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CO_2 EMISSION CALCULATIONS AND TRENDS

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ABSTRACT

This paper describes the compilation, calculation, and availability of the most comprehensive CO_2 emissions database currently available. The database offers global, regional, and national annual estimates of CO_2 emissions resulting from fossil-fuel burning, cement manufacturing, and gas flaring in oil fields for 1950–92. The methods of Marland and Rotty [1,2] are used to derive estimates from energy data published by the United Nations and the U.S. Department of Energy and cement production data published by the U.S. Bureau of Mines. This CO_2 emissions database is useful for carbon-cycle research, provides estimates of the rate at which fossil-fuel combustion and cement production have released CO_2 to the atmosphere, and offers baseline estimates for those countries compiling CO_2 emissions inventories.

According to these estimates, the annual total of CO_2 emissions from fossil fuel consumption, cement production, and gas flaring has grown almost fourfold since 1950. The 1992 estimate of 6097 million metric tons of carbon ends a string of 8 consecutive years of growth in global CO_2 emissions and represents a 1.2% decline from 1991. The 1991 estimate of 6172 million metric tons of carbon is the highest CO_2–emission estimate since the data record began in 1950, but it includes 130 million metric tons of CO_2 emitted to the atmosphere from the Kuwaiti oil–field fires.

Regionally, a marked decline in CO_2 emissions continued in 1992 for Eastern Europe, and Western Europe experienced its first decline in emissions since 1987–88. However, regions where populations continue to grow—such as Africa, Centrally Planned Asia, Central and South America, the Far East, and Oceania—showed increases in CO_2 emissions. In 1950, North America, Eastern Europe, and Western Europe (including Germany) accounted for 89.1% of global CO_2 emissions from fossil-fuel burning, cement production, and gas flaring, whereas the remaining six regions—Africa, Central and South America, Centrally Planned Asia, the Far East, the Middle East, and Oceania—accounted for only 10.9%. Now these six regions contribute 41.1% of the CO_2 emitted globally.

Nationally, the United States continued as the largest single source of fossil fuel–related CO_2 emissions, with 1332 million metric tons of carbon emitted in 1992. The top three emitting countries—the United States, China, and Russia—were responsible for 43.2% of the world's emissions from fossil fuel burning in 1992. The top 20 emitting countries accounted for ~80% of all the world's emissions.

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INTRODUCTION

Evidence that the atmospheric CO_2 concentration has risen during the past several decades is irrefutable [3,4,5]. Most of the observed increase in atmospheric CO_2 is believed to result from CO_2 releases from fossil-fuel burning. The United Nations (UN) Framework Convention on Climate Change (FCCC), signed in Rio de Janeiro in June 1992 [6], reflects global concern over the increasing CO_2 concentration and its potential impact on climate. One of the convention's stated objectives was the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Specifically, the FCCC asked all 154 signing countries to conduct an inventory of their current greenhouse gas emissions, and it set nonbinding targets for some countries to control emissions by stabilizing them at 1990 levels by the year 2000. Given the importance of CO_2 as a greenhouse gas, the relationship between CO_2 emissions and increases in atmospheric CO_2 levels, and the potential impacts of a greenhouse gas–induced climate change; it is important that comprehensive CO_2 emissions records be compiled, maintained, updated, and documented.

Keeling [7] was the first to establish a systematic method for estimating the amount of CO_2 emitted from fossil fuels. Keeling used energy data from the UN Department of International Economic and Social Affairs. Since 1973, both the energy data collection and the procedures for estimating CO_2 emissions have been refined and improved [1,2,8]. The distributions, trends, and patterns of these fossil-fuel CO_2 emissions have been studied and described [2,9–11].

Another source of CO_2 is cement manufacturing. Hydraulic cement, particularly Portland cement, is the most abundant and widely used type of cement. Portland cement is a combination of two types of raw materials: one rich in calcium, such as limestone, chalk, marl, or clam or oyster shells; the other rich in silica, such as clay or shale [12]. In a cement kiln, calcium carbonate ($CaCO_3$) is broken down (calcined) into CO_2 and calcium oxide (CaO) [13]. The CaO is used in manufacturing cement and the CO_2 is released to the atmosphere. Previous studies determined the amount of CO_2 emitted during cement manufacturing using data published by the UN or the U.S. Bureau of Mines [7,12]. Although the amounts of CO_2 produced from cement manufacturing are far less (~3% of 1992 global CO_2 emissions) than those from fossil-fuel consumption, the quantities are large enough to constitute an important source of CO_2 emissions.

Another source of CO_2 is the flaring of natural gas, a practice used in oil fields to eliminate waste gases and vapors. This practice is used for convenience in oil field operations that lack the ability to adequately handle and recover natural gas while producing oil, and is used as a mechanism to quickly eliminate excess gases during unexpected equipment failures or plant emergencies. Like those from cement production, emissions from gas flaring are far less (~1% of 1992 global CO_2 emissions) than those from fossil-fuel consumption. For some nations (e.g., Kuwait and Oman), however, CO_2 emissions from gas flaring constitute a sizeable portion of their total CO_2 emissions; these emissions were particularly high during the 1960s and 1970s, before the Middle Eastern countries had the infrastructure and impetus to recover natural gas at their oil fields.

CONTENTS OF THE CO_2 EMISSIONS DATABASE

Each year, the Carbon Dioxide Information Analysis Center (CDIAC) compiles a time series of CO_2 emission estimates using the methods of Marland and Rotty [1,2]. The current database contains annual CO_2 emission estimates for the period 1950–92 for the globe, 10 regions, and about 240 countries. The database also contains the data used in calculating these emission estimates: a large portion of the 1992 UN Energy Statistics (UNSTAT) Database [8], hydraulic cement production estimates compiled by the U.S. Department of Interior's Bureau of Mines [14], and supplemental data on gas flaring obtained from the U.S. Department of Energy's Energy Information Administration (DOE/EIA). In addition, annual per capita rates of carbon emission are included. These emission rates were calculated using population estimates published by the UN Statistical Division.

