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Calculating Primary Energy and Carbon Emission Factors for the United States' Energy Sectors

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Abstract

Energy consumption is the main source of most anthropogenic carbon emissions. For effectively reducing carbon emissions, a complete life cycle energy and carbon evaluation of products is important, which takes into account all primary and delivered energy used and lost in the manufacturing process. All delivered energy usage should be converted to primary energy units so that the actual total carbon emissions can be quantified. A set of constants, also known as primary energy factors (PEFs), are used to translate delivered energy into primary energy units. The PEFs can be converted into carbon emission factors (CEFs) using carbon intensities of fuels. To ensure completeness, a PEF for a delivered fuel should be calculated by including all direct and indirect energy consumed and lost in generating and supplying the delivered fuel. Literature points out the need to establish a standard and complete method to calculate PEFs and CEFs. In this paper, we investigate the current state of PEF calculation in order to establish a method to more completely calculate a PEF. We also calculated PEFs and CEFs for the United States' economy using three methods to compare results and highlight the issue of energy double counting. The results demonstrate that a process or input-output-based hybrid method can cover most direct and indirect energy inputs and provide a complete PEF calculation.

1. Background

The influence of an energy supply across national and global economies is evident in the positive correlation shared by energy consumption and economic indicators such as Gross Domestic Product (GDP).¹⁻² A growing GDP may indicate a proportional increase in energy consumption.³ The two main determinants of growing energy use and GDP include the rising levels of population and affluence.⁴⁻⁶ One primary impact of energy use for the environment is the increasing concentration of anthropogenic CO₂ in the earth's atmosphere, which is the lead cause of global warming.⁷⁻¹⁰ Most energy consumption is attributed to activities of electricity generation, transportation, construction, manufacturing, and building operations. The extraction, processing, generation, and distribution of energy sources also consume significant amounts of energy.^{7,9} A growing GDP may indicate rising levels of energy use and resulting carbon emissions, as illustrated in Figure 1 (global data based on UNDESA¹¹).

Insert Figure 1 here

1.1. Primary and Delivered (Secondary) Energy

1.1.1. Interpretation of Primary and Delivered Energy

Environmental evaluation techniques, such as life cycle assessment, involve energy and carbon emission accounting. When accounting for energy use and the resulting carbon emissions, distinguishing primary from delivered energy is critical.¹²⁻¹⁶ The energy consumed by various economic sectors is either primary or secondary.¹²⁻¹⁶ Primary energy is the energy of a fuel extracted directly from earth, which has not undergone any transformation process.¹⁷⁻¹⁸ Fossil fuels such as coal, crude oil, and natural gas are extracted directly from earth and are known as primary fuels. Delivered energy (also known as secondary energy) is generated by combusting or processing primary fuels.¹⁹⁻²⁰ For instance, gasoline that is processed and refined from crude oil, a primary fuel, is a secondary or delivered fuel. Another example of secondary energy is electricity, which is generated mostly by combusting primary fuels such as coal, petroleum, and natural gas. Overgaard²¹ provided various definitions of primary and delivered energy and argued that the most distinct characteristic defining both energies is the human factor. The energy that originates from the sun and moves through natural cycles of transformation becomes part of an energy system only when humans extract and transform it, he further explains. According to Overgaard:

“Primary energy is energy embodied in sources which involve human induced extraction or capture, that may include separation from contiguous material, cleaning or grading, to make the energy available for trade, use or transformation.”

“Secondary energy is energy embodied in commodities that comes from human induced energy transformation.”

Overgaard²¹ also cited the OECD/IEA/Eurostat manual, which categorizes electricity as both primary and secondary energy. Primary electricity is generated using natural sources such as hydro, wind, solar, and tide, whereas secondary electricity is obtained from combustible fuels. However, Overgaard²¹ suggested categorizing electricity from all sources as secondary energy to avoid confusion in energy calculations.

1.1.2. Significance of Primary and Delivered Energy Differentiation

Primary and secondary energies are also known as source and site energy, respectively. It is important to distinguish primary energy from secondary energy, as the two are not comparable and represent different amounts of energy.¹²⁻¹⁶ For example, it would be inaccurate to compare the energy use of two buildings if one is expressed in a primary unit (e.g., source energy in Btu) and the other in a secondary energy unit (e.g., electricity in kWh). The actual amount of energy embodied in electricity use could be significantly higher if converted to primary energy units. This is due to energy conversion and transmission and distribution (T&D) losses that incur while producing and distributing electricity.^{18, 22} Conventionally, the process of generating one unit of electricity consumes more than one unit of coal, oil, or natural gas.¹⁸ Similarly, the process of producing and distributing other secondary fuels, such as consumer grade natural gas and gasoline, also involves energy use and energy losses, which should be included in primary energy conversion. All secondary energy use quantities should be converted to primary energy units before an environmental evaluation is done.^{12, 18, 23} In the process of energy accounting, therefore, converting energy use from delivered to primary energy units is important in order to quantify actual primary fuel consumption.^{22, 24} Using primary energy in an energy analysis also ensures an accurate evaluation of environmental impacts such as carbon emission.¹⁸ Overgaard²¹ explained that differentiating primary and secondary energy provides a clear picture of conversion losses, T&D losses, and related environmental impacts, which can help formulate future energy and environmental policies.

1.2. Primary Energy Factor (PEF) and PEF Calculation

To convert energy use from delivered to primary energy units, a set of constants can be used to represent all energy consumption and losses. In most countries, a PEF is used to track all upstream energy depletion that incurs when supplying delivered energy.^{17, 18, 25, 26} The ratio of total energy consumed in supplying delivered energy to the total amount of energy delivered to end users is termed a PEF.^{22, 27} A PEF represents the total primary energy needed to produce and distribute one unit of delivered energy to end users. Hence:

$$\text{Primary Energy Factor (PEF)} = \frac{\text{Total Primary Energy Consumed in the Delivery}}{\text{Total Energy Delivered for End Use}}$$

Equation (1)

The above expression should be adjusted for energy losses that incur during extraction, processing, and distribution of delivered energy.²² The denominator in Equation (1) denotes delivered energy, for instance, electricity or consumer grade natural gas. The numerator represents the total primary energy used in the process of delivery (including the energy spent in extraction, processing, conversion, and distribution).^{22, 27} The total primary energy consumed or lost in the process of delivering energy for end use is composed of three major components: (1) energy used in energy conversion, (2) energy used in plant operation, and (3) energy lost during conversion, transportation, and distribution.^{17-19, 28} A delivered quantity of energy can be converted into primary energy by using the following equation:

$$\text{Primary Energy}_i = \text{PEF}_i \times E_{del,i}$$

Where, PEF_i and $E_{del,i}$ represent the primary energy factor and energy quantity of delivered energy “*i*.” A set of PEFs should be calculated for each energy source being delivered for end use.²⁸⁻²⁹

Most studies, such as Marcogaz²⁷ and Energy Star,¹⁸ have suggested using Equation (1) for calculating the PEF. However, when the PEF is calculated using Equation (1), studies differ in quantifying the numerator value. Based on how the total primary energy use in the numerator is calculated, there exist multiple variations of a PEF. For instance, if energy from renewable sources is included in the calculation, the calculated PEF is called a total PEF or else it is known as a nonrenewable PEF.^{17, 19, 27} Pout³⁰ suggested accounting for all energy obtained from both renewable and nonrenewable sources. Another parameter causing variations is the definition of a system boundary. A system boundary defines the energy and non-energy inputs included in a calculation.^{20, 31-32} Most studies define the system boundary subjectively since there are no system boundary guidelines.^{20, 33, 34} For instance, studies such as CEN¹⁷ and Dijk²⁸ covered all energy inputs from raw energy extraction to energy processing, transportation, and distribution in their system boundaries. However, the energy embodied in capital inputs and labor was not covered. CEN¹⁷, Pout³⁰, Molenbroek et al.¹⁹, and Energy Star¹⁸ also emphasized including all energy losses incurred when generating and distributing a delivered energy source. Among studies which defined a relatively comprehensive system boundary is Pout³⁰. In addition to all energy inputs and losses in the upstream and downstream of delivered energy, Pout³⁰ covered the energy embodied in materials (e.g., chemicals), machinery (e.g., generator), and infrastructure (e.g., transmission lines) used for energy generation and distribution. CEN¹⁷ recommended also adding the treatment and disposal of waste generated during energy extraction, processing, and distribution. Figure 2 illustrates a schematic system boundary for incorporating all direct and indirect energy inputs in PEF calculation. The following sections describe key energy input components covered by a comprehensive system boundary for calculating a PEF (based on Deru and Torcellini²² and Pout³⁰):

1.2.1. Primary Fuel Use

This component relates to the energy transformation stage in which a primary fuel is either combusted (e.g., in power plants) or used as a raw material (e.g., in oil refineries) to be processed or refined further. The total energy of a fuel consumed at this stage includes direct and indirect components. The direct component represents the energy of combustion, whereas the indirect component consists of pre-combustion energy (based on Deru and Torcellini,²² Pout,³⁰ and Molenbroek et al.¹⁹).

Combustion Energy: Combustion energy is the calorific value of energy released when the fuel is burnt. The amount of heat produced in the fuel combustion process represents the fuel’s combustion energy (see Figure 2). Combustion energy, for instance, is the energy of crude oil fed into a refinery or coal burnt in a thermal power plant. This energy use component represents the direct consumption of energy.

Pre-combustion Energy: Pre-combustion energy is energy consumed in extracting, processing, and distributing a fuel fed into energy generation facilities such as oil refineries and power plants. This fraction of energy covers all energy and non-energy inputs. The use of primary fuel as an energy input and as a feedstock material is included under the energy input category. The non-energy inputs cover all energy embodied in raw materials, equipment, and labor used in developing the infrastructure for processing, refining, and delivering the energy for end use.

1.2.2. Energy Use in Plant or Lease Operation and Energy Delivery

Energy processing plants, such as natural gas processing facilities, petroleum refineries, and electrical power plants, consume energy in their operations. Energy is also used when an energy source or fuel is distributed to end users. For instance, to move natural gas through a pipeline, pumps that consume electricity or natural gas as operating energy are used. Similarly, operations of oil and gas wells, coal and uranium mines, and related facilities also deplete a significant amount of energy. Such operations also need built structures, equipment, and raw materials, which consume energy in their construction, installation or manufacturing (based on Deru and Torcellini,²² Pout,³⁰ and Molenbroek et al.¹⁹). The total energy consumed by an energy processing plant is composed of direct and indirect energy:

Insert Figure 2 here

Direct Energy: The total primary and delivered energy directly used by energy plants, oil wells, or mine facilities in their operations is termed direct energy consumption. The energy consumed in distributing or transmitting the generated or processed energy is also added to the total direct energy. In addition, the energy of labor and capital investment (plant and equipment) is included (see Figure 2).

