



# The changing mix of fossil fuels used and the related evolution of CO<sub>2</sub> emissions

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## Abstract

To limit global climate change, ultimately it will be necessary to minimize the use of all fossil fuels for energy. Because the rate of CO<sub>2</sub> emissions per unit of primary energy varies among the fossil fuels, it is useful to focus first on reducing the use of coal, the fuel with the most CO<sub>2</sub> per unit of energy used. Although multiple factors are involved in the choice of which fuel will be used for a given purpose, data on CO<sub>2</sub> emissions show that over the last 25 years there has been an evolution in the fraction of emissions away from coal and toward natural gas. That is, although total emissions have continued to increase globally, the fraction attributable to coal has been decreasing in many places. This is true for the global sum of emissions, for Annex I countries, and for all regions except Asia Pacific. The fraction of emissions from oil products has varied largely with growth in the contribution of petroleum transportation fuels. Focus on decreasing the sum of all fossil fuels is needed, especially among the major energy users in the Asia Pacific region, but progress in the decreasing relative use of coal is promising.

**Keywords** CO<sub>2</sub> emissions · GHG mitigation · Ternary diagrams · Fossil fuel mix · CO<sub>2</sub> from coal · CO<sub>2</sub> emissions by sector

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## 1 Introduction

Concern over global climate change is focused on the principal driver of change, the combustion of fossil fuels – i.e. coal, oil, and natural gas. Combustion of fossil fuels releases the carbon in the fuels to the atmosphere as carbon dioxide (CO<sub>2</sub>). To limit global climate change, ultimately it will be necessary to achieve virtually complete replacement of fossil fuels with sustainable sources of energy that are not reliant on carbon releases (IPCC 2022). However, because the different fossil fuels have different rates of CO<sub>2</sub> release per unit of useful energy; initial, primary focus has been on minimizing the use of coal (see the Glasgow Climate Pact; (UN FCCC, 2021)). It was not until the December, 2023 international negotiations at the Congress of Parties 28 (COP28) to the UN Framework Convention on Climate Change that the assembled countries reached an agreement that “recognizes the need for...transitioning away from fossil fuels” generally (UN 2023). As summarized by the Intergovernmental Panel on Climate Change (IPCC 2006, tables 2.2–2.5), one terajoule of primary energy releases approximately (as examples of typical solid, liquid, and gaseous fossil fuels) 94,600 kg of CO<sub>2</sub> if the energy is derived from solid fuels (e.g. bituminous coal), 73,300 kg of CO<sub>2</sub> if derived from liquid fuels (e.g. crude oil), and 56,100 kg of CO<sub>2</sub> if derived from gaseous fuels (e.g. natural gas) – a ratio of approximately 5 to 4 to 3 – depending on the precise fuels involved. These numbers are based on the net calorific values.

Use of gaseous fossil fuels in place of solid fuels (e.g. natural gas in the place of coal) thus results in an important reduction of CO<sub>2</sub> emissions per unit of primary energy – if the two fuels can be used with the same end-use efficiency. It is primarily this replacement of coal by natural gas for electric power generation that has resulted, for example, in declining CO<sub>2</sub> emissions from the U.S. over the period 2005 to 2017 (U.S. EPA 2022). From year 1990 to 2020, natural gas use for electric power generation in the U.S. increased from 14.9% to 40.6% of total electricity generation (U.S. EIA 2023).

The mix of primary energy sources used in an economy depends on the structure of the economy, the availability of energy resources, and the mix of energy needs – but there are applications where the fuel choice can be based on environmental and other factors. For example, coal has been widely used for generating electricity and heat while petroleum products have been widely used for transportation systems. Most recently, however, there is interest in moving toward electricity-based and sustainable transportation systems to reduce total CO<sub>2</sub> emissions (e.g. IPCC 2022), and it becomes imperative to evaluate the primary energy source used for the electricity generation. It is now of interest to characterize primary energy sources generally and to be sensitive to what fuels are used for what purposes.