DATA SOURCES

The primary database used to estimate the amount of CO_2 emitted to the atmosphere from fossil-fuel burning, gas flaring, and cement production is the UNSTAT Database. The UNSTAT Database is a comprehensive collection of international energy data compiled by the United Nations Statistical Office.[1] This database provides data for primary and secondary forms of energy. The data are reported for almost every nation in the world and are reported by individual fuel types. The complete UNSTAT Database also contains data on production, consumption, capacity, reserves, losses, and trade of heat and power, renewable, and nuclear energy commodities; none of which are used for the calculation of CO_2 emissions. The complete 1992 version of the UNSTAT Database contains 440,623 records with 3,084,361 data values and requires ~13 megabytes of disk space. The energy statistics in the UNSTAT Database were compiled primarily from annual questionnaires distributed by the UN Statistical Office and were supplemented by data in official national statistical publications. Where official data were not available or were inconsistent, estimates were made by the Statistical Office based on governmental, professional, or commercial materials. These international statistics are published annually by the UN in the *Energy Statistics Yearbook* (originally published as *World Energy Supplies in Selected Years, 1929–1950*). There is typically a 2-year lag between the publication of the yearbook and the last year of data (i.e., the 1994 yearbook provides energy statistics through 1992).

The cement manufacturing data used to estimate emissions from hydraulic cement production were compiled by the U.S. Department of Interior's Bureau of Mines. The cement production database is a comprehensive collection of international data from 166 countries. These data, like those in the UNSTAT Database, are reported on an individual country basis. In cement production, CO_2 is released through calcination to the atmosphere:

$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2$$

Because cement manufacturing uses essentially 100% of the calcium oxide obtained from burning the calcium carbonate, the amount of calcium oxide in the finished cement provides a good measure of the amount of CO_2 released during production [12].

Gas-flaring CO_2 emission estimates are derived primarily from flaring estimates provided in the UNSTAT Database. The UNSTAT Database has an incomplete time series for many countries including China, France, Norway, Oman, and Russia and little data before 1970. Gas-flaring estimates provided by DOE/EIA were used to complete or supplement the flaring time series for these countries, and the resulting database contains estimates of gas flaring from 57 countries.

DATA PROCESSING AND CHECKING

The CO_2 emissions database is derived from a variety of sources and requires considerable data processing, selection, and integration (Figure 1). Each of the data sets used for calculating the CO_2 emission estimates is checked carefully. CDIAC works with the UN Statistical Division annually to quality-assure each new version of the UNSTAT Database. The review process is unable to detect some kinds of data problems but confirms that the UNSTAT Database meets high standards of data management and internal consistency. The following highlights the quality-assurance checks performed routinely on the **entire** UNSTAT Database, not just those data used in the CO_2 emission

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[1] The complete UNSTAT Database is available from the United Nations Statistical Division, 2 United Nations Plaza, New York, NY. 10017.

calculations.

Compare the New Database to the Previous Version

The 1992 UNSTAT Database, released in May 1994, was checked against the 1991 version to identify additions, deletions, and changes. In general, the oldest data (i.e., 1950–69) had no changes, whereas in the newer data (1970–92), there were many (>1000) differences. This reflects the dynamic nature of the UNSTAT Database and the constant addition, deletion, and revision of data as new information is obtained. The dynamic nature of the UNSTAT Database also requires that users of the CO_2 emissions database replace previous versions of the database in their entirety, instead of simply appending the most recent years' emission estimates.

Check for Duplicate Entries

The 1992 UNSTAT Database was sorted by country, year, commodity, transaction code, quantity, and units in a search for duplicate entries. Duplicate entries were deleted from the database.

Check for Questionable Data

The UNSTAT data were examined to identify suspect data. The checks that were performed identified:

- Inappropriate years (outside of the 1950–92 range)
- Invalid country codes (checked against the UN documentation)
- Invalid transaction codes (certain transaction codes are valid for only some commodities)
- Questionable import/export quantities (in relation to production quantities)
- Inappropriate units
- Improper signs (some transactions can be only positive or only negative)
- Gaps or large changes in quantities between adjacent years for the same country, commodity, and transaction

These checks have identified many "suspicious values." Some are clearly errors, whereas most suggest review by the UN Statistical Division and are referred back to them for consideration. Rarely, and only in the case of unmistakable errors and with the concurrence of the UN Statistical Division do the authors purge or change values before calculating the CO_2 emission estimates. Having performed this exercise for 7 years, and continually refining the quality-assurance process, we now find few "suspicious values" during the annual quality-assurance exercise.

CO_2 EMISSION CALCULATIONS

As indicated earlier, data from the UNSTAT Database were the primary data used to calculate the CO_2 emission estimates. Fuel production data were used in generating global CO_2 emission estimates because these data are more complete than energy consumption data. For regional or national emission estimates, however, one needs to know the amount of fossil fuels consumed, and not the amount produced, by an individual country in order to calculate the CO_2 emitted.

The calculation of CO_2 emissions from fossil fuels is conceptually very simple [2]. For each type of fuel, the annual CO_2 emissions are the product of three terms: the amount of fuel consumed, the fraction of the fuel that becomes oxidized, and a factor for the carbon content of the fuel [2]. That is,

$$CO_{2_i} = (P_i)(FO_i)(C_i) , \tag{1}$$

where subscript i represents a particular fuel commodity, P represents the amount of fuel i that is consumed each year, FO is the fraction of P that is oxidized, C is the average carbon content for fuel i, and CO_2 is the resulting CO_2 emissions for fuel i expressed in mass of carbon. For CO_2 emissions, fossil fuels can be divided into the usual groups of solid, liquid, and gas fuels. An identical procedure has been adopted by the Intergovernmental Panel on Climate Change (IPCC) in prescribing a methodology for countries to use in estimating and reporting greenhouse gas emissions [15].

Global total CO_2 emission estimates are generated using the above equation where P represents production data from the UNSTAT Database for all primary solid, liquid, and gas fuels. Because secondary fuels are derived from primary fuels, they need not be included.

Trade data are required to calculate regional and national CO_2 emission estimates. For these calculations, both primary and secondary fuel data are used. Table 1 lists the UNSTAT primary and secondary fuels used in these CO_2 emission calculations. Consumption [i.e., P_i in eq. (1)] is the sum of production and imports less exports, "bunkers", and stock changes. This is what the UN calls "apparent consumption" as it relies on production and trade data rather than end-use consumption data. That is,

$$consumption_i = production_i + imports_i - exports_i - bunkers_i - changes\ in\ stocks_i , \tag{2}$$

where i is a primary solid, liquid, or gas fuel. Bunkers refer to fuels consumed by ships and aircraft engaged in international trade. Stock changes refer to changes in stocks at producers, importers, and/or industrial consumers from the beginning to the end of each year.