Indirect Energy: The amount of energy consumed in extracting, processing, converting, and distributing the direct energy is called indirect energy. The energy embodied in built facilities, raw materials, equipment, and labor is also accounted for (see Figure 2).

1.2.3. Energy Lost and Gained

In the process of energy extraction, processing, conversion, and distribution, a significant amount of energy is lost.^{14, 24, 25} Like any other primary energy, this energy loss has both direct and indirect components.^{17, 30}

Direct Energy Loss: This direct component includes all energy lost when extracting, processing, and distributing an energy source. For instance, when oil and gas are extracted, some amount of gas is vented or flared. Similarly, when primary fuels are processed or refined, some energy is lost in the process. The total energy loss incurred during transmission and distribution is also counted. For instance, electricity transmission and distribution (T&D) involves significant energy loss (nearly 10%).

Indirect Energy Loss: This energy component includes all energy consumed in extracting, processing, converting, and distributing the lost or gained energy, including the energy embodied in structures, materials, equipment, and labor.

Since extraction and transportation of a primary fuel also requires energy use, a set of PEFs should be calculated for each category of primary and secondary fuels. When a primary fuel exists in its natural form in earth, its PEF equals 1.0, representing only its energy of combustion.²² When this fuel is extracted from the earth, some energy is consumed and lost, resulting in a PEF greater than 1.0 (see Figure 3). It's further processing, refining, and distribution requires building facilities, installing equipment, and procuring labor in addition to the direct energy use. Therefore, any additional processing of an energy source in the downstream results in an increase in its PEF (see Figure 3).^{18, 30} Each of the major primary fuels, such as coal, natural gas, petroleum, and uranium oxide, has a PEF greater than one. The process of electricity generation utilizes fuels such as coal, natural gas, and petroleum and should include their PEFs in quantifying total primary energy use.

Insert Figure 3 here

1.3. PEF Calculation: Major Issues and Recommendations

Although numerous studies have been published related to PEF calculation, some issues remain unaddressed. Molenbroek et al.¹⁹ and Deru and Torcellini²² warned that the PEFs have not been calculated using a standard scientific methodology in a complete and consistent manner. It is still unclear which energy and non-energy inputs should be included in a PEF calculation.^{19, 30} For instance, how to include the life cycle energy impacts of using, maintaining, and demolishing energy generation facilities is still unclear. While most direct energy inputs are easy to collect and quantify, indirect energy components are difficult to account for¹². Deru and Torcellini²², for instance, covered all direct energy use and loss but did not include the energy embodied in power plants and energy infrastructure, considering it insignificant.

Even though comprehensive system boundaries have been proposed, no standard method has been established to cover these boundaries. There are three methods to calculate a PEF for an energy source: (1) process-based, (2) input-output-based (IO-based), and (3) hybrid method.^{12, 13} In a process-based method, all actual energy use data is collected from energy processing plants and facilities. Since it is difficult to collect all energy inputs and, as a result, some inputs may be excluded from the calculation, a process-based method remains incomplete.^{34, 35} An IO-based method utilizes national IO accounts to quantify inputs required by energy providing sectors to produce a unit of energy. This method provides more complete results since it covers a wider system boundary.^{12, 13} However, issues of double counting of energy and assumptions of proportionality and homogeneity make its results unreliable.^{12, 13, 35} A hybrid method combines the benefits of process and IO-based methods. All direct energy inputs can be collected from energy processing plants.^{12, 13, 35} All indirect inputs can be quantified using the IO model. A hybrid method can be either process-based or IO-based. In a process-based hybrid method, IO data replace indirect inputs, whereas in an IO-based hybrid method, process data are inserted into an IO model. A detailed discussion of these methods can be found in Treloar¹² and Dixit.³

Since a wide range of energy sources are consumed by different industry sectors, PEF calculation at a national level is recommended.^{28, 29} It is also recommended that the values of PEFs be revised each year to maintain temporal representation due to fuel mix changes with time.^{19, 29} Most issues related to renewable energy generation have not been addressed properly. For example, conventionally, the PEF for renewable energy is assumed to be 1.0, which may not be accurate since the energy embodied in their systems' manufacture, transportation, installation, maintenance, and disposal is not accounted for.^{19, 30} Using only conventional IO analysis for calculating the indirect energy component of renewable energy generation may not be accurate, particularly when it is difficult to identify industry sectors that manufacture renewable energy systems.^{12, 13} According to Deru and Torcellini²², the energy embodied in storing and disposing of nuclear waste should also be included in the calculation; however, this is difficult due to the unavailability of reliable data.

Some countries, such as India and China, have more labor-intensive industry sectors than developed countries such as the United States.³⁶⁻³⁸ While machines consume generated energy, workers consume energy through food and other consumables. The energy embodied in human labor is seldom included in PEF calculation due to the lack of reliable data and a standard calculation method.^{20, 39} The energy required by an average worker can be quantified in a more straightforward manner than the energy of personal consumption (e.g., consumables) and transportation.^{39, 40} Although an IO model conventionally incorporates personal consumption expenditure, it remains external to the model.⁴¹ Even though it is internal to the IO model, the percentage of total personal consumption that should be allocated to work is unclear. Costanza⁴² quantified energy embodied in personal consumption by making the personal consumption expenditure column internal to the IO model. However, the entire amount of personal expense was allocated to work, which may not be accurate.³⁹ Other expenses, such as household energy and personal transportation, are also difficult to apportion. Cleveland³⁹ recommended using the difference between an earning and a non-earning person to allocate personal consumption.

Additionally, each industry sector of an economy invests in capital, such as building and non-building structures, automobiles, equipment, distribution infrastructure, and software.⁴³ Each capital input item consumes energy during its manufacture, packaging, transportation, and installation.^{20, 42, 44} This energy remains embodied in these capital items once they are installed by an industry sector. Since capital expenses are annual, they may not be included in detailed IO accounts, which are conventionally published every few years.^{12, 13, 45} For instance, more detailed Benchmark Input-output Accounts are published every five years in the United States. In such a case, the energy embodied in capital expenses may remain excluded from the PEF calculations, particularly if IO-based methods are used. According to Treloar¹² and Crawford¹³, the inability to include capital inputs in calculation represents a gap in this field of research. Studies often consider the energy embodied in labor and capital investment insignificant and exclude them from the calculation.^{46, 47}

1.4. Energy Consumption and Carbon Emission: Carbon Emission Factors (CEFs)

The process of fossil fuel combustion is a chemical reaction involving oxygen that results in release of water, carbon dioxide and heat.^{48, 49} The process of fuel combustion is optimized to produce maximum amount of energy per unit of fossil fuel combusted.^{50, 51} The efficiency of fuel combustion relates to the oxidation of the maximum amount of carbon contained in the fuel.⁴⁹⁻⁵¹ Since fossil fuels possess different amounts of carbon content,^{48, 52} their CO₂ emissions upon combustion differ. Not all of the carbon contained in a fuel is oxidized during the combustion process. A minute fraction (<1%) of the contained carbon escapes the oxidation process. However, Intergovernmental Panel on Climate Change (IPCC) guidelines assume 99-100% oxidation of the contained carbon in most fossil fuels.^{48, 52}

There are two important points that should be considered when quantifying carbon emission from energy use. First, the amount of carbon emitted to the atmosphere is directly proportional to the amount of fossil fuel combusted. Second, since each fuel has a different CO₂ emission,⁴⁸⁻⁵⁰ calculating environmental impact by summing up CO₂ emissions from each individual fuel would be more accurate. Organizations such as the IPCC, U.S. Department of Energy, and U.S. Environmental Protection Agency regularly publish CO₂ and carbon emission factors that provide the amount of CO₂ or carbon released per unit of fuel use. It is the emission factor that connects energy use and environmental impacts and can be used to translate PEFs into CEFs.^{48, 50, 51}

2. Research Goal and Objectives

To ensure a complete conversion of delivered energy to primary energy, PEFs must cover all direct and indirect energy use and loss incurred while supplying delivered energy.^{19, 30} In addition to all energy use, all non-energy material use should be included in the PEF calculation.^{14, 25} However, a complete and consistent method to calculate PEFs is still lacking.^{19, 22} According to Deru and Torcellini²² and Molenbroek et al.¹⁹, there is a need to develop a PEF calculation method that completely covers all energy and non-energy resource use and loss. The main goal of this paper is to investigate the current state of PEF calculation and propose a method for comprehensively calculating PEFs and CEFs for energy sources in the United States' economy. We also calculate and compare PEFs and CEFs using three different methods in order to highlight serious issues such as double-counting of energy sources. The research goal is accomplished by achieving the following objectives:

- Investigate the PEF calculation approaches to establish calculation methods that cover most direct and indirect energy use and loss
- Construct a conventional IO and IO-based hybrid model for calculating total and indirect energy use by energy providing sectors
- Calculate and compare a set of PEFs and CEFs for major energy sources using the established methods to highlight major methodological issues

3. Research Methods

There are five energy providing sectors in the United States' economy: (1) Oil and Gas Extraction; (2) Coal Mining; (3) Electric Power Generation, Transmission, and Distribution; (4) Natural Gas Distribution; and (5) Petroleum Refineries. Out of these, the first two sectors are primary energy sectors supplying primary fuels. The last three sectors use the energy supplied by the primary energy sectors to generate and distribute delivered energy. The total national energy demand is fulfilled by the energy obtained from these five sectors plus imports from foreign economies. In 2002, the United States imported over 66% of its crude oil supply from other countries.⁵³ Nuclear fuel is mined, processed, and delivered to power plants by subsector Uranium-Radium-Vanadium Ore Mining under the main mining sector Other Metal Ore Mining. In 2002, nearly 92% of the uranium loaded into U.S. nuclear power plants was imported from foreign countries.^{53, 54} It is important to distinguish between a sector extracting oil and gas and sectors distributing consumer grade natural gas and refined oil. For instance, most refined oil products come from petroleum refineries, which purchase crude oil from the Oil and Gas Extraction sector. Similarly, consumer grade dry natural gas is transported and distributed by the Natural Gas Distribution sector that receives natural gas from the Oil and Gas Extraction sector. It was assumed that all domestic natural gas and refined oil supply came from the Natural Gas Distribution and Petroleum Refineries sectors, respectively. Imported energy sources are treated in the similar manner as domestically produced products.