Recent international negotiations toward mitigation of global climate change (e.g. the 27th Congress of the Parties to the UN Framework Convention on Climate Change) state clearly the desire to reduce use of coal but have not yet phrased the objective of reducing use of all fossil fuels, e.g. including petroleum and natural gas (see e.g. Masood et al. 2022; Volcovici et al. 2022). Nevertheless, either a decrease in the applications for coal consumption or substitution by other fuels will be reflected in the ratio of the fossil fuel contributions to total CO<sub>2</sub> emissions.

In this paper we are interested in the mix of fossil fuels used. The mix of fuels varies over time and among countries, and we are interested in whether changes are occurring that are consistent with our motivations to alter the trends in total CO<sub>2</sub> emissions. The intensity of CO<sub>2</sub> emissions will change with the structure and the efficiency of an economy,

e.g. changes in the mix of fossil fuels will result from changes such as the increasing role of transportation versus electric power generation; but they will also result from changes such as electric power generation from natural gas as opposed to coal.

Analyses in this paper are based on the CDIAC CO<sub>2</sub> emissions estimates of Hefner and Marland (2023) and Hefner and Marland (2024). The CDIAC emissions estimates have been updated roughly annually since 1984, most recently at Appalachian State University, and are based primarily on energy data from the United Nations Statistics Division (see, for example, UNSD 2023). The UN energy data are comprehensive and consistent back to 1950 and have been gradually enriched over time. CDIAC has used other sources to extend the energy data back to 1751 (Hefner and Marland 2023). The traditional CDIAC estimates of national CO<sub>2</sub> emissions have been based on apparent fuel consumption at the country level, where apparent consumption is defined as production + imports – exports – changes in stocks – fuels used for international transport. Estimates of apparent consumption of major fuel groups at the country level have been available using UN data since the earliest CDIAC analyses in 1984. The UN has been gradually expanding coverage of energy data and now includes detailed consumption data, by economic sector, for fossil fuels. Examination of the UN data suggests that the consumption data are sufficiently comprehensive and complete to make direct estimates of CO<sub>2</sub> emissions, by country, by fuel and sector for years beginning in 1995. The Hefner and Marland (2023 and 2024) dataset is thus the first CDIAC dataset that includes emissions by fuel and economic sector – based on UN energy consumption data. The 2024 CDIAC CO<sub>2</sub> dataset thus provides estimates of emissions over 11 economic sectors. Because of the details of data collection, the treatment of non-fuel uses of fossil fuels (e.g. as lubricants, solvents, etc.) and uncertainty in the factors used to convert energy data to CO<sub>2</sub> emissions estimates, the sum of CO<sub>2</sub> emissions from a country are not exactly the same for the sum of sectors as for apparent consumption of the major fuel groups. We call this a statistical difference. National CO<sub>2</sub> estimates from apparent consumption of fuels are generally larger by a few percent than estimates based on sectoral energy consumption.

This paper examines, by country and region, how the source of CO<sub>2</sub> emissions has been changing over time. What is the mix of the major fuel groups in use and how does this vary among countries and over time? And what sectors are most responsible for the change in the mix of emissions? Sect. 2 of the paper examines the changing mix of fuels used globally and regionally over time, and Sect. 3 adds examination of the change in the sectoral composition of emissions. All fuels are aggregated into 3 major categories: solid fuels such as coal and lignite, liquid fuels such as gasoline and diesel fuel, and gaseous fuels such as natural gas. Section 4 discusses the patterns in CO<sub>2</sub> emissions as displayed in ternary diagrams, and Sect. 5 expresses conclusions.

