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Industry Energy Dependence Characteristics Under Different Energy Consumption Accounting Scopes: A Comparison Between China and the U.S.

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Abstract: Energy plays a vital role in the sustainable development of the economy and society. The key measures for achieving sustainable development include optimizing the energy structure, improving energy efficiency, and reducing reliance on non-renewable energy sources. This study constructs a monetary energy consumption database for China that distinguishes between energy resources used as raw materials and those used as other intermediate inputs, based on China's annual input–output table from 2001 to 2020. In this paper, the direct energy consumption and energy conservation potential of 33 industries in both China and the United States are compared under the following three energy consumption scopes: not excluding energy used as raw materials, excluding energy used as raw materials for the production of non-energy products, and excluding energy used as raw materials for the production of non-energy products or the production of energy products through non-combustion processes. This study also compares the direct energy dependence characteristics of these industries. The following conclusions are made: First, the energy consumption structure varies greatly under different scopes, of which the third scope is closest to the international standards. Second, China's raw materials industries have made some progress in energy conservation, and their gap with those in the U.S. has started to narrow. Third, China's high-tech industries still have potential for energy conservation and emission reduction.

Keywords: energy consumption accounting scopes; energy used as raw materials; input and output; energy dependence

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1. Introduction

1.1. Research Background

Energy is an important input factor in production processes, and it plays a vital role in the sustainable development of the economy and society. With the acceleration of economic growth, the increase in energy consumption has resulted in a series of environmental problems and socio-economic challenges. Balancing economic growth and sustainable development has become a major concern of the international community. The key measures for achieving sustainable development include optimizing the energy structure, improving energy efficiency, and reducing reliance on non-renewable energy sources. Therefore, in-depth studies on the energy dependence of industries are of great theoretical significance and practical value, will help us better understand the relationship between energy consumption and economic growth, and can provide theoretical support for energy policies and industrial policies. To achieve the goals of a "carbon peak" by 2030 and "carbon neutrality" by 2060, China must transition from a high-energy-consuming economy to a low-carbon economy as soon as possible. To adhere to the principle of common but differentiated responsibilities in global climate governance, China needs to strengthen its international comparative research on energy consumption and energy efficiency, improve its energy use efficiency, and transform into a low-carbon economy. Prior to all of the above, taking accurate measurements is the foundation for energy consumption studies.

1.2. Literature Review and Relevant Theories

Scholars have paid a lot of attention to energy consumption and energy efficiency among countries and regions. The existing studies have mainly focused on the changes in energy consumption and its structural decomposition [1–6], the impacts of energy consumption to economic growth and further forecasts [7–10], the impacts of economic growth to energy consumption [11], other impacts of energy intensity [12], the linkages between energy, economic growth and carbon emissions [13–15], and using the exchange rate method and the purchasing power parity (PPP) method to make international comparisons of energy intensity [16,17]. Most of these studies have conducted comparisons of the total energy consumption at the country level, and there is relatively little literature making international comparisons among industries. Energy consumption is usually measured in quantitative or monetary terms.

(1) Quantitative measurements of energy consumption. Quantitative measurements of energy consumption reflect the physical and technical correlation between energy and output more intuitively and are the most used in energy economics research. Scholars usually use physical or standard quantity data on energy consumption from sources including the environmental accounts of the World Input–Output Database (WIOD), the World Energy Balance of the International Energy Agency (IEA), and BP's World Energy Statistical Yearbook to conduct empirical analyses. The WIOD provides the total amount of energy each country uses and their total amounts of carbon emission-related energy consumption. The IEA and BP distinguish between the consumption of energy products for conversion processes and all energy products, but not between final energy products used as energy and raw materials. Countries such as the United States, Canada, and Australia and international organizations such as the European Union (EU) and OECD also have their own energy databases, which provide quantitative measurements of the supply and use of different types of energy products. The United States Energy Information Administration (EIA) and Australian Energy Accounts have provided additional contents, such as the monetary flows of energy products. Researchers have examined the increasing use of natural gas and oil as sources of feedstock and materials [18]. China's energy consumption studies usually directly adopt the final consumption of energy reported in the China Energy Statistical Yearbook for research [5,19–22]. The final consumption of energy from this data source includes the energy resources used as raw materials, which overestimates China's actual energy consumption.

(2) Monetary measurements of energy consumption. Although quantitative energy measurements receive more attention in energy analyses compared to monetary measurements, the problem of internal consistency between quantitative energy supply and use is difficult to resolve when conducting energy input–output analysis [23]. The use of monetary measurements of energy consumption can better reflect the economic relevance of energy. Existing studies have used monetary measurements of energy consumption from sources including the EU KLEMS database and the United States Bureau of Economic Analysis Integrated Industry-Level Production Account (KLEMS) [24] or have obtained monetary measurements of energy consumption by combining monetary flows from energy sectors in input–output tables [25,26]. These KLEMS databases are constructed based on the KLEMS model proposed by Jorgenson et al. in 1987 [27]. The KLEMS model is a multifactor productivity measurement model based on a growth accounting framework. It divides intermediate inputs into energy, raw materials, and purchased services, and then introduced them into a production function, along with capital and labor, to analyze economic growth and productivity in the U.S. after World War II. It uses industry outputs as the output indicators. K, L, E, M, and S represent the five factor inputs: capital, labor, energy, raw materials, and purchased services, respectively. In the KLEMS model, energy products are assigned to different intermediate input categories, i.e., energy or raw materials, according

to their actual use when they are consumed by different industries [28]. Countries such as the United States, Canada, and Australia and other international organizations such as the EU and OECD have constructed industry productivity accounts based on the KLEMS model, which provide monetary measurements of energy consumption by industry. These monetarily measured energy consumption data are integrated with the System of National Accounts (SNA) and thus help to elucidate the linkage between energy consumption and the macroeconomy. China does not have a KLEMS account or a monetarily measured energy consumption database that can be aligned with the SNA. Therefore, when Chinese scholars tend to use total intermediate inputs when conduct multiple factor productivity (MFP) analysis without breaking the intermediate inputs into energy, raw materials and purchased services [29], or even exclude intermediate inputs in growth accounting framework [30–32]. MFP data calculated in these studies are not under common standards and classifications as the World KLEMS project. As a result, the contribution of energy inputs to China's economic growth is opaque in these studies and MFP data is also incomparable across countries among the World KLEMS.