In this research, the PEFs for all major energy sources were calculated using three approaches. The first two approaches are hybrid methods, whereas the third approach is IO-based. In the first approach (process-based hybrid), the direct energy component was calculated using process data of actual energy use. The indirect energy component was then added using IO-based total and direct energy requirement coefficients. Using IO-based indirect coefficients ensured inclusion of most energy and non-energy inputs used to generate delivered energy. Direct requirements were subtracted from total requirements to estimate the indirect requirements. The direct energy process data and indirect energy IO data were then summed to calculate the total primary energy use. The PEFs for primary fuels (coal, natural gas, petroleum, and nuclear fuel) were calculated first. The PEF for electricity was then computed using the direct energy data and the calculated values of PEFs for the four fuels. There was no need to use the IO data for electricity, since the PEFs represented the indirect impacts of its production. When dealing with oil and gas supply, we calculated the PEF of the Oil and Gas Extraction sector first. This PEF accounted for all energy use and loss incurred while extracting crude oil and natural gas. We then used this PEF to calculate the PEFs for the Natural Gas Distribution and Petroleum Refineries sectors. Since the Oil and Gas sector produced both crude oil and natural gas, we used the energy contents of the total oil and gas production in 2002 to allocate the indirect impacts. Since we assumed that all natural gas and refined oil supply came from the Natural Gas Distribution and Petroleum Refineries sectors, it was important to allocate the indirect energy use of energy extraction to these sectors.

In the second approach (IO-based hybrid), the monetary flows from the energy providing sectors to other industry sectors of the IO model were replaced by the actual data of direct energy use. The energy inputs to all five energy providing sectors were also replaced with process data. Since some energy uses (e.g., energy used in repressuring reservoirs) and energy losses (e.g., T&D losses) did not show up in the IO table, the calculated PEFs were adjusted to accommodate these energy uses and losses. We then calculated the total energy intensity of energy providing sectors to quantify a set of PEFs. The third approach was purely IO-based. In this approach, the total requirement matrix was used to estimate the energy requirement (in \$) per \$ output of the energy providing sector. Sector specific energy prices were used to convert the energy requirements from \$ to energy units. The calculated values of PEFs for primary fuel were adjusted for energy use and losses not covered in the IO table. Similar to the first two approaches, the calculated PEFs were used to quantify the PEF for electricity generation.

Primary energy sectors such as Coal Mining deliver their output for final use (e.g., residential and commercial use), for inter-industry use (e.g., industrial use in iron and steel mills), and for producing electricity. Other primary energy sectors, such as oil and gas extraction, distribute their products mostly to other industries, electric power plants, natural gas distribution, and petroleum refineries for further processing. Figure 4 illustrates the total supply of energy in the country. A majority of electricity (69%) in 2002 was generated by combusting fossil fuels--coal, natural gas, and petroleum (see Figures 5 and 6). Also, petroleum products fulfilled nearly 40% of the total 2002 energy demand (see Figures 5 and 6). The following section describes the PEF calculation method in detail.

Insert Figure 4, 5, 6 here

3.1. PEF Calculation for Primary Fuels

The total fuel and electricity consumption data for the Oil and Gas sector were sourced from the 2002 Economic Census.⁵⁵ There are two subsectors that extract oil and gas:

1. Crude petroleum and natural gas extraction
2. Natural gas liquid extraction

The Oil and Gas Extraction sector drew crude oil and natural gas from the earth and processed the natural gas into a dry and consumable form in order to distribute it to end users. In natural gas processing plants, dry consumer-grade natural gas was produced by removing the liquefiable hydrocarbons and non-hydrocarbon gases (e.g., water vapor, carbon dioxide, helium, hydrogen sulfide and nitrogen) from the extracted volume of natural gas.^{56, 57} There were only two components of total primary energy use in these sectors: first, the energy used in lease and plant operations and second, the energy lost while extracting and processing oil and gas. The fuel consumption data were provided in energy and monetary terms. In the case of missing data in energy terms, sector-specific energy prices were used to convert the monetary data into energy use data. The combustion energy factor for oil and gas extraction was assumed to be 1.0.

In 2002, the total monetary output of the coal mining sector was 20,371.8 million dollars representing a total of nearly 1094 million short tons of coal. The processes of extracting, processing, and transporting coal are quite energy intensive and each unit of energy delivered by coal has some amount of embodied energy.⁵⁸ Over 92% of the total coal consumption went to electricity generation alone in 2002.⁵³ Most remaining quantities were consumed by coke plants and other manufacturing plants. The processed coal was transported by water, rail, or road transportation. Approximately 58% of the coal was transported by railroads in the United States.^{58, 59} Waterborne and truck transportation carried roughly 17% and 12% of the total coal, respectively, to end users.

Energy use data for the coal mining sector were provided by the 2002 Economic Census⁵⁵ under purchased fuel, supplies, and electricity. The coal transportation energy use was calculated from the 2002 Benchmark Input-output Accounts.⁶⁰ The supply and disposition accounting of coal was provided by the 2002 Annual Energy Review, which was used as a basis for identifying the quantities of coal produced, consumed, and unaccounted for. Total direct and indirect energy use and loss were calculated by summing the process and IO data. Similar to oil and gas extraction, the combustion energy factor for coal was also assumed to be 1.0. In the first approach, the PEFs for the Oil and Gas Extraction and Coal Mining sectors were calculated as follows:

$$EF_{C,pe} = 1$$

$$E_{d,pe} = \sum_{i=1}^n E_{i,d,pe}$$

$$E_{in,pe} = \sum_{i=1}^n E_{i,in,pe}$$

$$E_{i,in,pe} = IN_i \times O_i \times Tariff_i$$

$$EF_{P,pe} = \frac{(E_{d,pe} + E_{in,pe})}{E_{o,pe}}$$

The PEF for the primary energy source sector was calculated as:

$$PEF_{pe} = (EF_{C,pe} + EF_{P,pe}) \times (1 + L_{pe})$$

Where:

- $EF_{C,pe}$ - Combustion energy factor for primary energy source
- $EF_{P,pe}$ - Pre-combustion energy factor for primary energy source
- $E_{d,pe}$ - Direct energy use by primary energy source sector
- $E_{in,pe}$ - Indirect energy use by primary energy source sector
- $E_{o,pe}$ - Total energy output of primary energy source sector
- $E_{i,d,pe}$ - Total direct energy consumed by primary energy source sector including transportation
- $E_{i,in,pe}$ - Total indirect energy consumed by primary energy source sector including transportation
- IN_i - Indirect energy requirement coefficient per unit output
- O_i - Total output of energy source or fuel sector in \$
- $Tariff_i$ - Energy source tariff in MBtu/\$
- n - Number of energy sources or fuels used by primary energy source sector
- i - Represents an energy source or a fuel
- L_{pe} - Ratio of net energy loss to the total energy output of primary energy source sector

3.2. PEF Calculation for Delivered Energy Sources

3.2.1. Natural Gas and Refined Petroleum

In the case of the Natural Gas Distribution sector, energy was consumed mainly in the processes of compressing and moving gas in the pipeline.⁵⁷ Since it is assumed that nearly the entire natural gas supply for end users came from the Natural Gas Distribution sector, the calculation of PEF for natural gas included the energy consumed and lost while extracting, processing, and distributing natural gas. Figure 7 shows the flow of natural gas from its extraction to end user delivery. In 2002, the Oil and Gas Extraction sector yielded 57% and 43% of its output (in energy content terms) as natural gas and crude oil (including natural gas plant liquids), respectively. Accordingly, 57% of the total energy (direct and indirect) used by the Oil and Gas Extraction sector was allotted to natural gas in calculating its PEF. All natural gas losses from the Oil and Gas Extraction sector were allocated to the calculation of PEF for natural gas. The calculated value of PEF for natural gas represented the total energy consumed and lost in its extraction, processing, transmission, and distribution to end users. Similar to oil and gas extraction, the combustion energy factor for natural gas was assumed to be 1.0. The total electricity consumed in transmitting and distributing dry natural gas was sourced from USDOT.⁶¹ The data were reported for both oil and gas transportation collectively. The relative share of natural gas and oil in the total oil and gas supply was used to disaggregate the total pipeline transportation energy.

Insert Figure 7 here

In 2002, the United States produced and imported 5.82 and 9.05 million bbl. of crude oil every day, respectively.⁵³ Petroleum refineries refined crude oil to produce a range of fuel and chemical products such as gasoline, kerosene, and naphtha. Petroleum refining is a complex process that involves separating, cracking, restructuring, treating, and mixing hydrocarbons to produce a wide range of refined products. These processes consume energy and also result in energy losses or gains. In 2002, the refining of petroleum resulted in 0.117 million bbl. of unaccounted crude oil. In addition, a total of 349.15 million bbl. of petroleum was reported as energy gain. Similar to the natural gas sector, it was assumed that all petroleum products supplied to the national economy came only from the Petroleum Refineries sector. This means that all upstream energy use should be taken into account in the PEF calculation. As nearly 43% of the Oil and Gas Extraction sector output consisted of crude oil, 43% of its total energy use was allocated to petroleum products. The PEFs for the Natural Gas Distribution and Petroleum Refineries sectors were calculated in the following steps:

$$EF_{C,png} = 1$$

$$E_{d,png} = \sum_{i=1}^n (E_{i,d,png} + E_{i,d,og} \times F_{png,og})$$

$$E_{in,png} = \sum_{i=1}^n (E_{i,in,png} + E_{i,in,og} \times F_{png,og})$$

The value of $E_{i,in,png}$ was calculated in the same manner as coal and crude oil.

$$EF_{P,png} = \frac{(E_{d,png} + E_{in,png})}{E_{o,png}}$$

The PEF for natural gas and petroleum is estimated as:

$$PEF_{png} = (EF_{C,png} + EF_{P,png}) \times (1 + L_{png})$$

Where:

- $EF_{C,png}$ - Combustion energy factor for natural gas and petroleum
- $EF_{P,png}$ - Pre-combustion energy factor for natural gas and petroleum
- $E_{d,png}$ - Total direct energy use by Natural Gas Distribution & Petroleum Refineries sectors
- $E_{in,png}$ - Total indirect energy use by Natural Gas Distribution & Petroleum Refineries sectors
- $E_{o,png}$ - Total energy output of Natural Gas Distribution & Petroleum Refineries sectors
- $E_{i,d,png}$ - Direct energy (fuel wise) consumed by Natural Gas Distribution & Petroleum Refineries sectors
- $E_{i,d,og}$ - Total direct energy consumed by oil & gas extraction sector
- $E_{i,in,png}$ - Indirect energy (fuel wise) consumed by Natural Gas Distribution & Petroleum Refineries sectors
- $E_{i,in,og}$ - Total indirect energy consumed by oil & gas extraction sector
- $F_{png,og}$ - Natural gas or petroleum as a percentage of total energy output of oil and gas extraction sector
- n - Number of energy sources or fuels used by Natural Gas Distribution & Petroleum Refineries sectors
- i - Represents an energy source or a fuel
- L_{png} - Ratio of net energy loss or gain to the total energy output of Natural Gas Distribution & Petroleum Refineries sectors

3.2.2. Electricity

Electricity may be produced in electric power plants using a range of nonrenewable fuels, such as coal, natural gas, oil, and nuclear fuel. The process of electricity generation includes combusting fossil or nuclear fuels for producing steam to run turbines. In nuclear power plants, the fission process in nuclear reactors is used to generate steam. Renewable energy sources, such as wind, solar energy, hydropower, biomass, geothermal, and tidal energy, are also utilized to generate electrical power. The fuel mix used for generating electricity differs across geographic regions depending on the availability of energy sources. The combustion energy factor, which is conventionally assumed to be 1.0 for primary fuels, is greater than one in the case of electricity production.