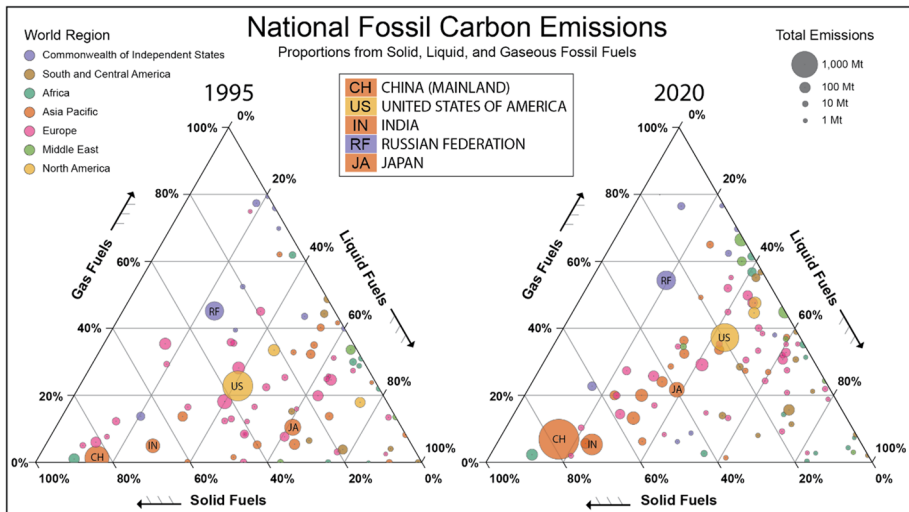
## 2 The mix of fossil fuels used

Using ternary diagrams, we examine how the fraction of emissions from solid, liquid, and gas fossil fuels compares across countries and regions and how these have changed with time. Although many factors are involved in a country's selection of fuels, the changes provide some insight on what has motivated changes and the prospects for continuing change. Point locations on ternary diagrams in these analyses represent the proportions of sources of a country's CO<sub>2</sub> emissions at a point in time. These diagrams do not illustrate fractions of energy derived from these sources or from renewable and non-fossil sources – they show

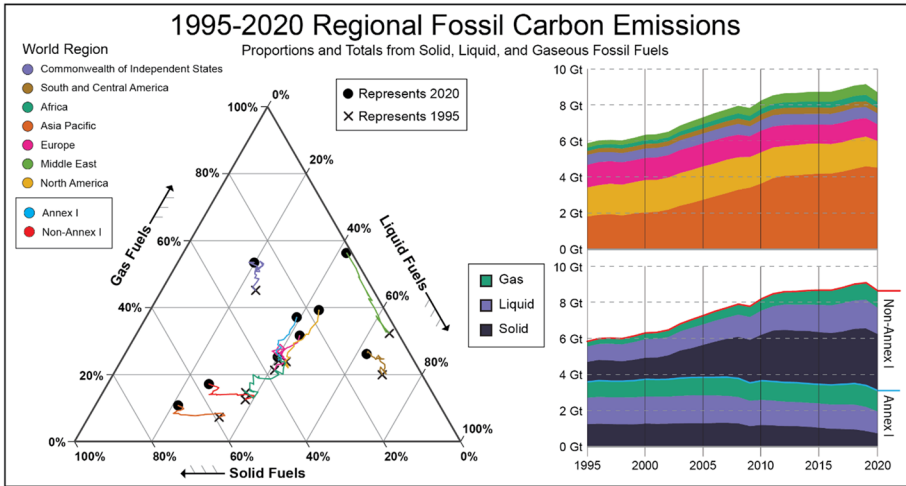
the fractions of CO<sub>2</sub> emissions emitted from the different fuel groups. As a consequence of solid fuels' aforementioned lower usable energy content per carbon content, more energy can be derived from fossil fuels per carbon emitted at locations further away from the solid fuel corner of the ternary diagrams.

In this paper, "total emissions" refers to emissions directly from the use of solid, liquid, and gas fossil fuels. These values are less than the total emissions column in the CDIAC source data, as those totals include emissions from gas flaring and cement manufacturing (Hefner and Marland 2023). Definitions of geographic regions are taken from the BP energy statistics database (BP 2022). Figure 1 shows fossil carbon emissions from many countries in both 1995 (on the left) and 2020 (on the right). Countries are represented by graduated circles on each diagram; the size and color of the circles representing total national emissions and geographic region, respectively. The reference year at 1995 was chosen for being the first year of the Conference of Parties of the United Nations Framework Convention on Climate Change. Because of political changes and varying levels of data availability (such as countries coming into and going out of existence), there are 83 countries on the 1995 diagram and 95 countries on the 2020 diagram. These are the countries for which emissions data are complete for each year for all three fuel types. If lacking a value for one fuel type, a country's supply data are judged complete only if there is an actual reported value of zero. Figure 1 shows, for example, that countries from the Middle East (green circles) concentrate along the liquid/gas line and that from 1995 to 2020 they have migrated toward the gas corner of the diagram (see also Fig. 2). For the Middle East, the contribution of emissions from coal is very small.