According to the existing literature, three unsolved problems remain. First, international comparisons of energy consumption lack industry-level studies. Second, the scopes of energy consumption measurements vary among studies. Some studies have included the energy resources used as raw materials while others have not. Third, China lacks a monetarily measured energy consumption database that can be aligned with the SNA and other KLEMS databases for productivity research and its international comparison. Recently, in order to implement the requirements for strengthening the statistical monitoring capacity in the 14th Five-Year Comprehensive Work Program on Energy Conservation and Emission Reduction, China's National Development and Reform Commission (NDRC) and the National Bureau of Statistics (NBS) issued the Circular on the Orderly Promotion of Energy Used as Raw Materials Not to be Included in the Control of Total Energy Consumption (hereinafter referred to as the Circular) in October 2022 (http://www.gov.cn/zhengce/zhengceku/2022-11/01/content_5723281.htm (accessed on 24 July 2023)), aiming at scientifically accounting China's energy consumption level and intensity.

Based on the annual monetary input–output table from 2001 to 2020, this study divided the energy resources used as raw materials (hereinafter referred to as energy materials) from the total direct energy resources consumed in intermediate inputs. In this paper, the direct energy consumption and energy conservation potential of 33 industries in both China and the United States are compared under the following three different energy consumption scopes: not excluding energy materials, excluding energy materials for the production non-energy products, and excluding energy resources for the production of non-energy products or the production of energy products through non-combustion processes. This study also compares the direct energy dependence characteristics of these industries.

The marginal contributions of this paper are as follows: First, we construct a monetary-based energy consumption database that is better aligned with the international KLEMS productivity accounts. By dividing the energy materials from the total energy consumption, this paper provides a more accurate monetary measure of China's energy consumption. Second, we consider the impact of energy prices on the energy dependence of industries by using a monetary ratio to describe their direct energy dependence, providing a new perspective. Third, we expand China's input–output tables to annual intervals, which better reflect the differences in energy consumption among industries and their trends. Fourth, the direct energy dependence characteristics of China and the United States are compared to clarify the effective paths and directions of China's endeavors for the close future.

The rest of the paper is structured as follows: Section 2 introduces the three energy consumption accounting scopes and the construction of the monetary-based energy consumption database. Section 3 analyzes the energy dependence characteristics of China and the United States under the different energy consumption accounting scopes. Finally, the conclusions and outlooks are presented in Section 4.

2. Data and Methodology

2.1. Scopes of Energy Consumption

Before determining the accounting scopes for energy consumption, it was necessary to understand the usage of energy in production process. There are four consumption modes of energy products: (a) combustion as fuel or power, (b) producing energy products through combustion processes, (c) producing energy products through non-combustion processes, and (d) producing non-energy products. The first two modes refer to the combustion of energy products, which is the source of carbon emissions. The latter two modes do not include a combustion procedure, and energy products are transformed into other energy products or non-energy products instead of greenhouse gases. differences among the four modes show that energy products, unlike other goods products, can be used as either energy or raw materials. The significance of these distinctions lies in the fact that carbon emission problems refer to greenhouse gas emissions from fossil energy combustion activities and do not apply to the consumption of energy materials. For example, when coal, oil, natural gas, etc. are used to produce olefins, aromatics, alkynes, alcohols, ammonia, etc. for non-energy purposes, the corresponding energy products are converted into non-energy products rather than greenhouse gases. According to the Greenhouse Gas (GHG) Protocol jointly developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), three GHG scopes have been defined for GHG accounting and reporting purposes. Scope 1 GHG emissions refer to direct emissions from energy combustion; Scope 2 GHG emissions refer to indirect emissions from purchased energy (including electricity, heat, refrigeration, etc.); Scope 3 GHG emissions are other indirect emissions not included in Scopes 1 and 2. China's current carbon emission inventory mainly focuses on Scope 1 [33].

Since energy used as raw materials (i.e., energy materials) and energy used as fuels or power play different roles in production process and have different impacts on carbon emissions, they should be treated as two different types of input factors. Separating these two types of energy can lead to better measurements and analyses of energy consumption and is of great significance to ensure sustainable development.

This paper compares the differences in energy consumption under the three scopes of energy consumption, with the total energy consumption appearing in decreasing order. The division of energy products under the three scopes of energy consumption is shown in Table 1.

Table 1. Division of energy products under three scopes of energy consumption.

Usage of Energy Products	Scope 1	Scope 2	Scope 3
(a) Combustion as fuel or power	Energy	Energy	Energy
(b) Producing energy products through combustion processes	Energy	Energy	Energy
(c) Producing energy products through non-combustion processes	Energy	Energy	Materials
(d) Producing non-energy products	Energy	Materials	Materials

Scope 1 treats all four modes of energy product consumption as energy consumption. That is, without excluding the energy materials, the input–output table is directly classified as energy, raw materials, or purchased services based on the attributes of the product sector. This scope corresponds to the final energy consumption in the China Energy Statistical Yearbook. Since energy materials are not excluded, the final energy consumption is overestimated.