The quantities of fuels consumed in generating electricity in the United States were sourced from the EIA monthly data.⁶² Each of the 50 states and the District of Columbia (D.C.) used different fuel mixes to produce electrical power. The quantity of electricity consumed in power plant operations and the total transmission and distribution losses were referenced from the 2002 Annual Energy Review.⁵³ Figure 8 shows the fuel mixes used by the 50 states and D.C. for generating electricity in 2002. If calculated individually, each of the states and D.C. would have a different combustion energy factor due to a varying fuel mix. However, an average combustion energy factor weighted by the states' share in the total national electricity production was calculated for the entire nation. The calculation of PEF for electricity included the direct and indirect energy of combusted fuel, energy used in power plant operations, and energy lost in energy conversion and electricity transmission and distribution. Figure 9 illustrates the system boundary for calculating the PEF for electricity. The calculation started with primary fuel extraction, included all direct and indirect energy use and loss during electricity production, and ended by covering the energy lost in transmission and distribution.

Insert Figure 8, 9 here

Deru and Torcellini²² proposed an approach for calculating the PEF of electricity in the United States, which included three energy components, namely combustion energy, pre-combustion energy, and total energy loss. To calculate the combustion energy factor, the approach suggested by Deru and Torcellini²² was applied, whereas to calculate the pre-combustion energy or indirect component, the calculated values of PEFs of primary and delivered fuels were used. To compute the combustion energy factors, the following information and variables were used (based on Deru and Torcellini²²):

- E_o - Total annual net generation of electricity in the United States
 E_j - Total annual generation of electricity for each state
 $EF_{C,i,j}$ - Combustion energy factor for each energy source or fuel and each state
 $EF_{C,j}$ - Combustion primary energy factor for electricity for each state
 L_{td} - Ratio of transmission and distribution losses to total electricity generation
 PEF_{elec} - Total primary energy factor for delivered electricity
 $Q_{i,j}$ - Quantity of energy of fuel used for electricity generation for each energy source or fuel and each state
 $\delta_{i,j}$ - Fraction of total electricity generation for each energy source or fuel and each state
 $\vartheta_{i,j}$ - Combustion energy factor for a unit of composite electricity for each energy source or fuel and each state
 $\varepsilon_{i,j}$ - Electricity generation for each energy source or fuel and each state
 ε_{pe} - Total plant energy used
 CMF_e - Combustion energy factor for all energy sources or fuels
 CMF_{pe} - Combustion energy factor for plant energy
 CMF_{elec} - Combustion energy factor for electricity
 PCF_{elec} - Pre-combustion energy factor for electricity
 $FRF_{in,i}$ - Indirect energy source or fuel requirement factor
 Q_i - Energy quantity of an energy source or fuel used for electricity generation
 Q_{pc} - Total pre-combustion energy of electricity generation
 L_{elec} - Energy loss factor for electricity
 Q_{loss} - Energy of electricity lost during transmission and distribution
 i - Represents an energy source or a fuel
 j - Represents a region

Combustion Energy Factor Calculation: Electricity

Apart from the four major fossil fuel sectors that provided primary and delivered fuels to the electricity generating sector, a subsector of the gold, silver, and other metal ore mining sector supplied fuel grade uranium to nuclear power plants. The total amount of uranium extracted, processed, and consumed domestically for generating electricity was used to disaggregate the sector for calculating indirect energy use for nuclear fuel. The following equations were used to calculate combustion energy factors:

$$\delta_{i,j} = \frac{\varepsilon_{i,j}}{E_j}$$

$$EF_{C,i,j} = \frac{Q_{i,j}}{\varepsilon_{i,j}}$$

$$\vartheta_{i,j} = \delta_{i,j} \times EF_{C,i,j}$$

$$EF_{C,j} = \sum_{i=1}^n \vartheta_{i,j}$$

$$CMF_e = \sum_{j=1}^m EF_{C,j} \times \left(\frac{E_j}{E_o}\right)$$

$$CMF_{pe} = \frac{\varepsilon_{pe}}{E_o}$$

$$CMF_{elec} = CMF_e + CMF_{pe}$$

Pre-combustion Energy Factor Calculation: Electricity

The pre-combustion energy of energy sources or fuels consumed for electricity generation was calculated by multiplying their quantities and their indirect fuel requirement factor. The indirect fuel requirement factor of a fuel was equal to its PEF minus one. No IO data were used for the purpose of calculating the pre-combustion energy factor to avoid double counting of fuel inputs. Major fuels that were considered in the calculation included coal, natural gas, petroleum, and nuclear fuel because these fuels together constituted over 94% of the energy used for generating electricity in 2002. It was assumed that the PEF for all other fuels including renewable energy sources was 1.0. The following calculations were done to derive the pre-combustion energy factor:

$$FRF_{in,i} = PEF_i - 1$$

$$Q_{pc} = \sum_{i=1}^n FRF_{in,i} \times Q_i$$

$$PCF_{elec} = \frac{Q_{pc}}{E_o}$$

Primary Energy Factor Calculation: Electricity

An energy loss factor for electricity was derived using the total transmission and distribution loss data for 2002. The calculated values of the combustion and pre-combustion energy factors were summed and multiplied by the energy loss factor to derive the PEF for electricity production. The following equations were used:

$$L_{elec} = (1 + \frac{Q_{loss}}{E_o})$$

$$PEF_{elec} = (CMF_{elec} + PCF_{elec}) \times L_{elec}$$

In the second approach, the PEFs were calculated as:

$$PEF_e = (\sum_{i=1}^n T_{i,en}) \times (1 + L_e)$$

Where:

- $T_{i,en}$ - Total energy requirement coefficient per unit of energy providing sector's output in energy units
- n - Number of energy sources or fuels used by primary energy source sector
- i - Represents an energy source or a fuel
- L_e - Ratio of net energy loss to the total energy output of primary or delivered energy sector

In the third approach, the PEFs were calculated using an IO approach in the following steps:

$$PEF_e = (\frac{\sum_{i=1}^n T_{i,m} \times O_i \times Tariff_i}{E_{o,e}}) \times (1 + L_e)$$

Where:

- $T_{i,m}$ - Total energy requirement coefficient per unit of energy providing sector's output in monetary units
- O_i - Total output of the energy providing sector in \$
- $Tariff_i$ - Energy source tariff in MBtu/\$
- n - Number of energy sources or fuels used by primary energy source sector
- i - Represents an energy source or a fuel
- L_e - Ratio of net energy loss to the total energy output of primary or delivered energy sector
- $E_{o,e}$ - Total energy output of primary or delivered energy sector

3.3. Carbon Emission Factor Calculation

As discussed earlier, carbon emission factors (CEFs) are more accurate if calculated by taking into account the use of each energy source rather than using an average carbon factor. We sourced CO₂ emission factors for coal, natural gas, and petroleum from the U.S. Department of Energy, Energy Information Administration website.⁶³ Since the petroleum fuel category included a wide range of energy products, we used an average CO₂ emission factor. In addition to coal, natural gas, and petroleum, electricity was also consumed in facilities operations. An average CO₂ emission per unit of energy was sourced from EIA⁶³ and used in the calculation. CO₂ emissions per unit of mass were converted to carbon emissions using a factor of 0.2727 provided by the EPA.⁶⁴ The CEF was calculated using the following equation:

$$CEF_{j,pmf} = PMF_j \times \sum_{i=1}^n CO_i \times P_i$$

$$CEF_j = (CEF_{j,pmf} + CEF_{j,cmf}) \times L_e \times 0.2727$$

Where CEF , PMF , cmf , CO , P , L_e denote carbon energy factor, pre-combustion energy factor, combustion energy factor, carbon dioxide emission factor, percentage of a fuel “ i ” in total energy use to deliver a delivered energy “ j ”, and energy loss factor, respectively. In the case of electricity, we used the relative share of coal, natural gas, petroleum, and nuclear fuel to quantify the pre-combustion and combustion CEFs.

3.4. Human and Capital Energy Calculations

The human energy calculation included three energy components: (1) energy embodied in food, (2) energy of personal expenditures, and (3) household and transportation energy use. We used the approach suggested by FAO⁶⁵ to calculate the total energy of food consumed by an average worker in the U.S. in 2002. To apportion personal consumption to employment, consumption of an earner was compared against that of a non-earner as suggested by Cleveland³⁹. We calculated and allotted about 30% of personal expenditure to work. Similarly, total personal transportation energy was apportioned using the work-related transportation data published by the U.S. Department of Transportation. About 27% of total personal transportation was allocated to employment. Data of annual capital expenditure were collected from sources such as the U.S. Census Bureau and the Bureau of Labor Statistics. The total capital expenditure was broken down into three categories: (1) structures, (2) automobiles, and (3) equipment and software. Calculating and using IO-based energy coefficients, energy intensities of each category were determined. A more detailed explanation of human and capital energy calculation and data sources can be found in Dixit.³⁵

4. Findings

4.1. Combustion Energy: Direct Energy Usage

As mentioned in the Research Methods section, the combustion energy factor (CMF) for primary and secondary fuels such as coal, petroleum, and natural gas is assumed to be 1.0. All indirect upstream energy use was counted under the category of pre-combustion energy. In the calculation of CMF for electricity using approach 1, we found that each state differed in its fuel mix for electricity generation. As a result, the calculation for each of them showed a different CMF. Figure 10 illustrates the calculated values of combustion energy factors for 50 states and D.C. The highest CMF was calculated as 4.04 for D.C., which had only petroleum-based electricity generation in 2002. The lowest CMF was 2.41 for Rhode Island where approximately 95% of total electricity was generated using natural gas. Among the most coal-intensive electricity production states were Indiana, Utah, Wyoming, West Virginia, and North Dakota, where more than 90% of electricity was produced using coal. Approximately 14% of the total electricity in the state of Vermont came from renewable energy sources. The average CMF across all states and D.C. was 3.05. This means that on average, electricity production in the United States in 2002 required combustion of approximately 3 times more energy to generate a single unit of electricity.