The five countries with the largest total CO<sub>2</sub> emissions in 2020 are identified in Fig. 1. From greatest to least emissions, these are: China, the United States, India, the Russian Federation, and Japan. These are the same countries with the largest cumulative emissions



**Fig. 1** Fossil carbon dioxide emissions (measured in Mt of carbon) from countries in 1995 (left) and 2020 (right). The color and size of the circles represent the geographic region and total national emissions, respectively. The five largest emitters of 2020 are individually labeled. The country nearest the coal corner in both diagrams is South Africa, and the country with the highest proportion of emissions from natural gas in both diagrams is Armenia



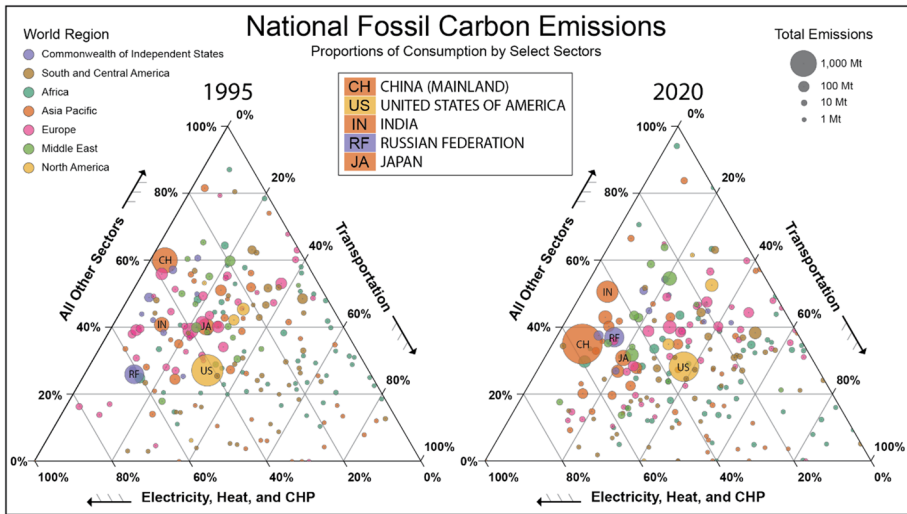
**Fig. 2** (Left) Ternary diagram of the evolution of CO<sub>2</sub> emissions by fuel group for world regions, Annex I, and Non-Annex I countries for 1995–2020. (Top right) Total emissions by world regions. (Bottom right) Solid, liquid, and gas-fuel emissions by Annex I and Non-Annex I countries. Values are in Gt of carbon

from 1995 to 2020, with nearly the same rank order except that the Russian Federation had more cumulative emissions than India despite larger emissions from India in 2020. The source fuel proportions and total emissions each year for these countries are shown in Table 1. The national identity and data for all points in Figs. 1 and 3 can be obtained as described in the Data Availability note at the end of this paper.

Notably, the proportion of United States emissions from solid fuels fell between 1995 and 2020 while Japan’s grew – see Table 1 and Fig. 1. Both the US and Japan saw reductions in total emissions. The Russian Federation saw a slight increase in total emissions with decreases in liquid fuel and solid fuel proportions, and a notable increase in the gas proportion. Among the most noticeable changes from 1995 to 2020 were for China and India, both of which retained high proportions of emissions from solid fuels—among the highest of any country—and both saw significant increases in total emissions – 221% and 192% growth, respectively. China moved slightly away from the solid fuels corner. India moved very little.