Adjustment is made for the fraction of crude oil converted into non-energy products (e.g., lubricants, asphalt, naphthas). National totals for emissions from petroleum products are based on energy uses only and do not include emissions from the oxidation of nonfuel products while the global totals do include an estimate of emissions from oxidation of the non-energy products.

Once consumption and production values have been calculated, these estimates are multiplied by a factor that reflects the fraction of each broad fuel category that is oxidized [i.e., FO in Eq. (1)] and the average carbon content (C) of each fuel category. Table 2 lists the values and units of P, FO, and C for each fuel category.

CO_2 Emissions from Cement Manufacturing

Because cement manufacturing uses essentially 100% of the calcium oxide obtained from burning the calcium carbonate during calcination, the amount of calcium oxide content in the finished cement is a good measure of the amount of CO_2 released during production [12]. To determine the amount of CO_2 released from cement manufacturing, one needs to know how much cement was manufactured, the average calcium oxide content per unit of cement, and a factor to convert the calcium oxide content into carbon dioxide. Cement production data published by the U.S. Bureau of Mines are currently reported in thousand short tons, but before 1970 the data were reported in barrels. To ensure consistent units throughout the 1950–92 record, two equations were used to convert cement production estimates to units of metric tons. Cement production before 1970 was calculated using:

cement production (in metric tons) = 0.17055 × *quantity of cement produced (in barrels)* , (3)

where 0.17055 is the metric-ton equivalent for a barrel.

After 1969, net cement production was calculated using:

cement production (in metric tons) = 0.90718474 × *quantity of cement produced (in short tons)* , (4)

where 0.90718474 is the metric-ton equivalent for a short ton. The amount of CO_2 produced from cement production was calculated using:

$$CO_2 \; production \; (in \; metric \; tons \; of \; C) = 0.136 \text{ metric tons of C per metric ton cement} \times quantity \; of \; cement \; produced \; (metric \; tons) \quad (5)$$

This conversion factor was obtained by dividing the molar mass of carbon by the molar mass of calcium oxide and multiplying this quotient by the average fraction of calcium oxide contained in cement:

$$(12.01 \text{ g C/mole } CaCO_3 \div 56.08 \text{ g CaO/mole } CaCO_3) \times 0.635 \text{ g CaO/g cement} = 0.136 \text{ g C/g cement} \quad (6)$$

The consensus that 63.5% of the typical cement in the world is composed of calcium oxide is based on the opinions of experts consulted in the field, as well as inspection of composition data by type and country [12].

Per Capita CO_2 Emission Rates

Using the UN population data, the authors estimate per capita CO_2 emission rates for individual countries using the equation:

$$national \; per \; capita \; CO_2 \; emission \cdot year^{-1} = total \; national \; CO_2 \; emission \; estimate \cdot year^{-1} \div national \; population \quad (7)$$

The resulting per capita estimates are expressed in metric tons of carbon $\cdot$ person^{-1} $\cdot$ year^{-1}.

TRENDS IN CO_2 EMISSIONS

According to these estimates, the global total of CO_2 emissions from fossil-fuel consumption, cement production, and gas flaring has grown almost fourfold since 1950 (Table 3 and Figure 2). The 1992 estimate of 6097 million metric tons of carbon ends a string of 8 consecutive years of growth in global CO_2 emissions and represents a 1.2% decline from 1991. The 1991 estimate of 6172 million metric tons of carbon is the highest CO_2–emission estimate since the data record began in 1950, but it includes 130 million metric tons of CO_2 emitted to the atmosphere from the Kuwaiti oil–field fires.

Globally, liquid and solid fuels accounted for 79% of the emissions from fossil-fuel burning in 1992. Combustion of gas fuels (i.e., natural gas) accounted for ~17% (1045 million metric tons C) of total emissions from fossil fuels in 1992 and reflects a gradually increasing global utilization of natural gas. Emissions from cement production increased slightly and now account for ~3% of total emissions. Emissions from gas flaring declined 10.5% from 1991 to 1992 to 68 million metric tons C (just 1% of the global total) and remain well below the levels of the 1970s. This trend for gas flaring is not fully clear because of uncertainty about the gas-flaring data for Russia.

Regionally, Eastern Europe continued to have a marked decline in CO_2 emissions, North American emissions increased 1.3% during 1992 after 2 successive years of declining emissions, and

Western Europe experienced its first decline since 1987–88 (Figure 3). However, regions where populations continue to grow—such as Africa, Centrally Planned Asia, Central and South America, the Far East, and Oceania—showed increases in CO_2 emissions (Figure 4). In 1950, North America, Eastern Europe, and Western Europe (including Germany) accounted for 89.1% of global CO_2 emissions from fossil-fuel burning, cement production, and gas flaring, whereas the remaining six regions accounted for only 10.9%. Now these six regions—Africa, Central and South America, Centrally Planned Asia, the Far East, the Middle East, and Oceania—contribute 41.1% of the CO_2 emitted globally.

The top 20 emitting countries accounted for ~80% of all the 1992 world CO_2 emissions from fossil-fuel consumption (Figure 5). The top three countries—the United States, China, and Russia—were responsible for 43.2% of the world's emissions from fossil fuel burning in 1992. Spain, the 20th-highest CO_2-emitting nation, contributed slightly less than 1% to this total. The United States continued as the largest single source of fossil fuel–related CO_2 emissions, with 1332 million metric tons of carbon emitted in 1992. In fact, U.S. emissions are ~45% higher than those of the world's second largest emitter, China. U.S. emissions in 1992 were nearly twice those of 1950, although the U.S. share of global emissions declined from 44% to 23% over the same interval because of higher growth rates in other countries.

LIMITATIONS

Marland and Rotty [2] estimated that the uncertainty on the annual global CO_2 emission estimates derived from the United Nations' energy data was ~6–10%. The reliability of the CO_2 estimates presented here is bounded by the accuracy and completeness of the values reported by each country to the UN Statistical Office. The values published by the UN are consistent with numbers published elsewhere and represent the best efforts of a staff dedicated to the sole task of bringing together all the available global energy information. It is not possible to independently verify each number reported by individual countries to the UN. When inconsistencies arise in the official data, the UN Statistical Office makes its own estimates based on governmental, professional, or commercial materials.