Insert Figure 10 here

4.2. Pre-combustion Energy: Indirect Energy Usage

The indirect energy of energy source generation and distribution was calculated using indirect energy coefficients. Table 1 lists indirect energy coefficients for various energy commodities for their use of primary and delivered energy sources. These indirect energy coefficients cover all economy-wide indirect impacts of resource use incurred due to the generation of a dollar's worth of energy. The gold, silver, and other metal ore mining sector included the extraction of uranium. Since the indirect energy coefficients were per unit of monetary output, the total indirect energy use was dependent upon the total national output of the energy commodity. Table 2 provides the calculated values of direct and indirect energy use along with the energy embodied in labor and capital investments. Among the highest indirect energy uses were electricity production (8.54 quad Btu) and petroleum refineries (8.51 quad Btu). Electricity clearly dominated all energy sources in terms of the total direct energy usage (39.54 quad Btu). Among the most labor and capital input-intensive energy providing sectors were electricity production and oil and gas extraction. These sectors together consumed nearly 1.0 quad Btu of energy embodied in labor and capital inputs. Table 2 also lists the total loss factors for the five energy providing sectors. The transmission and distribution of electricity incurred approximately 10% of energy losses in 2002.

Insert Table 1, 2 here

In approach 2, we integrated process data into the IO-model and calculated the total energy coefficients for all five energy providing sectors. Table 3 provides the total energy coefficients calculated using the IO-based hybrid model. The total energy coefficients represent the sum of direct and indirect energy usage. These coefficients were calculated without using energy prices. Table 3 also lists the total energy coefficients quantified using the conventional IO-model. In this calculation, we used energy prices to convert energy intensities to embodied energy. Similar to the IO-based hybrid analysis, we adjusted the calculated values for the inputs excluded by IO-accounts, since any usage or loss of energy that does not involve a monetary transaction may not show up in the national IO accounts. For instance, loss of natural gas through flaring or venting would not be a part of IO accounts. Therefore, an adjustment was made to the total energy coefficients to cover such inputs or losses (see Table 3).

4.3. Primary Energy and Carbon Emission Factors

Using CMF, indirect energy, and energy loss data, we calculated PEFs for the five energy providing sectors. Table 4 presents the list of the calculated PEF values. The values of PEF calculated using the first and second approaches were close (0.8-5% within the results of Approach 1). However, the values of PEF calculated using the conventional IO-based approach were quite different, particularly for natural gas (33% more than Approach 1) and petroleum (77% more than Approach 1) supplying sectors. For electricity generation and distribution, the values of PEF calculated using the conventional IO-based method were 13% greater than the values from Approach 1. Figure 11 illustrates the PEF values calculated using the three approaches.

Insert Table 3, 4 here

Insert Figure 11 here

Figure 12 illustrates the relative share of each energy source in the total energy consumed in generating and supplying the four delivered energy sources. We calculated CEFs using only Approaches 1 and 2 results, since the results of the conventional IO-based approach were not reliable due to energy double counting demonstrated by the PEF results. However, CEFs for the IO-based approach can be calculated using the same method. Approximately 67% of direct and 64% of total energy combusted for electricity production came from fossil fuel-based energy sources. Nearly 50% of electricity was generated by burning coal in thermal power plants. Table 5 lists the pre-combustion, combustion, and total carbon emission factors per MBtu of energy use for the four energy sources. Electricity and natural gas remain the most and the least carbon-intensive energy sources, respectively. The pre-combustion carbon component represented approximately 30-35% of total carbon emissions incurred in supplying natural gas and petroleum. In the case of electricity, pre-combustion energy use contributed to approximately 14-20% of total carbon emissions.

5. Discussion

The PEF values were calculated using the conventional and hybrid input-output-based approaches for each energy providing sector. As discussed in the Literature Review section, using PEFs can avoid the counting of energy inputs multiple times in an IO-based analysis. As mentioned earlier, if a PEF is applied to embodied energy calculation, its value should be calculated rather than obtained from a secondary source. Since all energy and non-energy inputs were kept at zero in the input-output model, a PEF should account for all these inputs.

In this study, the PEFs for primary fuels such as coal, crude oil, and natural gas were initially calculated, then used later in deriving PEFs for delivered electricity, dry natural gas, and refined petroleum. One important aspect of PEF calculation was the treatment of energy imports. For instance, more than 60% of the United States' daily total supply of oil came from foreign economies in 2002. The imported energy was assumed to be extracted and processed domestically. This assumption was reasonable to account for all energy used in extracting and delivering the imported primary energy. In addition, the energy of human and capital inputs was added to the total PEF calculation. The hybrid calculations (Approaches 1 and 2), therefore, covered a much wider system boundary. The results of the first two approaches seemed consistent, whereas they varied in the third approach. Major variations occurred in the case of delivered energy such as dry natural gas, refined petroleum, and electricity. This was due to the double counting of energy inputs inherent in an input-output model, since these delivered energy sectors received large quantities of primary fuel. The issue of energy double counting in IO-based analyses has been pointed out by Treloar¹² and Crawford.¹³ The difference was negligible in the case of coal due to low energy input requirements, resulting in lower error.

Table 6 provides a comparison of the calculated values with those published in the literature. The values of PEF calculated in this study are higher than previous reported values, except for coal. The PEF calculation, in this research, accounted for all indirect energy impacts, human energy, capital energy, and energy of imports. Inclusion of these inputs caused the calculated values of PEF to differ from the published values. The energy conversion efficiency is improving with time due to better technology, and PEFs for years since 2002 may be smaller. The system boundary differences also caused variations in the reported values of PEFs. Figure 13 illustrates the correlations between the PEF values from the three approaches and the literature average. The PEF values calculated using Approaches 1 and 2 show a very strong and positive correlation with the average PEF values in the literature. Although the PEF values calculated with conventional IO-based method also show a strong positive correlation with the literature average, they should not be used due to double counting error.

The energy embodied in labor and capital inputs represented about 1.3-5.1% of total energy use. Their share is smaller but may not be insignificant. Note that this study examined the United States economy which is less labor-intensive than other economies of the world. Table 7 lists the use of human and capital energy per unit of the total output of an energy source. The electricity production sector was the most capital and human energy intensive sector, requiring about 62kBtu of human and capital energy per MBtu of its output. This can be expected looking at the large power plant facilities and T&D infrastructure required for electricity production and distribution. The coal sector required the least amount of human and capital energy.

The CEF values were calculated using the relative share of each energy source and its respective CO₂ emission factors. If an average value of CO₂ emission factors were used, due to a higher CO₂ intensity, coal and electricity would have caused the total carbon emissions to be overestimated, particularly in the case of natural gas and petroleum. The results of this study demonstrate that if indirect energy and resulting emissions remain excluded, an error between 3-35% may occur in the total carbon emission calculation. Indirect emissions are significant, particularly in the case of natural gas, petroleum, and electricity. Due to a lower energy conversion efficiency and higher T&D losses, electricity use causes more carbon emissions than any other energy source. The results of this study show that natural gas is the least carbon-intensive fossil fuel. The results also hint at three levels of improvement needed in the energy sector to achieve a drastic decrease in carbon emissions. First, manufacturing and construction technology needs to be further improved to be less dependent on fossil fuel-based electricity. Second, the fuel mix for electricity production must shift toward natural gas and renewable energy systems. Third, technology and infrastructure needed for energy generation and transmission needs to be more efficient with higher energy conversion rates and lower energy losses.

Insert Table 5, 6 here

Insert Figure 13 here

6. Conclusions

Any life cycle energy and carbon analysis remains incomplete and misleading if performed in delivered energy rather than primary energy units. To quantify the true environmental impacts of energy use, an energy source should be traced back to its extraction from the earth. Therefore, a set of PEFs is critical to convert delivered energy to primary energy. Using PEFs also avoids the double counting of energy sources, a problem inherent in traditional IO-based analyses. However, using such PEFs requires keeping all energy and non-energy inputs to energy providing sectors at zero in the IO model. Curtailing all inputs means that all direct and indirect inputs are removed, and need to be replaced by the calculated values of PEFs. Therefore, the calculation of PEFs necessitates that each major and minor direct and indirect input is included. In addition, PEFs must be calculated by taking into account the contribution of each energy source, which facilitates an accurate translation of energy use into carbon impacts. To ensure completeness, a wider system boundary and IO-based hybrid methods can be used to quantify PEFs.

The results of the three approaches confirmed assertions in the literature regarding the double counting of energy inputs in IO-based analyses. The PEF values calculated using the conventional IO method were higher than Approaches 1 and 2 due to the double counting issue. Based on the results of this research, we conclude that the PEF should be calculated using either a process-based (Approach 1) or an IO-based hybrid method (Approach 2) and should include human and capital inputs. Using a PEF quantified through a conventional IO-based analysis may produce erroneous results.