**Table 1** Countries with the largest CO<sub>2</sub> emissions both cumulatively between 1995 and 2020 and in 1995 and 2020. Emissions are shown in kt of carbon

	1995				2020			
	Solid	Liquid	Gas	Total (ktC)	Solid	Liquid	Gas	Total (ktC)
CHINA (MAINLAND)	83.4%	15.2%	1.4%	840,726	77.7%	15.4%	6.9%	2696253
UNITED STATES	36.2%	40.9%	22.9%	1384937	19.5%	43.2%	37.3%	1206475
INDIA	67.1%	27.8%	5%	211986	69.9%	24.8%	5.3%	469229
RUSSIAN FEDERATION	31.1%	23.7%	45.3%	436943	26.1%	19.5%	54.4%	469229
JAPAN	28.2%	61.3%	10.6%	314379	39.7%	38.6%	21.7%	265616



**Fig. 3** Ternary diagram of CO<sub>2</sub> emissions by economic sector: transportation, electric power generation, and the sum of all other sectors. The figure shows changes in the mix of CO<sub>2</sub> sources as economies evolve and emissions sources evolve. CHP is combined heat and power plants. Circle size represents the sum of all sectors; thus, many countries appear slightly smaller than in Fig. 1 due to statistical differences in the energy data, as described in the text

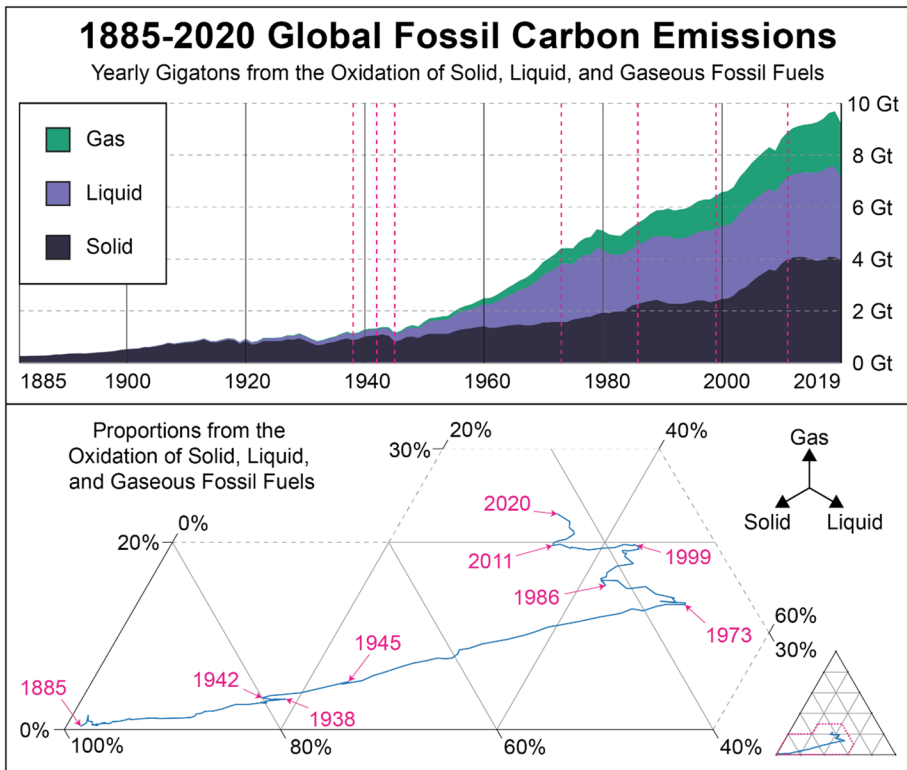
From 1995 to 2020, North American countries moved away from the solid-fuel corner, with the exception of Mexico, whose solid-fuel proportion increased by 1.2%. Twenty-five of the 31 European nations for which there are complete data for both years saw a decrease in their solid-fuel CO<sub>2</sub> proportion. Thirteen European countries decreased their proportion of emissions from solid fuels by more than 10%, and only one – Bosnia and Herzegovina – had an increase of more than 8%. Europe as a whole saw a 26% decline in total emissions. Two-thirds of Iran’s emissions, the largest in the Middle East region, came from gas fuels in 2020, up from one-third in 1995.