Scope 2 treats the first three modes of energy product consumption as energy consumption and the fourth as raw materials consumption. The Circular defines energy materials as the energy resources used to produce non-energy products but not those used as fuel or power. It emphasizes that the use of energy materials to produce non-energy products, i.e., energy products under the third mode, are still regarded as energy. Scope 2 excludes energy materials following the direction of the Circular. The "non-energy use" items of the industrial final consumption in the national energy balance of the China Energy Statistical Yearbook are recorded as energy materials under Scope 2. This scope also overestimates energy consumption.

Scope 3 treats the first two modes of energy product consumption as energy consumption, and the last two as raw materials consumption. That is, it excludes the energy resources used as raw materials, defined as the energy resources used to produce non-energy products or to produce energy products through non-combustion processes. Energy products used as raw materials for producing other energy products, which are categorized as "inputs of transformation" in China's energy statistics, have two consumption modes. In one mode, energy is consumed as fuel in the generation of secondary energy, e.g., thermal power or heating supply, and should be categorized as energy inputs. In the other mode, energy is refined or transformed into another energy product, e.g., coal washing, coking, petroleum refineries, and gas works, and should be categorized as energy materials, i.e., material inputs. In this paper, Scope 3 is consistent with the GHG Scope 1 and is also comparable to the monetary energy consumption data based on the international KLEMS databases.

Notably, the three scopes in this paper and the U.S. monetary energy data do not include all expenses and energy consumptions related to sustainable energy production. GHG Scopes 2 and 3 measure indirect emissions, so it was necessary to construct a proper scope to include additional energetic sustainability costs. From the perspective of the energy consumption accounting scopes, sustainable energy production refers to electricity generation that does not directly emit carbon dioxide, including nuclear, hydroelectric, wind, solar, and geothermal energy. Sustainable energy production has received considerable attention due to increasing concerns about climate change, and scholars have researched its relationship to the sustainable development goals [34], its contributions and effects [35–37], and more detailed sustainable energy solutions [38]. While sustainable energy production does not directly consume energy to generate electricity and is often seen as environmentally friendly, it involves additional costs and energy consumption that are often overlooked in traditional energy accounting scopes, such as facility manufacturing and maintenance, damaged part substitutions and recycling, and carbon pathways emitted by fulfilling the demands of sustainable energy-related industries. The sustainable energy production industry encompasses multiple sectors of the national economy. These sectors consume energy while producing sustainable products or services. However, due to the lack of detailed energy consumption data, especially specific data from different stages of production, it is difficult to calculate the corresponding sustainability costs associated with sustainable energy production in these industries. For example, energy convertors on solar panels are used to produce solar power and are themselves produced in the semiconductor industry, requiring substantial consumption of electricity and natural gas at stages such as silicon material purification, cell manufacturing, and module assembly. Since the energy consumption data for these production stages are often scattered and opaque, it is challenging to comprehensively assess the total energy consumption of the production process, thereby affecting the accounting of its sustainability costs. However, neither China nor the U.S. energy databases have provided the necessary data required to disaggregate these costs at the industry level. These data limitations highlight the need to improve future energy statistics works in both countries.

2.2. Constructing a Monetary Energy Consumption Database for China

Figure 1 summarizes the methodology of constructing a monetary energy consumption database for China. The data sources included the monetarily measured China input–output (IO) tables and the quantitatively measured China energy statistical data. The details of each step are described in the following subsections.