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Table 1: Indirect energy coefficients for energy providing sectors (2002)

Commodities	Oil and gas extraction	Coal mining	Electric power generation, transmission, and distribution	Natural gas distribution	Petroleum refineries	Gold, silver, and other metal ore mining
Oil and gas extraction	0.0154	0.0181	0.0170	0.0330	0.0877	0.0250
Coal mining	0.0019	0.0064	0.0045	0.0020	0.0032	0.0063
Electric power generation, transmission, and distribution	0.0073	0.0085	0.0058	0.0125	0.0188	0.0121
Natural gas distribution	0.0029	0.0042	0.0029	0.0063	0.0101	0.0063
Petroleum refineries	0.0070	0.0108	0.0086	0.0216	0.0201	0.0091

Table 2: Total energy use (trillion Btus) and loss factors for energy providing sectors (2002)

	Direct Energy Use	Indirect Energy Use	Energy of Labor	Energy of Capital Inputs	Energy Loss Factor
Coal	309.03	356.66	7.56	28.29	1.01
Oil & Gas	5,252.94	930.08	10.01	302.34	1.03
Natural Gas	5,285.73	1,978.98	8.65	63.73	1.05
Petroleum	7,189.76	8,513.21	6.30	70.83	1.00
Electricity	39,537.86	8,539.60	54.10	709.15	1.10

Table 3: Hybrid and IO-based total energy coefficients for year 2002

	Approach 2: IO-based Hybrid	Approach 3: IO-based	Inputs not Covered
	Total Energy Coefficient	Total Energy Coefficient	by IO Data
PEF, O&G	1.05	1.06	0.123
PEF, Coal	1.02	1.08	0.002
PEF, Electricity	3.77	4.09	0.061
PEF, Natural	1.33	1.68	0.133
Gas			
PEF, Petroleum	1.23	2.51	0.047

Table 4: Calculated values of PEFs in year 2002

Fuel/Energy Type	Approach 1	Approach 2	Approach 3
Coal Mining	1.04	1.03	1.09
Oil & Gas Extraction	1.23	1.21	1.22
Natural Gas Distribution	1.43	1.53	1.90
Petroleum Refineries	1.44	1.27	2.55
Electricity Generation	4.12	4.22	4.64

Table 5: Carbon emission factors (CEFs) for various energy sources in year 2002

Pre-combustion			
	Carbon Factor (Kg/MBtu)	Combustion Carbon Factor (Kg/MBtu)	Carbon Emission Factor (Kg/MBtu)
Approach 1			
Coal	0.75	26.14	26.89
Natural Gas	6.50	15.24	21.73
Petroleum	8.47	19.00	27.47
Electricity	15.88	63.12	79.00
Approach 2			
Coal	0.60	26.14	26.74
Natural Gas	8.22	15.24	23.46
Petroleum	7.14	19.00	26.14
Electricity	11.07	69.69	80.76

Table 6: PEF values from literature

Sources	Electricity	Coal	Petroleum (Oil)	Natural Gas
Energy Star ¹⁸	3.34	1.00	1.01	1.05
Ueno & Straube ⁶⁶	3.37		1.16	1.09
Czachorski et al. ⁶⁷	3.13		1.13	1.09
Deru & Torcellini ²²	3.32	1.06	1.18	1.09
ODEQ ⁶⁸	3.20	1.12	1.05	1.12
AGA ⁶⁹	3.10		1.20	1.10
Literature Average	3.24	1.06	1.12	1.09

Table 7: Human and capital energy per unit of energy output (2002)

	Human Energy (kBtu/MBtu)	Capital Energy (kBtu/MBtu)
Coal	0.34	1.25
Natural Gas	0.62	10.21
Petroleum	0.28	5.28
Electricity	4.36	57.13

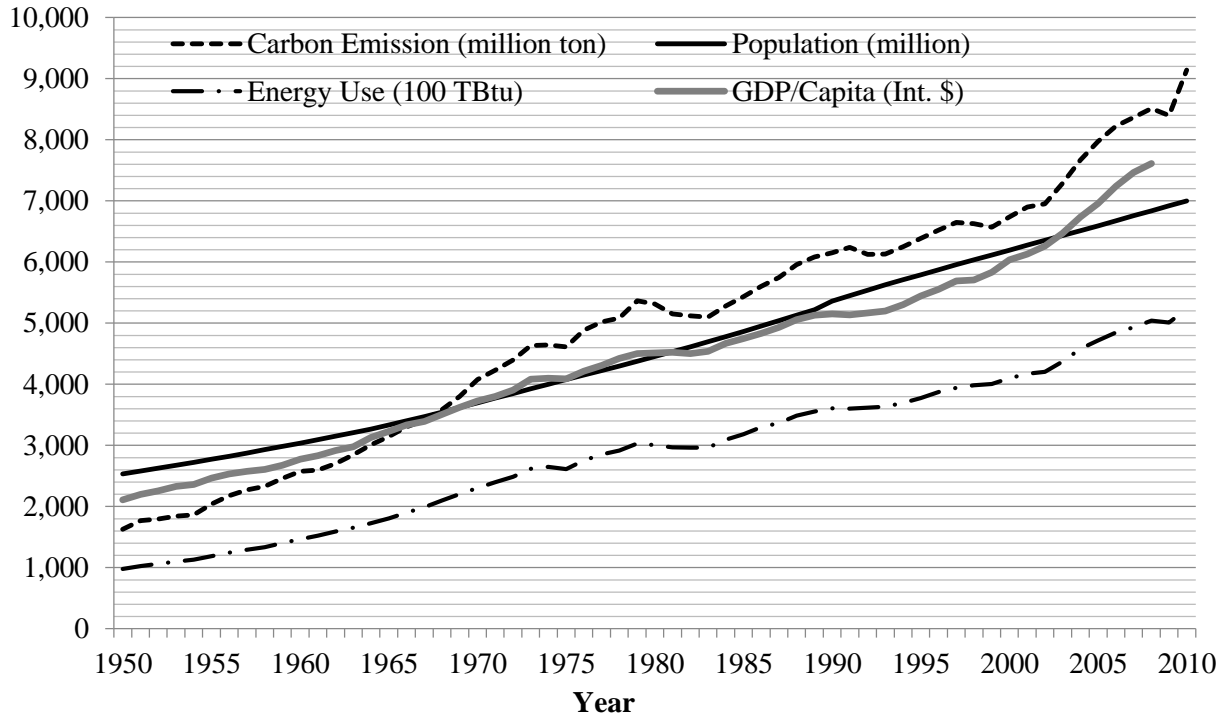


Figure 1: Relationship among global population growth, GDP, energy use, and carbon emission

Energy Component		Energy Type	Includes	Estimated From
Primary Fuel Combustion	Direct Fraction	Combustion Energy	Heat of combustion of primary fuels	Process data
	Indirect Fraction	Pre-combustion Energy	Energy of fuel & nonfuel inputs used in extraction, processing & delivering combusted fuel	Calculated PEF for primary fuels using process and IO data
Plant or Lease Operation & Energy Distribution	Direct Fraction	Operating Energy	Energy consumed by plant equipment, built facilities & labor	Process data
	Indirect Fraction	Indirect Fraction of Operating Energy	Energy of fuel & nonfuel inputs used in extraction, processing & delivering the operating energy	Calculated PEF for primary fuels using process and IO data
Energy Losses & Gains	Direct Fraction	Energy Lost or Gained	Energy lost or gained in processing, refining, converting & distributing primary & secondary energy	Process data
	Indirect Fraction	Indirect Fraction of Lost or Gained Energy	Energy of fuel & nonfuel inputs used in extraction, processing & delivering the lost or gained energy	Calculated PEF for primary fuels using process and IO data