The country at the bottom and left-most position on both diagrams, having the highest fraction of emissions from solid fuels of any country for both years, was South Africa, whose solid-fuel proportion was 89.4% and 87.0% in 1995 and 2020, respectively. South Africa also had the largest total emissions of any African country for both years. Notably, there is a large spread in the source proportions of African countries. Egypt and Algeria, for example, had solid-fuel proportions of less than 5% in both years, appearing near the liquid–gas edge of the diagrams, with Egypt joining Algeria in 2020 as having a majority of emissions from gas fuels. South and Central American countries for which the data are complete remained clustered near the liquid corner of the diagram, with only Argentina and Venezuela dropping just below 50% of emissions from liquid fuels in 2020 in favor of gas fuels.

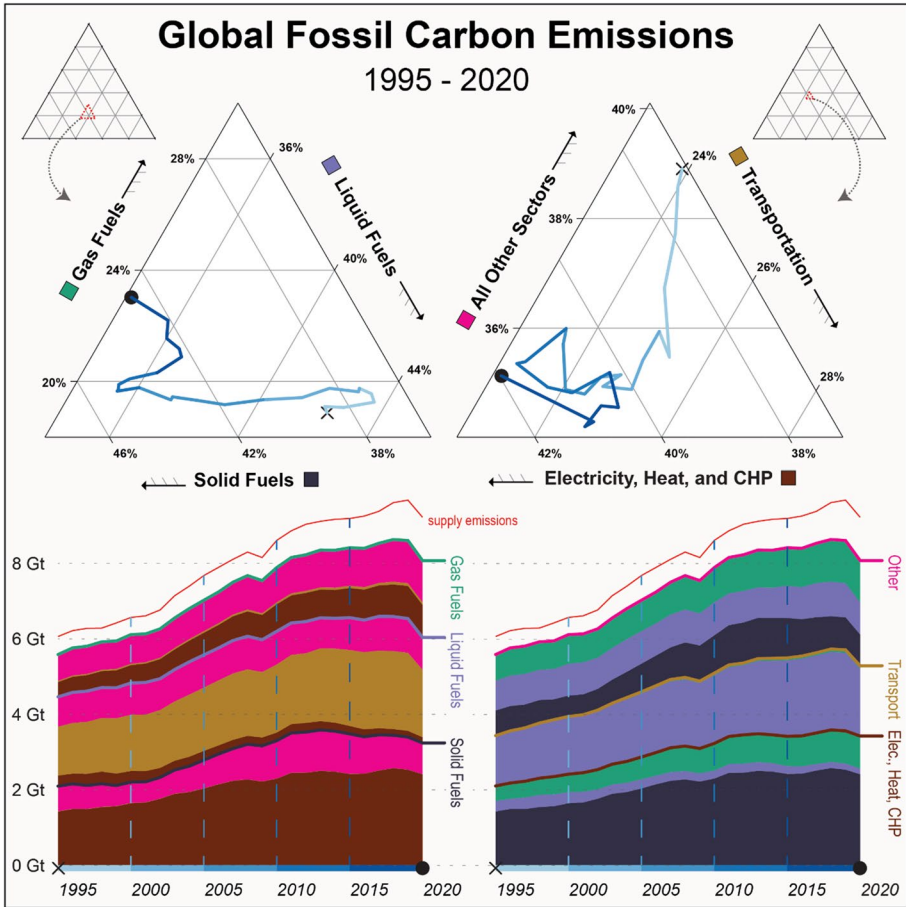
An important feature of Fig. 1 is illustration of how countries in the Asia Pacific region clustered toward the solid-fuel corner and emissions grew in size. Fifteen of the 18 countries (including Hong Kong and Taiwan as distinct entities) in the region with complete data increased their solid fuel proportion from 1995 to 2020. Six (the Philippines, Indonesia, Afghanistan, Malaysia, Vietnam and Pakistan) increased the

proportion of their emissions from solid fuels by more than 20%, and only two (Australia and Hong Kong) decreased their total emissions. This trend can be seen in Fig. 2 as well.