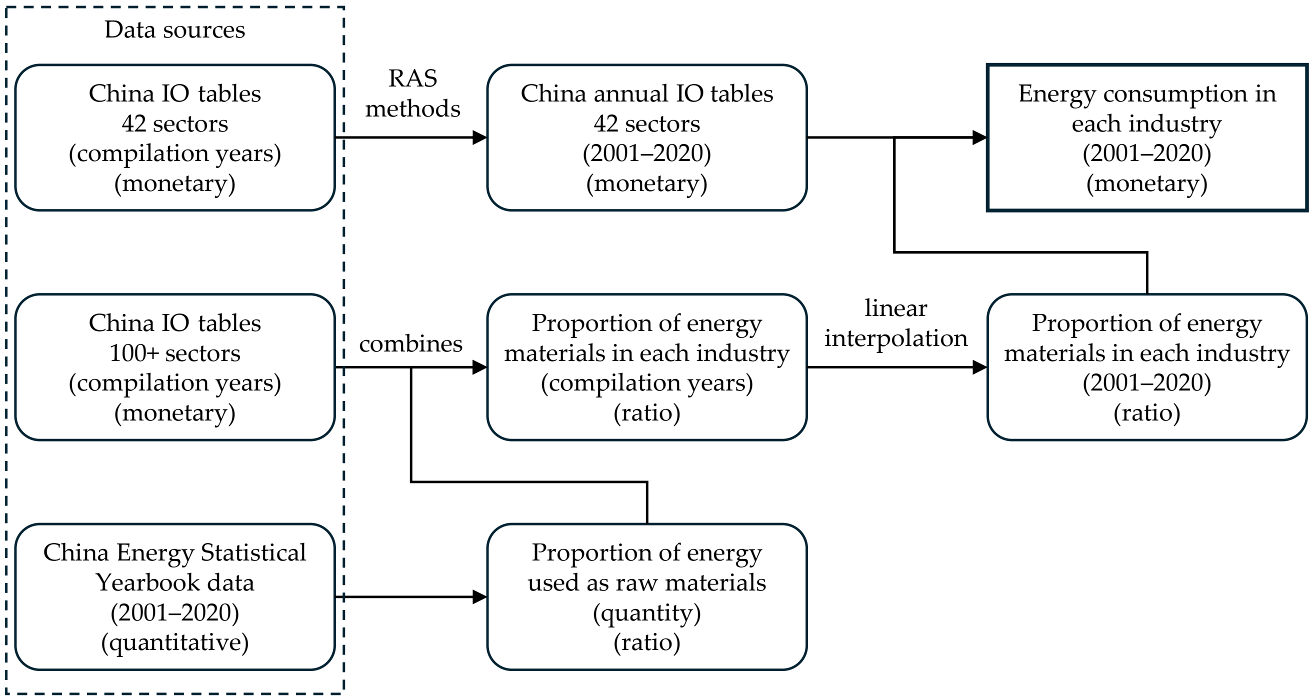

Figure 1. Methodology of constructing the monetary energy consumption database for China.

2.2.1. Constructing Annual Input–Output Tables

The National Bureau of Statistics of China has released China's input–output tables for six compilation years, i.e., 2002, 2007, 2012, 2017, 2018, and 2020. Based on these input–output tables and economic data from the China Statistics Yearbook, we used RAS methods to update the IO tables and constructed China's annual IO tables from 2001 to 2020 in current Chinese yuan. The RAS method is also called the biproportional scaling method and is the most used method for updating input–output matrices. It uses the row sums and column sums of the target matrix X as marginal controls and the structure of the initial matrix X^0 as the original entry, and it generates a target matrix through iterations. In this study, the improved generalized RAS (IG-RAS) method was used to extrapolate the IO table in 2001, and the recurrence IG-RAS method was used to interpolate the remaining IO tables (see Table 2) (Detailed IG-RAS method can be found in the work of Huang et al. [39]. In recurrence IG-RAS method, IO tables from the previous and subsequent compilation years are both included in the model as original entries. See the work of Li for more details [40]). The annual data used as the marginal controls were obtained from the National Bureau of Statistics of China. The IO tables in the six compilation years were used as the original entries.

Table 2. Projection methods for non-compilation years.

Non-Compilation Years (Target Entries)	Data Used from Compilation Years (Original Entries)	Projection Methods
2001	2002	IG-RAS, extrapolation
2003–2006	2002, 2007	Recurrence IG-RAS, interpolation
2008–2011	2007, 2012	Recurrence IG-RAS, interpolation
2013–2016	2012, 2017	Recurrence IG-RAS, interpolation
2019	2018, 2020	Recurrence IG-RAS, interpolation

2.2.2. Calculating the Proportions of Energy Resources Used as Raw Materials

In this study, we first focused on the energy-producing sectors: (a) the mining and washing of coal, (b) the extraction of petroleum and natural gas, (c) the processing of petroleum, coal, and other fuels, (d) the production and supply of electric power and heat power, and (e) the production and supply of gas. Using the final energy consumption by industrial sector and the energy balance data from the China Energy Statistical Yearbook, we calculated the proportions of energy resources used as raw materials and non-materials when consumed by different sectors. The categorization process included the following three cases:

(1) When the energy-using sector is an agricultural or service sector, the energy products are always consumed as fuel and power, i.e., the ratio of raw materials equals zero.

(2) When the energy-using sector is a non-energy industrial sector, the energy used are all final consumption, i.e., the ratio of raw materials equals the energy used as raw materials over total final consumption.

(3) When the energy-using sector is an energy-producing sector, the energy products are not only used as final consumption, but also transformed into secondary energy. Depending on the definition of energy materials, the calculation method is different for the different scopes, as shown in Table 3. Among them, the inputs of energy transformation are categorized into different energy-producing sectors according to the energy-using sector, as follows: Thermal power and heat supply are not counted as energy materials. Coal washing is attributed to mining and washing in the coal sector. Coking, petroleum refining, and coal-to-liquids and briquettes are attributed to processing in the petroleum, coal, and other fuel sectors. Gas works and natural gas liquefaction are attributed to production and supply in the gas sector.

Table 3. Calculation of proportions of energy used as raw materials under different scopes.

Energy Consumption Scope	Proportion of Energy Used as Raw Materials
Scope 1	0
Scope 2	$\frac{\frac{FC_{raw\ materials}}{FC_{industrial\ sector}} \times FC_{enengy\ sector}}{TF+FC_{enengy\ sector}}$
Scope 3	$\frac{\frac{FC_{raw\ materials}}{FC_{industrial\ sector}} \times FC_{enengy\ sector}+TF}{TF+FC_{enengy\ sector}}$

Here, $FC_{raw\ materials}$ is the energy products used as raw materials in the energy final consumption, $FC_{enengy\ sector}$ is the final energy consumption of the energy-producing sectors, $FC_{industrial\ sector}$ is the total final energy consumption of all industrial sectors, and TF is the input amount for transformation.

This study mapped various energy products to the relevant product sectors in the input–output table for the compilation years, and then aggregated the monetary values of these energy products. The results are the proportions of energy resources used as raw materials by different sectors.

Among the products of the five energy-producing sectors, electricity and heat are always consumed as energy, i.e., their proportion as raw materials is zero. Figure 2 shows the proportions of the remaining four energy sectors when energy products are consumed by different sectors. The insights from Figure 2 are as follows: (a) The difference between Scopes 1 and 2 is mainly reflected in the amounts of petroleum and petroleum product inputs in the industrial sectors. As important raw materials for the chemical industry, one-fifth of petroleum products are consumed as raw materials. (b) The difference between Scopes 2 and 3 is mainly reflected in the raw materials proportions of coal, crude oil, and natural gas. This is because high proportions of these primary energy resources are used to generate secondary energy through refining processes, which is recorded as raw materials consumption under Scope 3.