CO_2 emission estimates for some individual countries and regions are less reliable than the global CO_2 emission estimates. Global totals depend on only production data with some representation of fuel chemistry and fractions of fuels that are oxidized. Regional and national data rely further on information for additional transactions (e.g., refinery product mix by country, imports, exports, bunker loadings). For some countries, it is difficult for the UN to obtain sufficient production, consumption, and trade data. Also, even though the authors account for all of these mass transfers, we do not attempt to deal with the different carbon content of various products.

The sum of the CO_2 emissions for all of the individual countries for a given year, as reported here, will **not** equal the global total. There are 3 primary reasons for this. First, the national data rely on internal data on imports and exports and the reported total (over all countries) of exports does not exactly equal the reported total for imports. Also, we have used different treatment of nonfuel and bunker fuel uses in the global and national calculations. Nonfuel uses and bunker fuel usage are accounted for in the production data used for the global calculations, but are not included in national estimates. The difference between the sum of the individual countries and the global estimates is generally less than 5%.

AVAILABILITY OF THE CO_2 EMISSIONS DATABASE

The CO_2 emission estimates and underlying data are available in machine-readable form, upon request, from CDIAC without charge. CDIAC will also distribute subsets of the database as needed. This database may be acquired from CDIAC's anonymous File Transfer Protocol (FTP) area (see FTP access instructions below), or may be requested on 9-track or 8-mm magnetic tape, or on IBM- or Mac-formatted floppy diskettes. Requests for 9-track magnetic tapes should include preferred tape specifications (i.e., 1600 or 6250 BPI, labelled or nonlabelled, ASCII or EBCDIC characters, variable- or fixed-record lengths). Requests should be addressed to:

Carbon Dioxide Information Analysis Center
World Data Center—A for Atmospheric Trace Gases
Oak Ridge National Laboratory
Post Office Box 2008
Oak Ridge, TN 37830-6335, U.S.A.

Tapes, diskettes, and documentation may also be ordered by telephone, facsimile, or electronic mail:

Telephone: (423) 574-3645 or (423) 241-4842
Fax: (423) 574-2232

Electronic mail: cdiac@ornl.gov
CDIAC home page on the World Wide Web: http://cdiac.esd.ornl.gov/cdiac

The following are FTP access instructions.

FTP access: ftp cdiac.esd.ornl.gov (or 128.219.24.36)
Enter "anonymous" as the userid.
Enter your electronic-mail address as the password (e.g., "tab@ornl.gov").
Change to the directory "/pub/ndp030r6".

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TABLES

TABLE 1. LISTING OF THE PRIMARY AND SECONDARY FUELS FROM THE UNITED NATIONS ENERGY STATISTICS DATABASE USED IN CALCULATING CO_2 EMISSION ESTIMATES. THE TWO-LETTER COMMODITY CODE USED BY THE UNITED NATIONS FOR EACH FUEL TYPE IS SHOWN IN PARENTHESES.

Gas Fuels	
Primary gas fuels	*Secondary gas fuels*
Natural gas (NG)	Gasworks gas (GG)
	Coke-oven gas (OG)
	Refinery gas (RG)
Liquid Fuels	
Primary liquid fuels	*Secondary liquid fuels*
Crude petroleum (CR)	Aviation gasoline (AV)
Natural gas liquids (GL)	Plant condensate (CD)
	Gas-diesel oils (DL)
	Feedstocks (FS)
	Jet fuel (JF)
	Kerosene (KR)
	Liquefied petroleum gas (LP)
	Motor gasoline (MO)
	Natural gasoline (NT)
	Residual fuel oils (RF)
	Secondary nonenergy liquid fuels
	Bitumen/asphalt (BT)
	Lubricants (LU)
	Naphthas (NP)
	Petroleum coke (PK)
	Other petroleum products (PP)
	Petroleum waxes (PW)
	White spirit/industrial spirit (WS)
Solid Fuels	
Primary solid fuels	*Secondary solid fuels*
Coal (CL)	Lignite (brown coal) briquettes (BB)
Lignite/brown coal (LB)	Hard coal (patent fuel) briquettes (BC)
Oil shale (OS)	Brown coal coke (BK)
Peat (PT)	Peat briquettes (BP)
	Gas coke (GK)

TABLE 2. FACTORS AND UNITS FOR CALCULATING CO_2 EMISSIONS FROM FUEL PRODUCTION AND TRADE DATA $[CO_{2i} = (P_i)(FO_i)(C_i)]$

From primary and secondary gas fuel production and trade[1]

CO_{2g} = CO_2 emissions in 10^6 metric tons of carbon
P_g = annual production or consumption in thousands of 10^{12} joules
$FO_g = 0.98 \pm 1\%$
C_g = carbon content in 10^6 tons per thousand 10^{12} joules = $0.0137 \pm 2\%$

From crude oil and natural gas liquids production[2]

CO_{2l} = CO_2 emissions in 10^6 metric tons of carbon
P_l = annual production or consumption in 10^6 tons
$FO_l = 0.918 \pm 3\%$
C_l = carbon content in tons C per ton fuel = $0.85 \pm 1\%$

From primary and secondary liquid fuel production and trade[3]

CO_{2l} = CO_2 emissions in 10^6 metric tons of carbon
P_l = annual production or consumption in 10^6 tons
$FO_l = 0.985 \pm 3\%$
C_l = carbon content in tons C per ton fuel = $0.85 \pm 1\%$

From liquid bunker fuel consumption[4]

CO_{2l} = CO_2 emissions in 10^6 metric tons of carbon
P_l = annual production or consumption in 10^6 tons
$FO_l = 1.0 \pm 3\%$
C_l = carbon content in tons C per ton fuel = $0.855 \pm 1\%$

From primary and secondary solid fuel production and trade[5]

CO_{2s} = CO_2 emissions in 10^6 metric tons of carbon
P_s = annual production or consumption in 10^6 tons coal equivalent[6]
$FO_s = 0.982 \pm 2\%$
C_s = carbon content in tons C per ton coal equivalent = $0.746 \pm 2\%$

From natural gas flaring[7]

CO_{2f} = CO_2 emissions in 10^6 metric tons of carbon
P_f = annual production or consumption in 10^{12} joules
$FO_f = 1.0 \pm 1\%$
C_f = carbon content in tons C per 10^{12} joules = $13.454 \pm 2\%$

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[1] With respect to the above gas-related calculations, the following procedures and assumptions should be noted:

(1) If a solid was produced and then converted to a gas that was subsequently consumed, the assumption was made that the solid was produced and consumed. In this situation, none of the gas records were influenced.