Figure 2 shows the paths of change for proportions of collective, regional CO<sub>2</sub> emissions for each year from 1995 to 2020. The path for Asia Pacific moves steadily toward the solid corner until an abrupt change after 2011. The path of Non-Annex I countries closely follows this path; Asia Pacific accounted for 74.4% of the cumulative emissions from Non-Annex I countries over this time period. For all other regions, the general trend from 1995 to 2020 is toward an increased fraction of emissions from gas and away from solid fuels. The migration to gas fuels is particularly evident for the Middle East. The increase in solid-fuel emissions from Non-Annex I countries and total emissions from Asia Pacific over the 1995–2020 time period is clear in the time series plots on the right side of Fig. 2. In 1995, Non-Annex I countries accounted for only 36% of global total emissions. By 2020, emissions from solid fuels alone from Non-Annex I countries was roughly equivalent to (99.6% of) the total value of emissions from all fuel sources in Annex I countries. Of emissions from Non-Annex I countries solid fuels, 93.2% came from Asia Pacific in 2020. The impact on global source proportions from the size of these increased emissions from solid fuels is also reflected in the trend observed between 1999 and 2011 in Figs. 4 and 5.



**Fig. 4** (Top) Global emissions from solid, liquid, and gas fossil fuels in Gt carbon. (Bottom) Ternary diagram of proportions of global total emissions by major fuel group. The Covid pandemic effect on the use of liquid transportation fuels in 2020 is apparent with decreases in both parts of the Figure



**Fig. 5** (Top) An extract of the ternary diagrams of global emissions proportions from 1995 to 2020 by (Left) fuel type and (Right) sector. The small red triangles show the fractions of the ternary plots that are extracted. As in Fig. 2 the x represents the proportions in 1995 and the dark circles show the proportions in 2020. The track lines move from lighter to darker blue in 5-year increments to make clear the directionality from 1995 to 2020. (Bottom) Stacked area plots of emissions by (Left) sectors within the 3 fuel types and (Right) fuel types within 3 sector groupings. Values of emissions are in Gt carbon. Colors on the left are as labeled and on the right as in Fig. 4. The red line at the top shows the total emissions estimates based on apparent consumption so the difference between the red line and the top of the stacked area plots is the statistical difference (see text)

Since 1995 North America, Europe, and Africa have significantly reduced the solid-fuel proportion of their CO<sub>2</sub> emissions. The Commonwealth of Independent States' emissions largely track with the movement of the Russian Federation observed in Fig. 1, much as the Middle East largely tracks with the emissions of its largest contributor, Iran. The ternary diagram in Fig. 2 also reveals that, while every region observed an increase in the gas proportion of their emissions, Asia Pacific's increase was the smallest.



### 3 The sectoral composition of CO<sub>2</sub> emissions sources

Because different fossil fuels are often used for different purposes, the mix of CO<sub>2</sub> emissions will reflect the mix and prevalence of the different economic sectors. As an economy evolves and different sectors increase or decrease in relative importance, the relative prevalence of fuels used can change as well. Changes in CO<sub>2</sub> emissions can thus be a reflection of changes in the structure of the economy rather than a purposeful change in the mix of fuels used. To illustrate within our ternary diagrams the distribution of CO<sub>2</sub> emissions as a function of the structure of the economy, we have summed emissions across 3 sectoral groupings that characterize the major sources of emissions: transportation, electrical power generation (including heat plants and combined heat and power plants), and the sum of all other sectors. Figure 3 shows, for all countries with complete consumption data, emissions for 1995 and 2020. The most striking feature of Fig. 3 is a slight migration toward emissions from electric power generation. Electric power, heat, and combined heat and power plants were responsible for 37.2% of global emissions in 1995; this increased to 42.0% in 2020. The migration is striking in the largest global emitter, China (from 36.2% in 1995 to 57.3% in 2020), but countered slightly by the second largest emitter, the USA (from 41.6 to 34.4%). Notably, electric power is a sector with multiple alternatives for moving to energy sources that do not depend on fossil fuels (see e.g., IEA 2023, p. 123–129).

