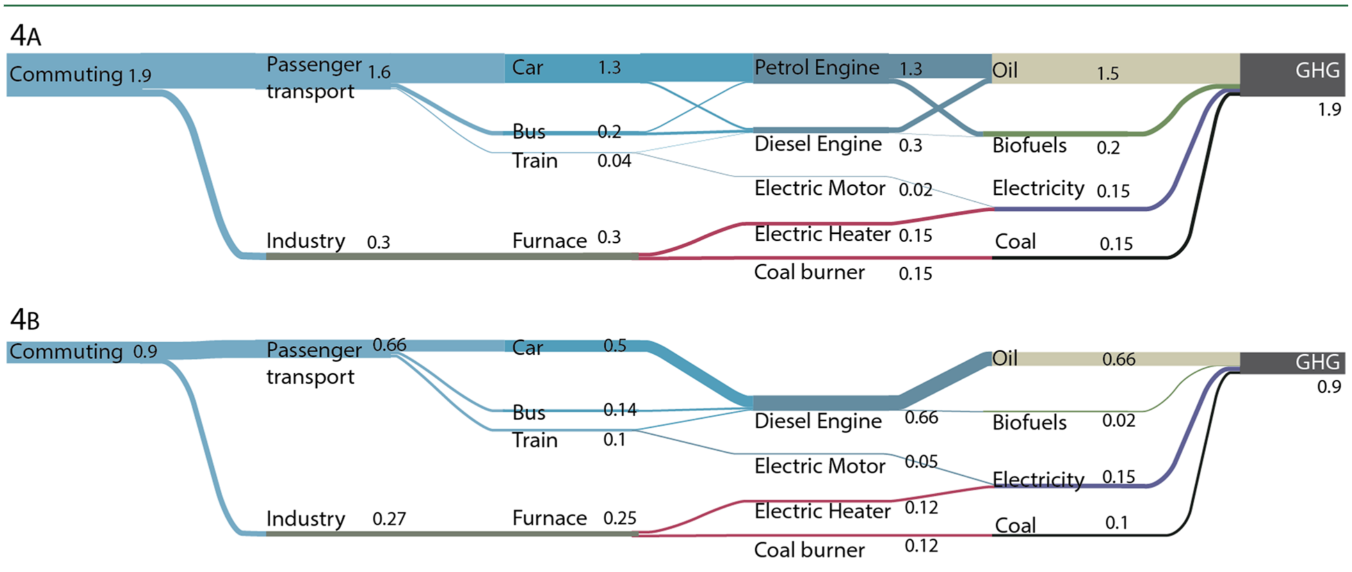

Figure 4. The technical potentials of a portfolio of options to mitigate the emissions of commuting.

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Table 2. Estimated Ranges of Uncertainty in the Data Used in This Analysis

sources	total emissions: middle value	assumed range of uncertainty	services	total emissions: middle value	calculated range of uncertainty from sources
CO_2 from fossil fuels	29 800	±5%	travel	4340	±16%
CH_4 from fossil fuels	3600	±25%	commuting	1680	±16%
N_2O from fossil fuels	410	±25%	freight	4330	±16%
$C0_2$ from cement and lime	1700	±5%	washing	4350	±14%
nonenergy fossil fuels	520	±50%	thermal comfort	5030	±11%
F-gases	940	±50%	illumination	1600	±7%
agriculture	5730	±50%	communication	2360	±15%
waste	1650	±70%	textiles	730	±19%
land-use change	6160	±70%	industrial equipment	1470	±25%
			construction of buildings and infrastructure	7650	±23%
			food	15 290	±45%
			waste	1680	±70%

in particular for Final services, Equipment and Device inventories.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information to this paper comprises 21 tables of data, specifying all the numbers used in the analysis with detailed notes on sources. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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