(2) If a solid was produced and then converted to a gas that was exported, it was assumed that in the producing country a solid was produced and the gas was exported. As a result, gas consumption for this country could show a negative value (consumption = production + imports − exports: C = (0 + 0) −exports). In the consuming country, gas was imported and consumed.

(3) An amount of gas equivalent to 98% of the marketed production (net production) was oxidized during a given year.

(4) Natural gas contains 13.7 metric tons of carbon per terajoule.

(5) The units seem contrived but are chosen to accomodate data reported in the primary data sources.

[2] With respect to the above global liquid-related calculations, the following procedures and assumptions should be noted:

(1) Crude petroleum, natural gas liquids, and all secondary energy liquids were summed on an equal basis in mass units. That is, a ton of any liquid contains the same fraction of carbon.

(2) When calculating global total CO_2 emissions from liquids, we have estimated that a quantity of liquids equivalent to 6.7% of liquids produced are not oxidized each year and another 1.5% passes through burners unoxidized or is otherwise spilled. Hence, 91.8% of annual liquid production is oxidized each year.

(3) Liquid fuels contain 85.0% carbon by weight.

[3] With respect to the above national liquid-related calculations, the following procedures and assumptions should be noted:

(1) Crude petroleum, natural gas liquids, and all secondary energy liquids were summed on an equal basis in mass units. That is, a ton of any liquid contains the same fraction of carbon.

(2) When calculating CO_2 emissions by country, nonenergy secondary liquids were subtracted at the time of production and additional transactions (i.e., imports, exports, changes in stock) were not accounted further. Therefore, CO_2 production is only for energy products and CO_2 production from the oxidation of nonenergy products is not included.

(3) When calculating national total CO_2 emissions from liquids, we have estimated that a quantity of liquids equivalent to 1.5% passes through burners unoxidized or is otherwise spilled.

(4) Liquid fuels contain 85.0% carbon by weight.

[4] With respect to the above bunker liquid-related calculations, the following procedures and assumptions should be noted:

(1) Crude petroleum, natural gas liquids, and all secondary energy liquids were summed on an equal basis in mass units. That is, a ton of any liquid contains the same fraction of carbon.

(2) When calculating national total CO_2 emissions from liquids, we have estimated that a quantity of liquids equivalent to 1.5% passes through burners unoxidized or is otherwise spilled.

(3) Liquid bunker fuels contain 85.5% carbon by weight.

(4) Emissions from bunker fuels are calculated at the point where final fuel loading occurs but are not included in any national totals.

[5] With respect to the above solid-related calculations, the following conversion assumption should be noted:

(1) Where no conversion factor exists in the UN data set for a country/commodity, the following standard factors (kcal/kg) are used:

Coal	7000
Lignite brown coal	2695
Peat	2275
Coke-oven coke	6300
Gas coke	6300
Brown coal coke	4690
Hard coal briquettes	7000
Brown coal briquettes	4690

[6] The data for annual fuel production must recognize that all coal is not of the same composition, and thus may have varying energy content and CO_2 potential. There is a strong correlation between energy content and C content so the C content is quite constant when production is in units of tons coal equivalent where 1 ton coal equivalent is defined as 29.31×10^9 joules.

[7] With respect to the above gas flaring–related calculations, the following derivation and assumption should be noted:

(1) The carbon conversion factor of 13.454 metric tons of C TJ^{-1} is the result of dividing the average carbon content of a cubic meter of flared natural gas (i.e., 525 g C/m^3) by the average heating value of a cubic meter of flared natural gas (i.e., 39.021 $TJ/10^6\ m^3$).

(2) These calculations assume that flared gas is released to the atmosphere immediately as CO_2, even though it is known that a small fraction is actually discharged as methane.

[3] With respect to the above national liquid-related calculations, the following procedures and assumptions should be noted:

(1) Crude petroleum, natural gas liquids, and all secondary energy liquids were summed on an equal basis in mass units. That is, a ton of any liquid contains the same fraction of carbon.

(2) When calculating CO_2 emissions by country, nonenergy secondary liquids were subtracted at the time of production and additional transactions (i.e., imports, exports, changes in stock) were not accounted further. Therefore, CO_2 production is only for energy products and CO_2 production from the oxidation of nonenergy products is not included.

(3) When calculating national total CO_2 emissions from liquids, we have estimated that a quantity of liquids equivalent to 1.5% passes through burners unoxidized or is otherwise spilled.

(4) Liquid fuels contain 85.0% carbon by weight.

[4] With respect to the above bunker liquid-related calculations, the following procedures and assumptions should be noted:

(1) Crude petroleum, natural gas liquids, and all secondary energy liquids were summed on an equal basis in mass units. That is, a ton of any liquid contains the same fraction of carbon.

(2) When calculating national total CO_2 emissions from liquids, we have estimated that a quantity of liquids equivalent to 1.5% passes through burners unoxidized or is otherwise spilled.

(3) Liquid bunker fuels contain 85.5% carbon by weight.

(4) Emissions from bunker fuels are calculated at the point where final fuel loading occurs but are not included in any national totals.