Figure 2: Three energy components of a complete system boundary

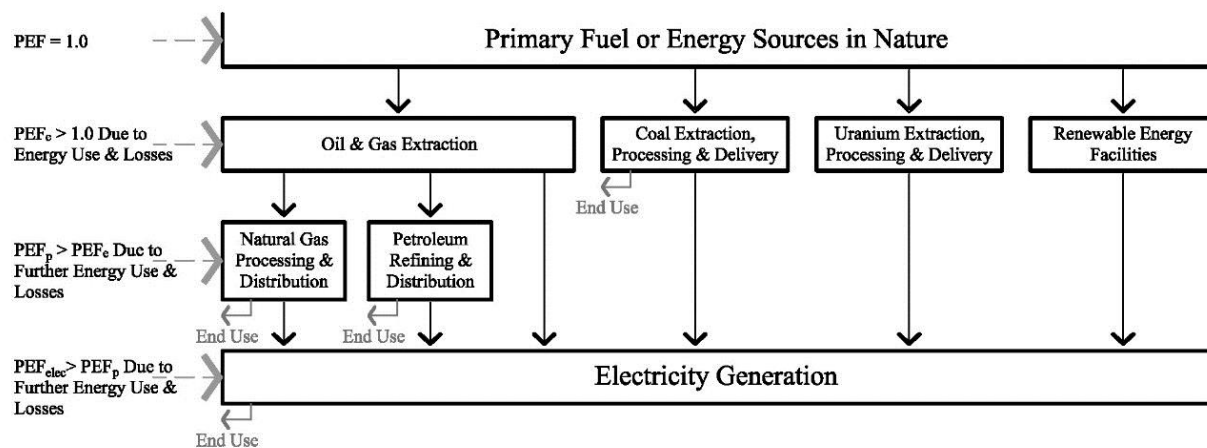


Figure 3: Energy extraction, processing, and its relationship with a PEF

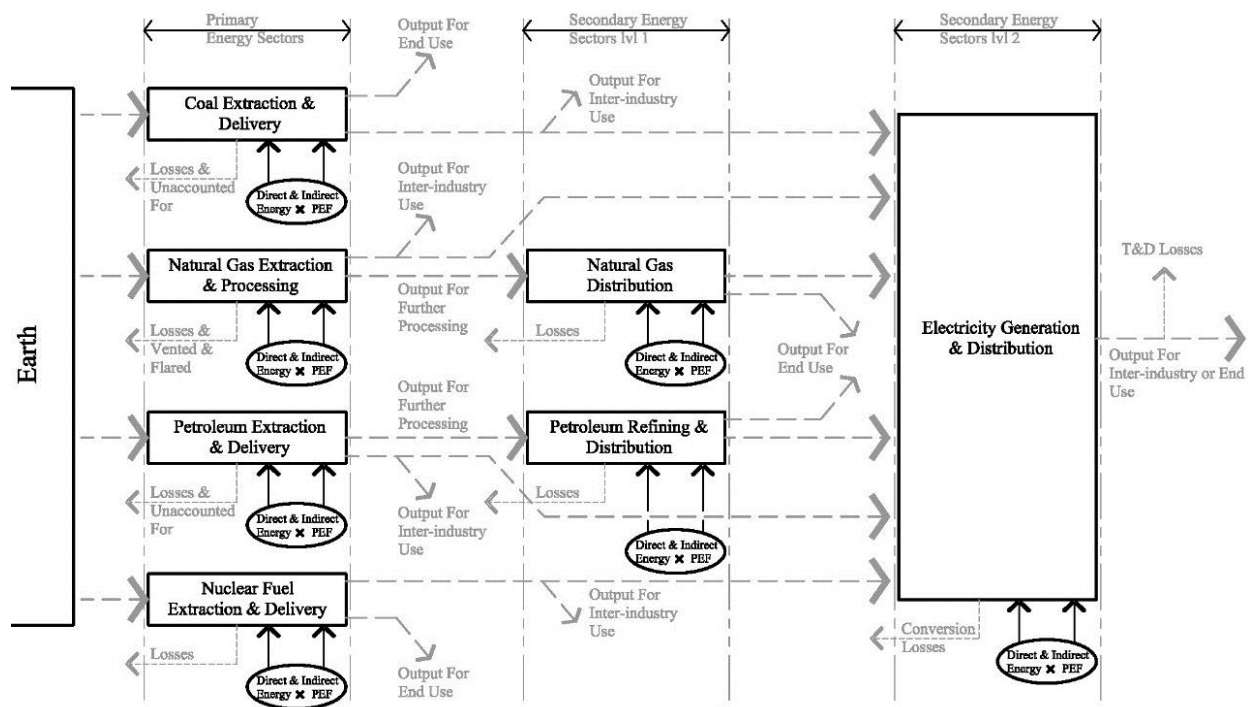


Figure 4: Energy supply in the United States^{53, 54}

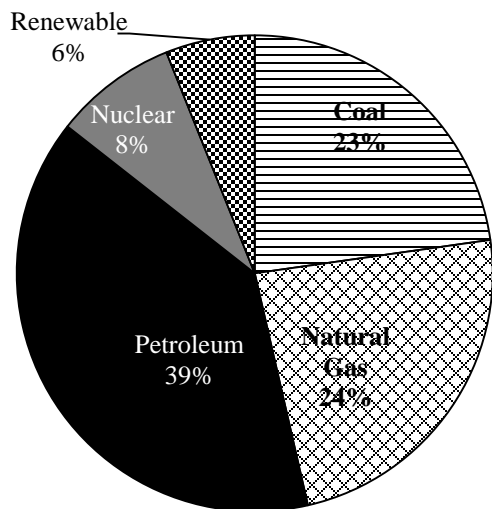


Figure 5: Total U.S. energy supply in 2002⁵³

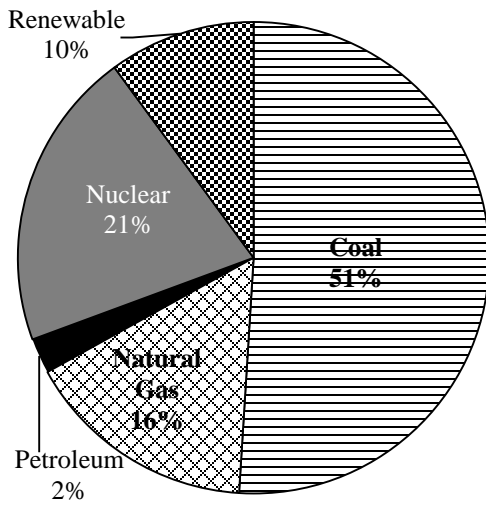


Figure 6: Fuel mix for electricity production in U.S. in 2002⁵⁴

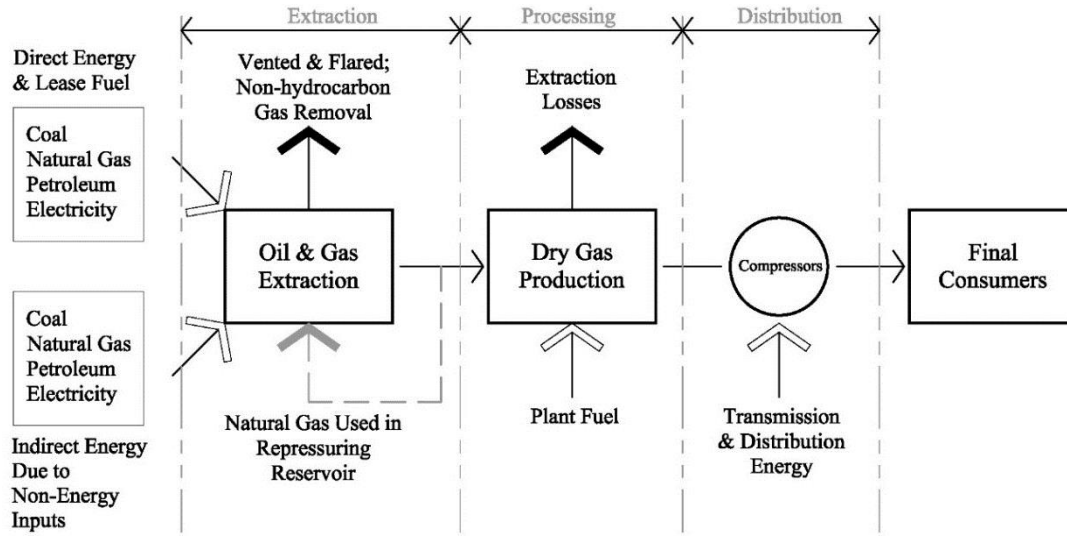


Figure 7: Flow of natural gas in U.S.

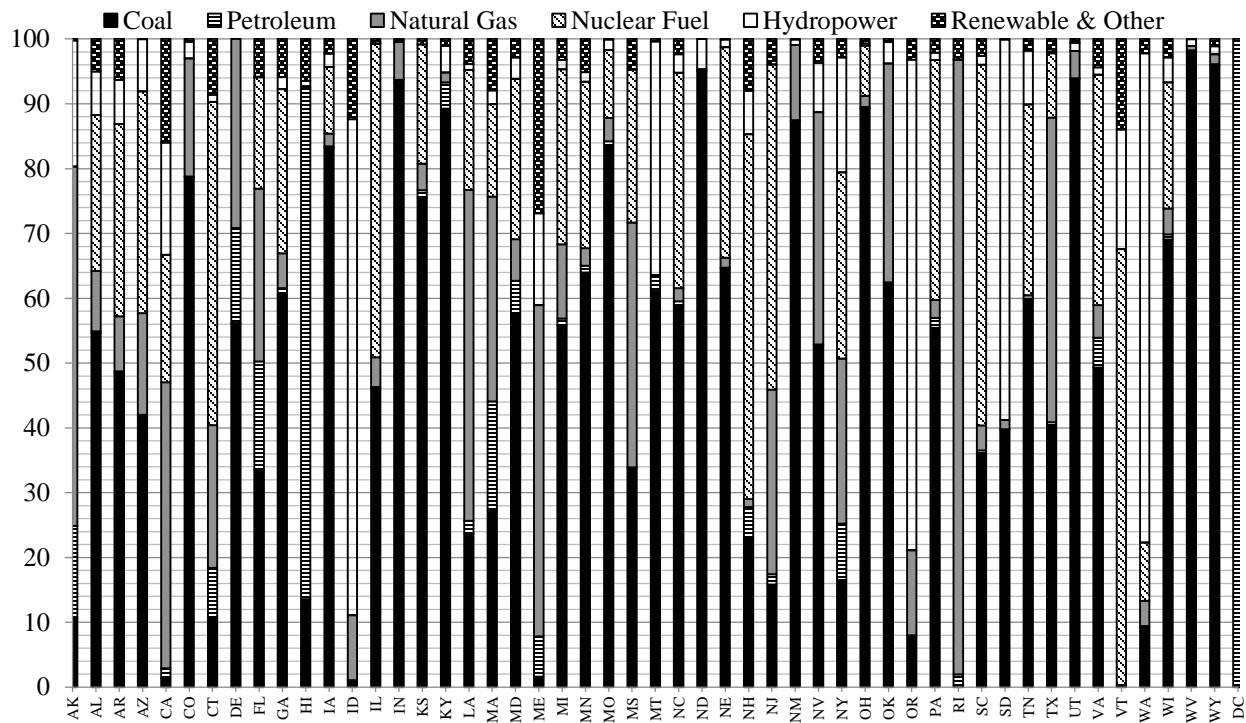


Figure 8: 2002 Fuel mix for electricity production in different states and the D.C.

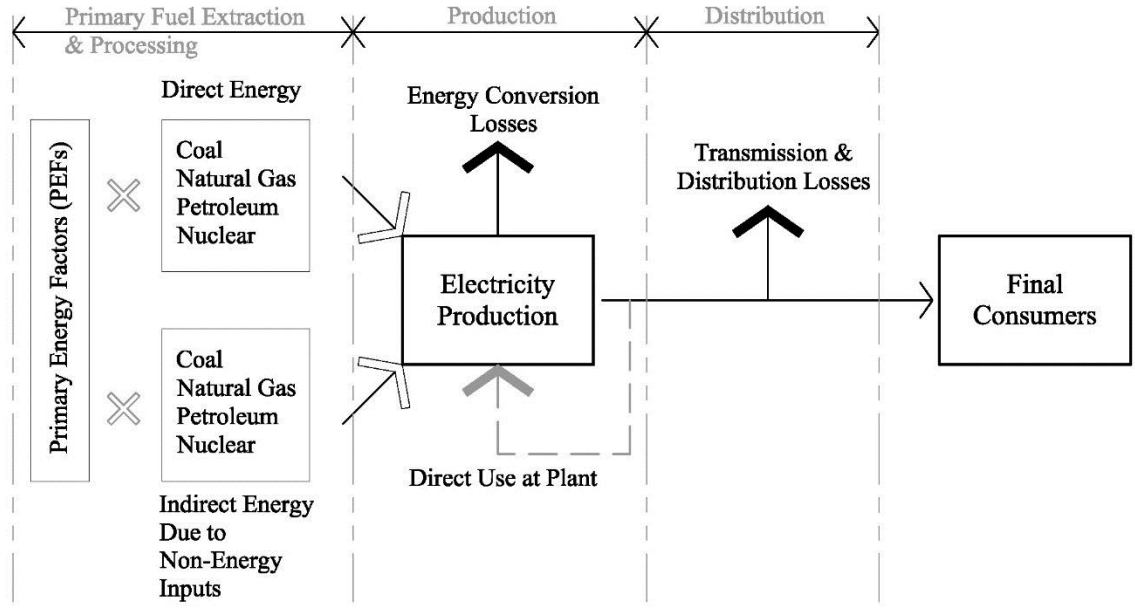


Figure 9: System boundary for PEF calculation for electricity

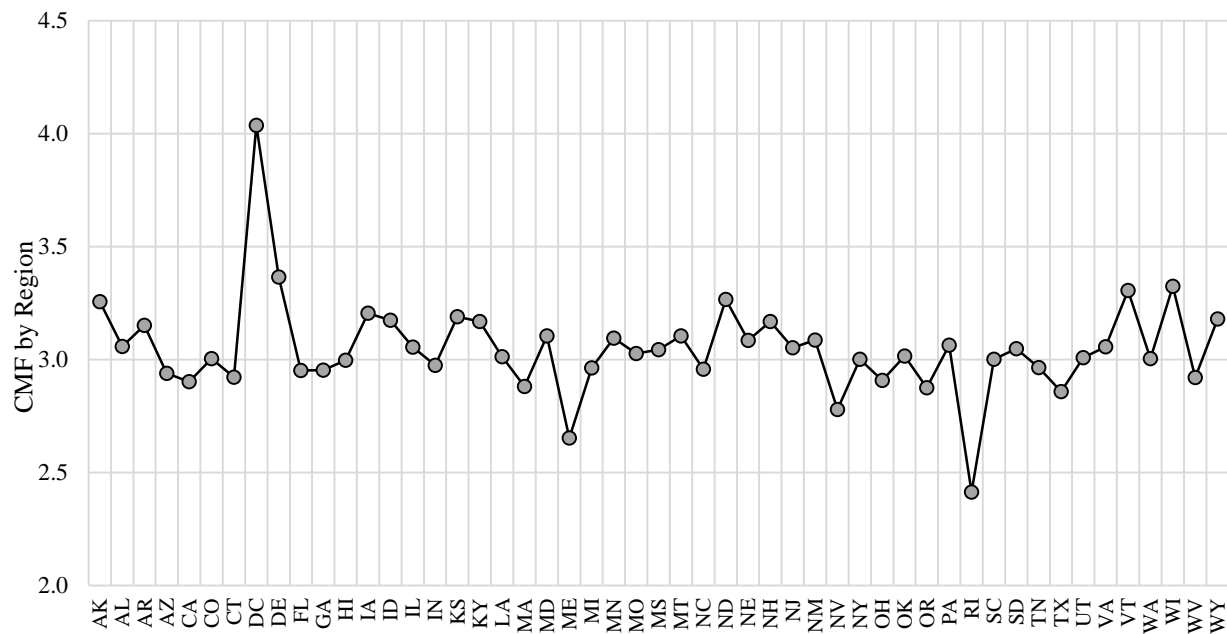


Figure 10: Combustion energy factors (CMFs) for 50 states and D.C.