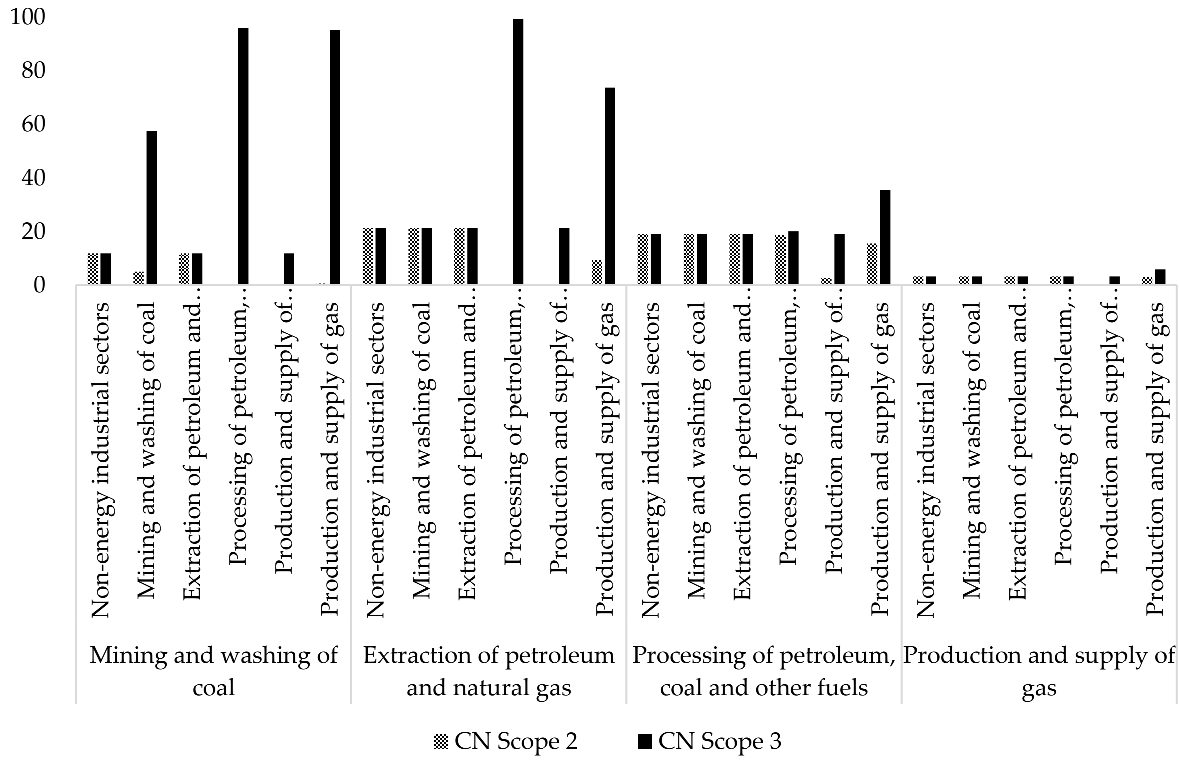

Figure 2. Estimated proportions of energy materials under different scopes (%) by sector, 2001–2020 average. Note: In this study, we assumed that each non-energy industrial sector had the same proportion of each kind of energy materials. This assumption may underestimate the proportions of energy materials used by the chemical industry and overestimate the proportions of other industries.

2.2.3. Calculating the Proportions of Industry Energy Materials in the IO Table's Compilation Years

In this study, we separated the intermediate inputs of the monetary-based input–output tables to estimate the monetary-based energy consumption by industry. According to Jorgensen's KLEMS growth accounting framework, intermediate inputs are divided into energy, raw materials, and intermediate inputs. Some of the energy production sectors in China's input–output table also contain service products, i.e., mining supporting activities, so before dividing the intermediate inputs, it was necessary to divide the service products in the energy-producing sectors, and then divide the energy and raw materials under the three scopes. The steps were as follows:

(1) The service products were separated from the energy sectors. Mining support activities appeared in the statistics in 2012. The outputs of this industry's subsector, activities supporting oil and gas extraction, accounted for more than 95% of all mining support activities according to the data from the China Economic Census Yearbook. For ease of calculation, only the service products in the activities supporting oil and gas extraction were separated from the energy sectors. According to the economic census data, the total industrial outputs of activities supporting oil and gas extraction in 2004, 2008, and 2013 were 12.5%, 15.9%, and 13.2% respectively, of the industry. The service coefficients of the industry were projected to be 11.0% and 15.0% in 2002 and 2007, respectively, using the interpolation method.

(2) The energy resources used as raw materials and non-materials were separated. Combining the proportions of energy resources used as raw materials with the intermediate inputs after separating the service products, we divided the intermediate products of the energy-producing sectors into energy, raw materials, and purchased services in the KLEMS framework. The other sectors were divided in accordance with their product scopes.

(3) The energy-splitting coefficients were calculated under the three scopes for each compilation year. Using the energy coefficients, we separated the energy input flows from the intermediate flows in the 42 sectoral input–output tables.

2.2.4. Projecting the Proportions of Industry Energy Materials into the Non-Compilation Years of the IO Table

Based on the time series of energy coefficients for each cell of the IO table of the compilation years, we carried out linear interpolation and extrapolation to project the energy coefficients for each cell of the non-compilation years using the proportions of the neighboring compilation years (see Table 2). Using the energy coefficients for the compilation years under the three scopes, the energy coefficients were obtained for the non-compilation years.