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TABLE 3. GLOBAL ANNUAL CO_2 EMISSIONS FROM FOSSIL-FUEL BURNING, GAS FLARING, AND CEMENT PRODUCTION FOR 1950–92

	Carbon dioxide emissions (million metric tons of carbon)						Per capita CO_2 emissions (metric tons of carbon)
Year	Total	Solid	Liquid	Gas	Cement	Gas flaring	
1950	1638	1077	423	97	18	23	0.65
1951	1775	1137	479	115	20	24	0.69
1952	1803	1127	504	124	22	26	0.69
1953	1848	1132	533	131	24	27	0.70
1954	1871	1123	557	138	27	27	0.69
1955	2050	1215	625	150	30	31	0.74
1956	2185	1281	679	161	32	32	0.78
1957	2278	1317	714	178	34	35	0.80
1958	2338	1344	732	192	36	35	0.80
1959	2471	1390	790	214	40	36	0.83
1960	2586	1419	850	235	43	39	0.86
1961	2602	1356	905	254	45	42	0.85
1962	2708	1358	981	277	49	44	0.86
1963	2855	1404	1053	300	51	47	0.89
1964	3016	1442	1138	328	57	51	0.92
1965	3154	1468	1221	351	59	55	0.95
1966	3314	1485	1325	380	63	60	0.97
1967	3420	1455	1424	410	65	66	0.98
1968	3596	1456	1552	445	70	73	1.01
1969	3809	1494	1674	487	74	80	1.05
1970	4084	1564	1838	516	78	87	1.10
1971	4235	1564	1946	554	84	88	1.12
1972	4403	1580	2055	583	89	94	1.14
1973	4641	1588	2240	608	95	110	1.18
1974	4649	1585	2244	618	96	107	1.16
1975	4622	1679	2131	623	95	93	1.13
1976	4889	1717	2313	647	103	109	1.18
1977	5028	1780	2389	646	108	104	1.19
1978	5076	1796	2383	674	116	107	1.18
1979	5358	1892	2534	714	119	100	1.23
1980	5290	1949	2407	726	120	89	1.19
1981	5119	1920	2271	736	121	72	1.13
1982	5080	1983	2176	731	121	69	1.10
1983	5070	1989	2161	733	125	63	1.08
1984	5242	2081	2185	791	128	58	1.10
1985	5417	2238	2170	822	131	57	1.12
1986	5609	2299	2279	840	137	54	1.14
1987	5736	2350	2289	903	143	51	1.14
1988	5961	2412	2393	946	152	58	1.17
1989	6070	2447	2429	982	156	56	1.17
1990	6099	2389	2481	1008	156	65	1.15
1991	6172	2320	2587	1028	162	76	1.15
1992	6097	2344	2470	1045	171	68	1.12

FIGURES

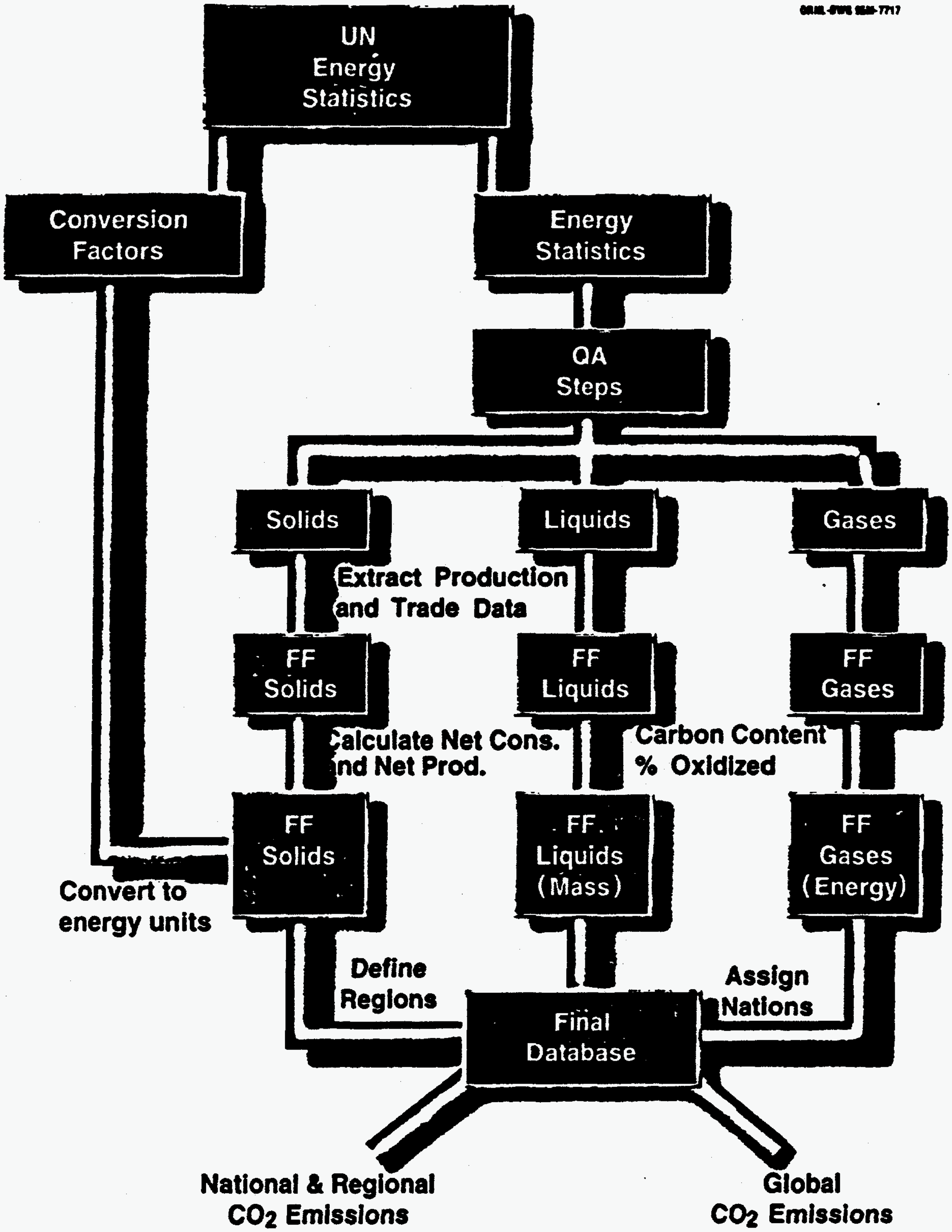

FIGURE 1. DATA PROCESSING AND SELECTION OF THE UNITED NATIONS ENERGY STATISTICS DATABASE (FF DENOTES FOSSIL FUELS)