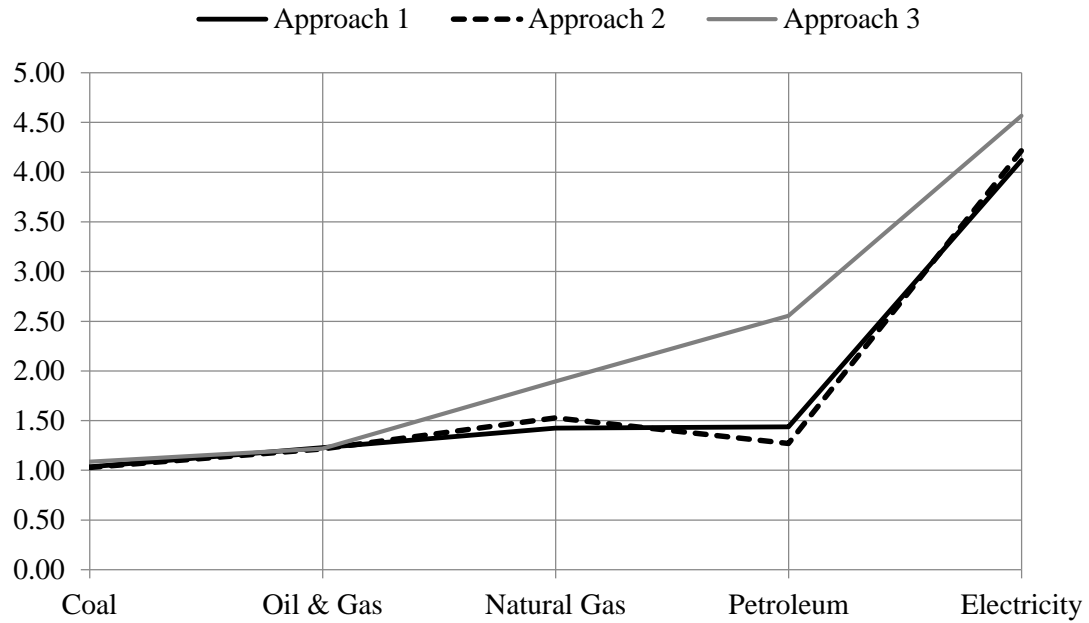


Figure 11: Calculated values of PEFs with the three approaches

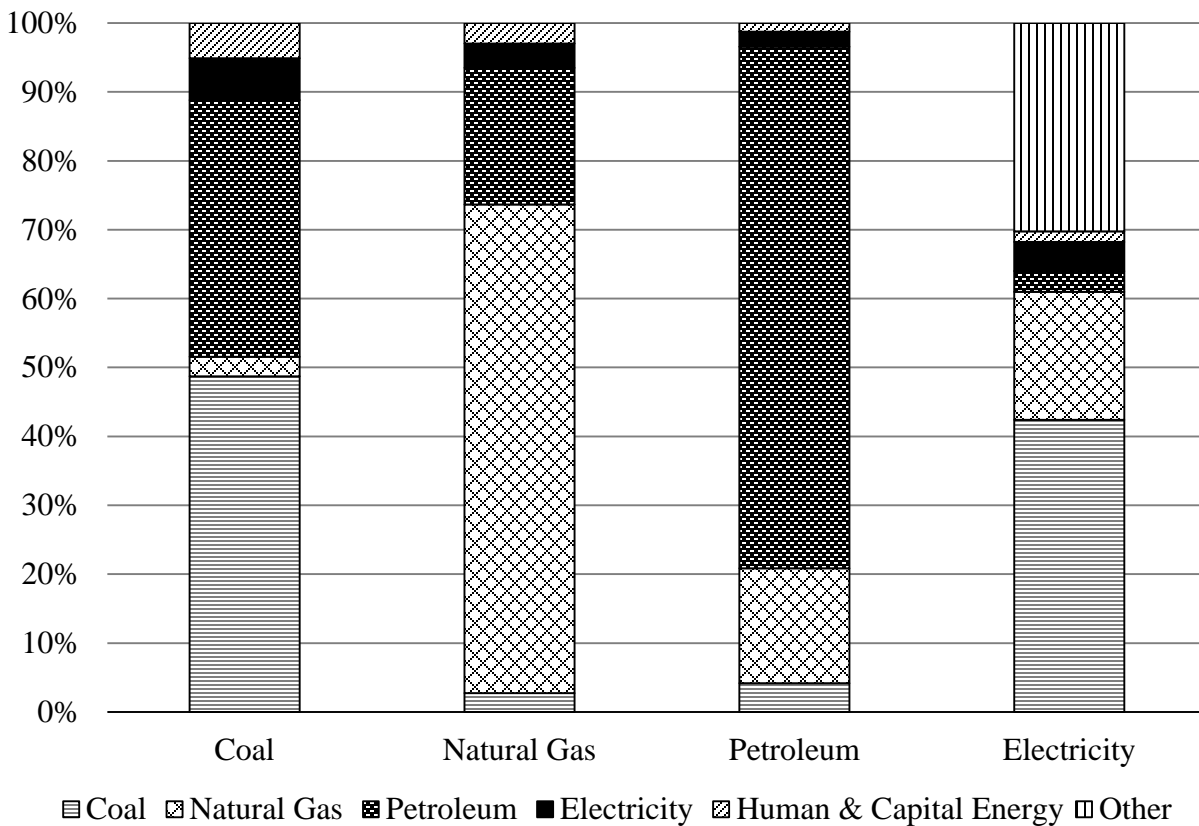


Figure 12: Share of each energy source in the total energy consumption

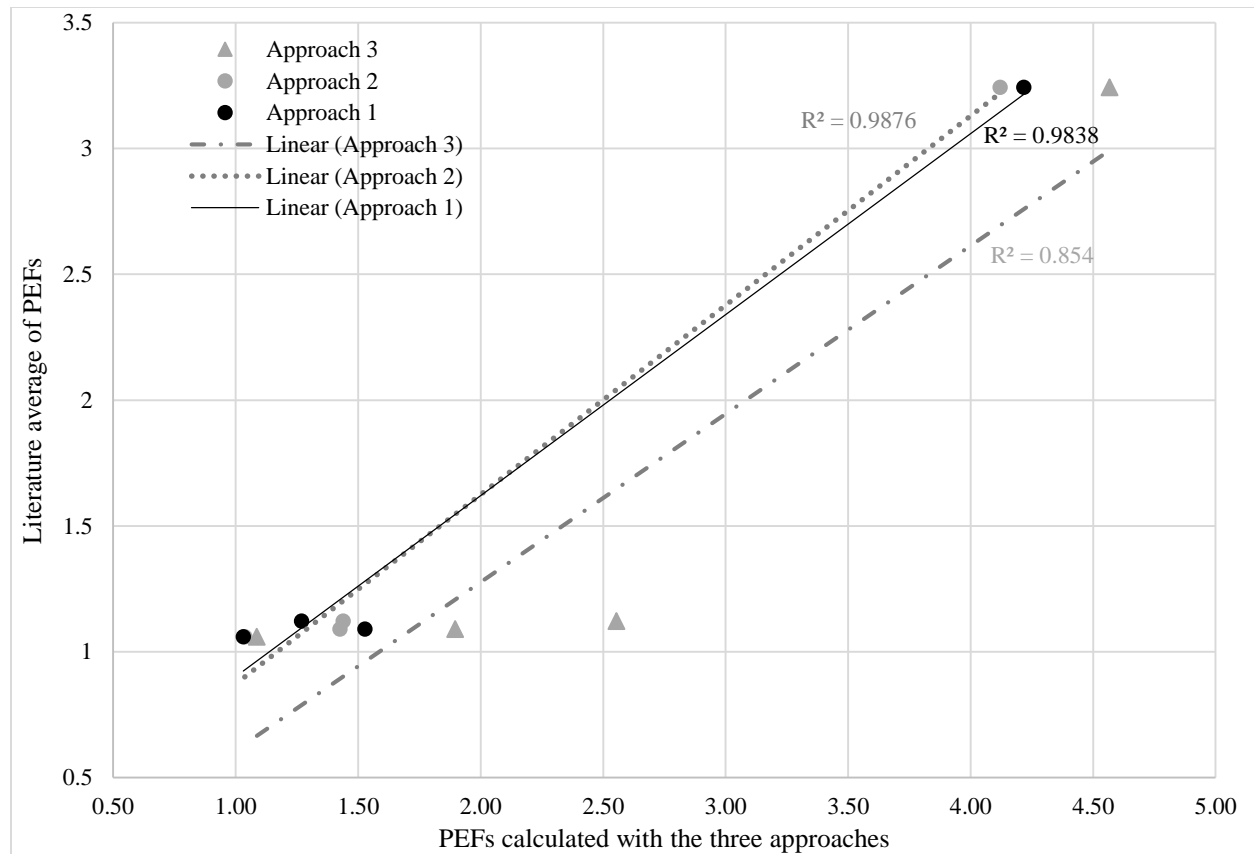


Figure 13: Correlation of calculated PEF values with the average values from literature