2.2.5. Calculating the Energy Inputs Under the Three Scopes

We multiplied the resulting energy coefficients with the intermediate flows from 2001 to 2020 and obtained the energy intermediate flow matrix for 42 industries from 2001 to 2020 annually. Aggregating the energy flows by column provided the energy inputs for the 42 industries under the three energy consumption scopes. These data were used for the production in each sector under the input–output framework.

2.3. Obtaining Monetary Energy Data for the United States

2.3.1. Data Source

The United States energy data were derived from the Composition of Gross Output by Industry table in GDP by Industry Database, published by the United States Bureau of Economic Analysis (BEA) on its website (https://www.bea.gov/itable/gdp-by-industry (accessed on 13 March 2023)). This table is an important data source for the US KLEMS productivity account. It provides industry-level total input composition data from the production perspective in current dollars, including the compensation of employees, taxes on production and imports less subsidies, gross operating surpluses, energy inputs, materials inputs, purchased-services inputs, etc. The main features of this table are as follows: (a) continuous, containing annual data from 1997 to 2022; (b) monetary-based, containing data reported in the current dollar value and the 2012 constant dollar values; (c) industry-segmented, containing data for 18 sectors and 43 broad industries according to the North American Industry Classification System (NAICS); (d) distinguishes energy materials from energy. Feature (d) indicates that each detailed intermediate product is categorized into three input categories, i.e., energy, raw materials, or purchased services, according to the product's nature and cost category. In most cases, a particular product is consumed in one of three input categories, while in some cases, the product may also be categorized into multiple cost categories depending on the industry in which it is consumed. For energy products, the primary energy is categorized as energy input when it generates secondary energy through a combustion process, e.g., thermal power generation, but as materials inputs when it generates secondary energy through a refining process. For example, petroleum products are categorized as energy inputs when consumed by most industries, but as materials inputs when consumed by the petroleum-processing industry [28]. This database uses continuous, industry-segmented, monetary-based input–output data and distinguishes between energy and energy materials; thus, it is comparable to the Chinese energy database constructed above.

2.3.2. Aligning Industry Classifications to Form Comparable Data

The China monetary energy consumption database built in Section 2.2 includes 42 sectors based on China's industrial classification for national economic activities and the input–output table's industry sectors. However, the monetary energy data for the United States used in this study are based on the NAICS. To conduct comparative analyses between China and the United States, we aligned the 42 sectors in the China monetary energy consumption database with the industries in the Composition of Gross Output by Industry table published by the BEA. If multiple industries in one country corresponded to the same industry in another country, the multiple industries were merged. After alignment, 33 aligned industries were obtained. Due to space constraints, the industry alignment list is presented in Table A1 in Appendix A.

2.4. Indicators for Energy Dependency Analysis

Various indicators can be used to analyze energy dependence, one of which is the energy intermediate input rate (hereinafter referred to as the "energy input rate"). Similar to the direct consumption coefficient, the intermediate input rate refers to the ratio of intermediate inputs to the total inputs in each industry, reflecting the proportion of intermediate inputs needed to produce a unit of output value of products in the production process of each industry. After dividing the intermediate inputs into energy and non-energy items, the industry's energy input rate reflects its direct dependence on energy inputs in the production process. The calculation is shown in Equation (1):

$$ER_i = \frac{E_i}{Y_i} \tag{1}$$

where ER_i is the energy input rate for industry i, E_i is the energy input for industry i, and Y_i is the total input for industry i. Both the energy input and total input are measured at current prices.

The energy input rate is the monetary ratio of energy value to the total input value. Since the total input contains all kinds of input factors that cannot be measured by quantitative units of energy, using a monetary indicator connects the energy input with the total input under the system of national accounting. Ratios using energy consumption measured in energy units over indicators of economic activity measured in monetary units, such as energy intensity, measure the efficiency of the energy output rather than the proportion of energy in the total inputs, i.e., the dependency on energy input. The energy input rate allows for better integration with other value-based indicators and can still reflect technical dependencies after price adjustments. It incorporates energy prices, which are subject to variations due to supply and demand across different countries and stages of development. For example, energy prices are higher in China and lower in the United States, which significantly influences the monetary value of energy consumed in production processes.

The intermediate input rate is affected by the industrial structure, technological progress, the nature of the industry, the division of labor, etc. Since industry differences exist in energy input rates, we focused on analyzing the energy dependence gap of the same industry between China and the United States.

3. Results and Discussion

This section compares the energy dependence characteristics of China and the United States under different energy accounting scopes from the perspective of industry energy dependence.

3.1. Trends in Energy Input Rates

From the perspective of different energy consumption scopes, China's energy input rates under the three scopes show consistent trends, while the level of energy dependence varies, with a smaller gap between Scopes 1 and 2, and a larger gap between these two and Scope 3. From 2001 to 2007, China's output growth mainly relied on the increase in material inputs. Energy consumption then accelerated and outpaced economic growth. The economy's dependence on energy increased, as evidenced by a continuous increase in the energy input rate, with a total increase of more than 50 percent under all three scopes. The Outline of the Eleventh Five-Year Plan in 2006 proposed to comprehensively improve the energy conservation policy system and adjust the energy strategy. Since then, the consumption of purchased services has continued to increase, along with economic development and technological advancement, and the energy input rate has begun to decrease, with the energy input rate remaining on a downward trend from 2010 onward. Energy input rates fell back to 2001 levels under all three scopes starting in 2019.