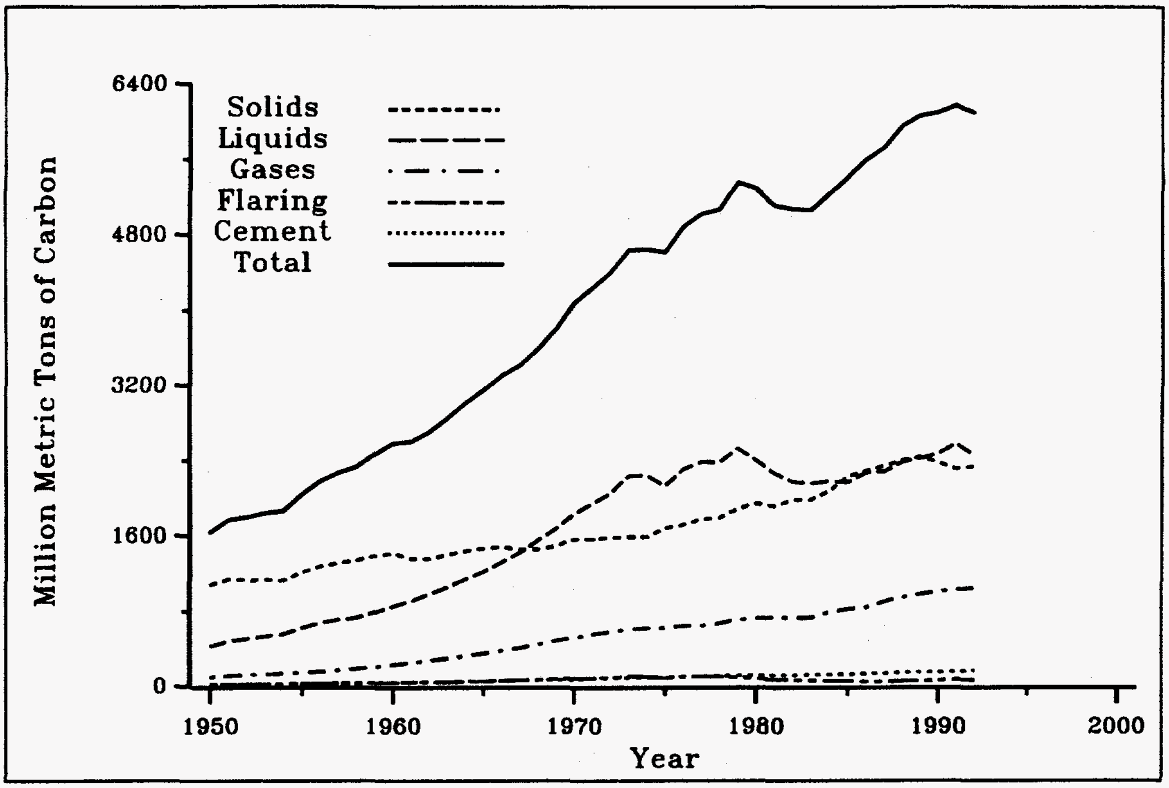

FIGURE 2. GLOBAL CO_2 EMISSIONS FROM FOSSIL FUEL BURNING, CEMENT PRODUCTION, AND GAS FLARING FOR 1950–92.

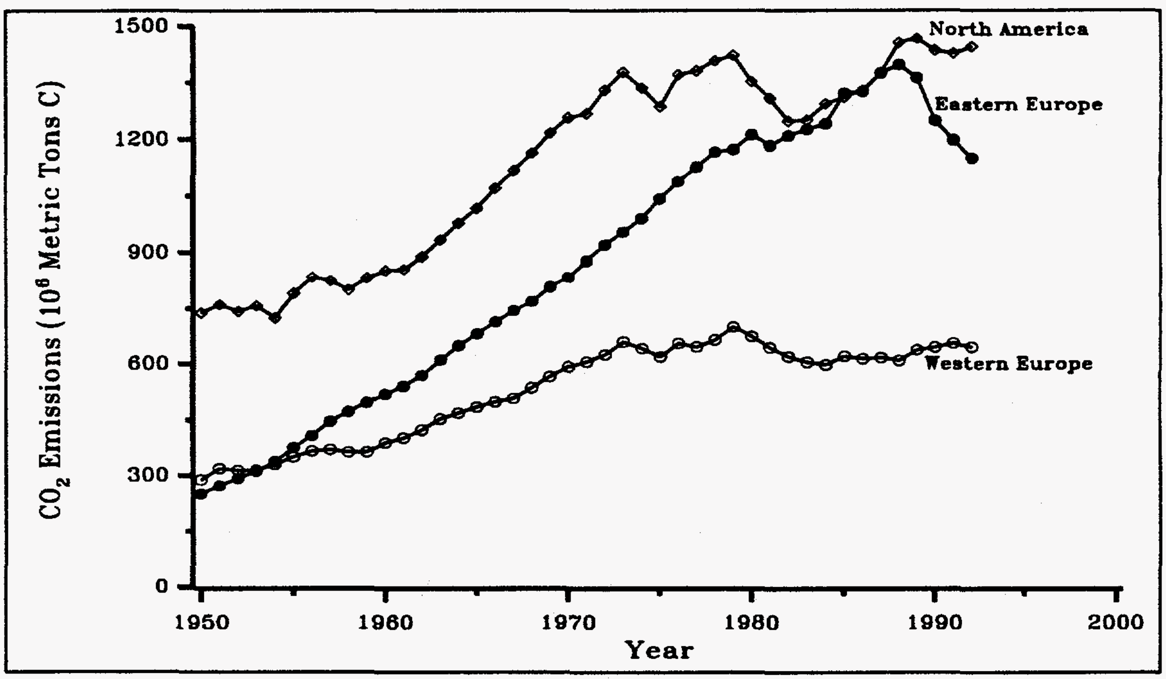

FIGURE 3. REGIONAL CO_2 EMISSIONS FROM FOSSIL FUEL BURNING, CEMENT PRODUCTION, AND GAS FLARING FOR 1950–92 FOR NORTH AMERICA, EASTERN EUROPE, AND WESTERN EUROPE.