### 4 Discussion

Figure 4 shows global total CO<sub>2</sub> emission proportions by major fuel group plotted over time since 1885 as a stacked area plot (on the top) and in ternary space (on the bottom). The figure shows apparent inflection points, marked with pink indicators on both diagrams. The inflection points generally coincide with major geopolitical events. The diagrams in Fig. 4 start in 1885 for visual clarity, as emissions from gas fuels prior to that year round to zero megatons. The long trend toward 1973 follows the growing use of liquid transportation fuels. From 1885 to 1938, there was a consistent relative decrease in the proportion of emissions from solid fuels, from 98.4% to 77.8%, and an increase in the liquid proportion, from 1.6 to 18.9%. During the early years of World War II, the global solid-fuel proportion of emissions increased and peaked at 79.9% in 1942, dropping to 71.1% by the end of the war in 1945.

From 1945 to 1973 there was a mostly consistent and significant decrease in the solid-fuel proportion of emissions (from 71.1% to 35.9%) and an increase in the liquid proportion (from 23.8% to 50.8%), with a modest increase in the gas proportion (from 5.1% to 13.3%). The end of this trend coincides with the 1973 oil crisis and a decreasing fraction of emissions from liquid fuels, as access to natural gas increased for both heating and power generation. The liquid proportion dropped steadily during the oil crises of the 1970s and until 1986. The proportion of emissions from natural gas continued to increase through to 2020. From 1999 to 2011 there was a rise in the global solid-fuel proportion, from 37.1% to 44.9%, coinciding with significant increases in economic growth and solid-fuel emissions from Non-Annex I countries, as shown in Fig. 2. Long term, the proportions of emissions from solid, liquid, and gas fuels, as shown in Figs. 1, 2, 4, and 5, reflect economic trends and the mix of fuel applications seen in diagrams of the major economic sectors responsible for emissions, as shown in Figs. 3 and 5.

Figure 5 originates in 1995, the point at which the UN energy data are sufficiently comprehensive to accurately represent global emissions by economic sector, and noting that 1995 was the first year of meetings of the Conference of Parties of the United Nations Framework Convention on Climate Change. Figure 5 shows, for example, the 2020 impact of the Covid pandemic, which is seen to have had a major effect on transportation emissions and on liquid fuels. Figure 5 shows, in the top left, that from 1995 to 2020 emissions moved slightly toward solid and gaseous fuels and away from liquid fuels while, in the top right, the balance of emissions moved toward power generation, away from the sum of all other sectors, and very little with respect to transportation (except in 2020).

Globally, and in most geographic regions, the current trend is away from coal and toward natural gas for electric power generation. This results in the desired outcome of a decreasing trend in CO<sub>2</sub> emissions per unit of fossil fuel energy consumption.

## 5 Conclusions

Mitigation of global climate change will require migration away from the use of fossil fuels for energy. A broad range of studies suggests that this needs to happen strongly and soon (e.g. IPCC 2021) and this has been stated emphatically in the report from COP28 (UN 2023). Most notably, there is agreement that, in the near term, this needs to involve migration away from the fossil fuel with the highest ratio of carbon emissions per unit of primary energy – coal – but inevitably from all fossil fuels. Historically, the mix of fossil fuels used has depended on the structure of the economy, the availability and cost of energy resources, the mix of energy needs, and sometimes on environmental and other factors. Mapping the ratio of fuels used globally and in different regions shows striking trends in evolution over time. Notably, with the exception of the Asia–Pacific region, from 1995–2020 there has been a migration away from emissions from solid fuels and toward emissions from gas fuels. Although total global CO<sub>2</sub> emissions from fossil fuels continues to increase (Friedlingstein 2023), the fraction of emissions from coal is declining in most countries and regions. Historically, CO<sub>2</sub> emissions have been tied to classic uses of solid, liquid, and gaseous fuels. In addition to substitution of fossil fuels for alternatives altogether, recent deceleration trends in emissions have been related to substitution of lower-carbon gaseous fuels for electric power generation – an effect that will grow with migration of transportation from liquid fuels to electricity. Protection of the global climate system, however, will require global accord and global action to move away from coal in all regions and ultimately away from all fossil fuels universally.

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**Data availability** All of the data illustrated in this paper, plus identification—by country—for each of the points plotted in Figs. 1 and 3 are available at <https://datadash.appstate.edu/cdiac/>. The R Script for the Figures is available on request.

## Declarations

**Competing interests** The authors report that there are no competing interests and nothing to declare.

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