A gap still exists between China and the United States in terms of their energy input rates; this gap shows a tendency of first expanding and then narrowing. On the one hand, the United States, as a developed country, has a large share of services in its industrial structure, so its intermediate inputs are also dominated by outsourced services. Its economic growth not only relies on energy consumption but also on the application of high technology. The United States' structure of three types of intermediate inputs is relatively stable, and its reliance on energy is relatively low, with the energy input rates decreasing from 0.032 in 2001 to 0.019 in 2020 (see Figure 3). On the other hand, compared to China, which has long relied on energy imports, the U.S. is a large energy producer with relatively low energy prices. The energy input rate gap between China and the United States shows a narrowing trend. Under Scope 2, the gap narrowed from an average of 0.050 in the 2001–2010 period to 0.041 in the 2011–2020 period. Using Scope 3 energy consumption had a greater impact on the energy input rate, with the gap narrowing from an average of 0.034 in the 2001–2010 period to 0.027 in the 2011–2020 period. The gap under Scope 3 was 33 percent lower than the gap under Scope 2.

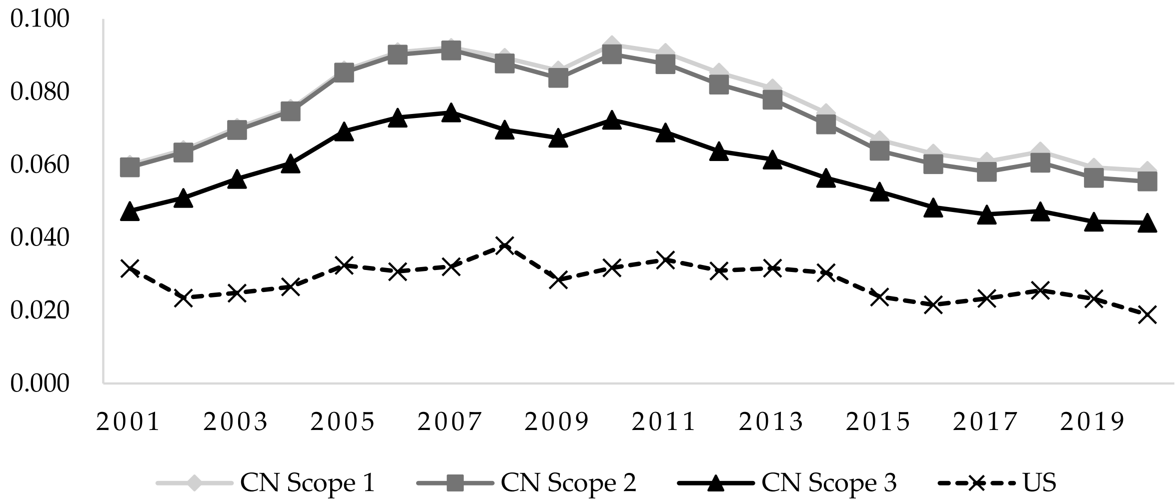

Figure 3. Comparison of energy input rates between China and the United States, 2001–2020.

3.2. Comparison of Industry Energy Dependency Between China and the United States

Since there are large discrepancies in energy dependence and energy efficiency among different industries due to their production nature, different industries should be analyzed separately. In this study, we divided the 33 aligned industries into three groups: raw materials industries, high-tech industries, and the remaining industries. The raw materials industry group included six industries: (a) mining, except oil and gas, (b) the extraction of petroleum and natural gas, (c) the processing of petroleum, coal, and other fuels, (d) the manufacture of chemical products, (e) the manufacture of non-metallic mineral products, and (f) the smelting and pressing of metals. The high-technology industry group also included six industries: (a) the manufacture of machinery and equipment, (b) the manufacture of transport equipment, (c) the manufacture of electrical machinery and devices, (d) the manufacture of communication, computers, and other electronic equipment, (e) information services, and (f) research and development. The production and supply industry of water, electric, heat, and gas is listed separately due to its significant share of energy consumption.

As can be seen in Figure 4, China and the U.S. have different energy consumption structures. Under the three scopes, the proportions of the energy inputs in China's raw materials industry to the whole country were 50.0%, 49.1%, and 38.9% respectively, much higher than that of the U.S., which had an average of 8.9%. The production and supply of water, electric, heat, and gas are more dependent on energy, with energy input proportions of about 20% for China and 14.6% for the U.S. The energy inputs in the high-tech industries of both countries are relatively close to each other, accounting for about 4 to 6 percent of each country's total.

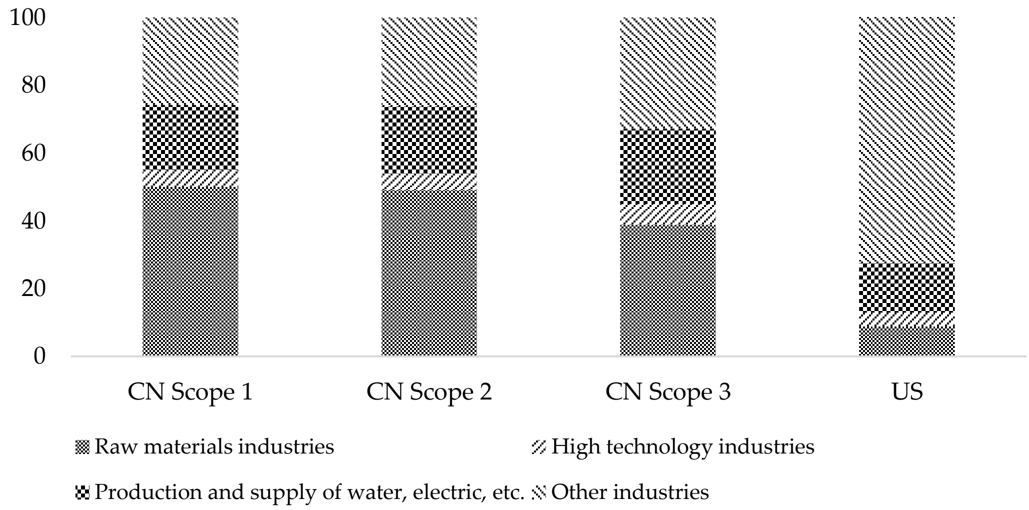

Figure 4. Energy inputs as proportions of the whole country (%), 2001–2020 average.