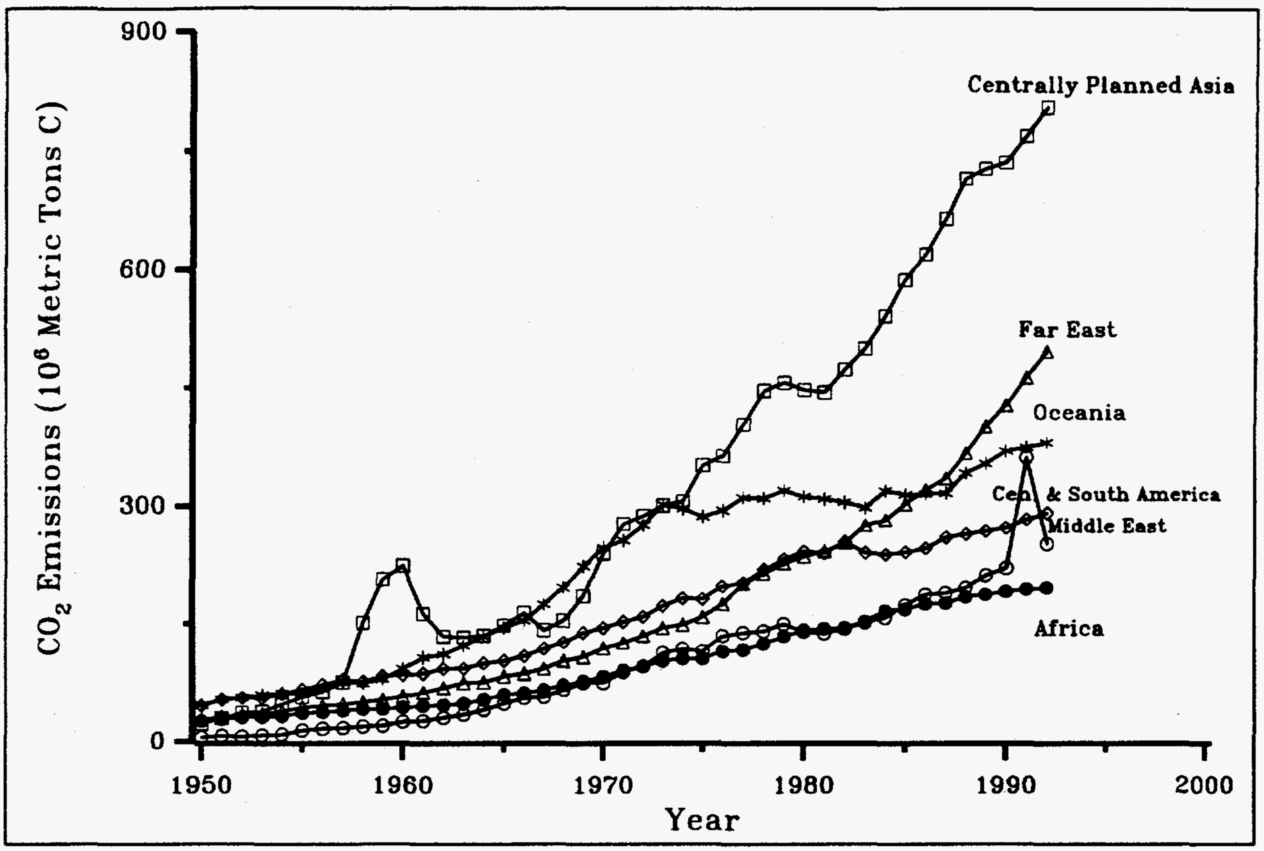

FIGURE 4. REGIONAL CO_2 EMISSIONS FROM FOSSIL-FUEL BURNING, CEMENT PRODUCTION, AND GAS FLARING FOR 1950–92

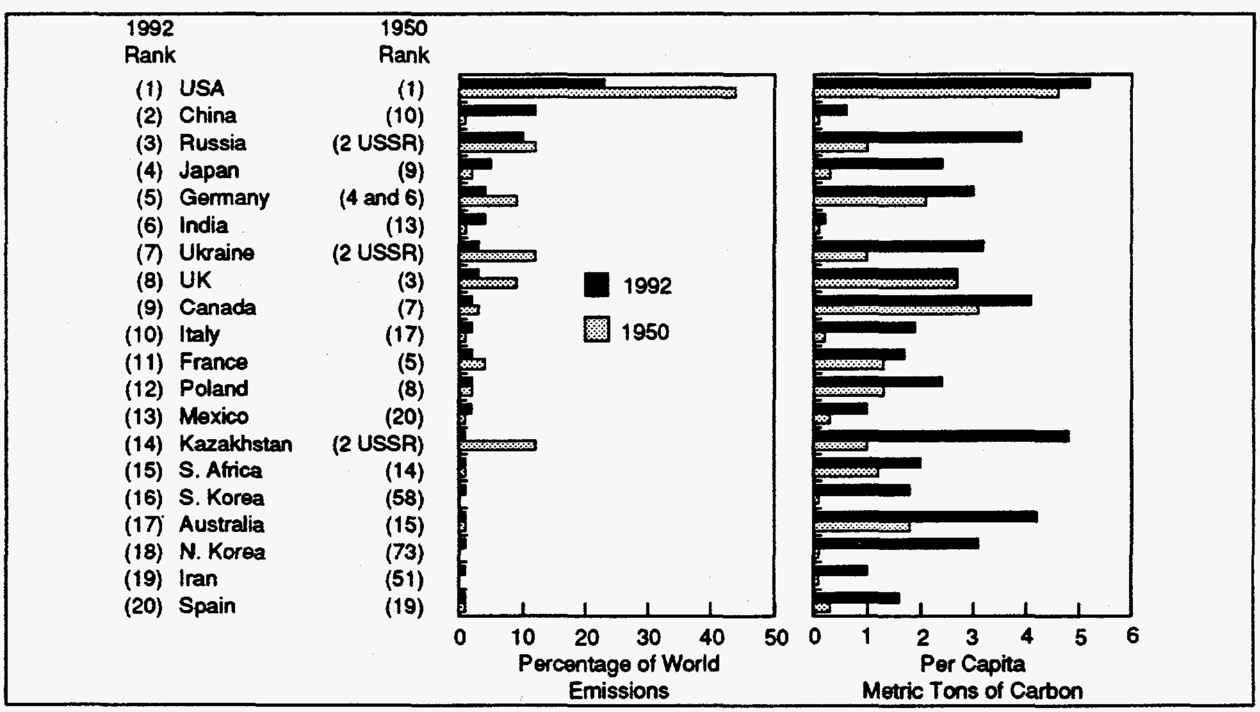

FIGURE 5. RANKING OF THE 20 HIGHEST CO_2-EMITTING COUNTRIES IN 1992 AND THEIR RANK IN 1950, CONTRIBUTIONS TO GLOBAL EMISSIONS, AND PER CAPITA CO_2 EMISSION RATES