Table 4 illustrates the average energy input rates by industry in the U.S. and China from 2001 to 2020. From the perspective of the scopes, the energy dependence of China's industries under Scope 3 is lower than under Scopes 1 and 2, but closer to that in the U.S. Specifically, the energy dependence of the processing of petroleum, coal, and other fuels under Scope 3 is at the same level as the U.S. but one-eighth to one-ninth of that under Scopes 1 and 2, since the energy materials are not excluded from the total energy consumption under Scopes 1 and 2. From the perspective of the industries, the energy dependence of U.S. industries is generally lower than that of Chinese industries. There are eight industries where the U.S. has higher energy dependence than China. In administrative management services, real estate, agriculture forestry and fishing, and the manufacture of paper and paper products, the energy input rates under Scope 3 are 1 percentage point lower in China than in the U.S. This is mainly because these U.S. industries have higher levels of scale and technological advancement, and the use of large-scale machinery and equipment increases energy consumption. Conversely, there are 25 industries where China's energy dependence is significantly higher than that of the U.S. In the production and supply of water, electric, heat, and gas and in raw material industries, the energy input rates under Scope 3 are over 5 percentage points higher than in the U.S. This is primarily because U.S. enterprises in these industries have more efficient energy management and more advanced technologies, leading to higher energy utilization efficiency.

Table 5 illustrates the average annual growth rate of the energy input rate by industry in the U.S. and China from 2011–2020. This period was chosen to reflect a more recent trend, and Scope 3 was chosen to better represent China's situation. According to Table 5, differences also exist in the average annual growth rate of the energy input rate across industries in China and the U.S. Compared to China, high-tech industries in the U.S. have had significant technological advancements and are shifting toward the miniaturization and integration of components, leading to more energy-efficient production processes and a rapid decline of energy dependence. Compared to the U.S., the energy dependence of China's petroleum-related industries has declined rapidly. This rapid decline can be attributed to technological advancements and energy mix adjustments under strong policy support. For example, the document "Guidance on Promoting Green Development of the Petrochemical Industry" proposes promoting green extraction technologies aimed at fostering green development in the petroleum and natural gas extraction industry (https://www.ndrc.gov.cn/xxgk/zcfb/tz/201712/t20171212_962614.html (accessed on 18 May 2023)). The document "Opinions on Accelerating the Utilization of Natural Gas" aims to promote the widespread use of natural gas in various sectors, reducing dependence on oil and improving energy utilization efficiency (https://www.gov.cn/xinwen/2017-07/05/5207958/files/258c2c4d2100473ba69b45fb8b4b9b3a.pdf (accessed on 18 May 2023)). Since U.S. petroleum-related industries are experiencing a low decline or increases in energy dependence, the U.S. should intensify its policy efforts to promote the transition to green energy sources, increase the use of clean energy, and reduce dependence on oil and petroleum.

Table 4. Energy input rates, by industry, 2001–2020 average.

Aligned Industry Name	CN Scope 1	CN Scope 2	CN Scope 3	US
Production and supply of water, electric, heat and gas	0.448	0.447	0.401	0.244
Transport, warehousing and postal services	0.157	0.157	0.157	0.114
Manufacture of non-metallic mineral products	0.135	0.124	0.124	0.062
Mining, except oil and gas	0.170	0.161	0.122	0.054
Smelting and pressing of metals	0.120	0.109	0.109	0.052
Public administration, social security and social organizations	0.025	0.025	0.025	0.052
Manufacture of paper and paper products	0.032	0.030	0.030	0.041
Agriculture, forestry and fishing	0.020	0.020	0.020	0.036
Accommodation and food services	0.025	0.025	0.025	0.032
Manufacture of chemical products	0.126	0.112	0.112	0.032
Manufacture of textile	0.027	0.026	0.026	0.031
Real estate	0.011	0.011	0.011	0.028
Construction	0.030	0.030	0.030	0.027
Educational services	0.029	0.029	0.029	0.019
Extraction of petroleum and natural gas	0.096	0.089	0.089	0.018
Processing of timber, manufacture of woods and furniture	0.032	0.031	0.031	0.018
Manufacture of foods and tobacco	0.014	0.013	0.013	0.018
Manufacture of metal products	0.057	0.055	0.055	0.016
Wholesale and retail trade	0.021	0.021	0.021	0.015
Arts, entertainment, and recreation	0.018	0.018	0.018	0.015
Processing of petroleum, coal and other fuels	0.631	0.652	0.074	0.015
Leasing and business services	0.033	0.033	0.033	0.013
Manufacture of textile, wearing apparel and accessories	0.011	0.011	0.011	0.011
Health care and social assistance	0.017	0.017	0.017	0.010
Administrative management services	0.037	0.037	0.037	0.010
Manufacture of electrical machinery and devices	0.016	0.016	0.016	0.009
Other manufacture	0.033	0.031	0.031	0.008
Finance	0.011	0.011	0.011	0.008
Manufacture of machinery and equipment	0.028	0.027	0.027	0.007
Manufacture of transport equipment	0.015	0.015	0.015	0.006
Manufacture of communication, computers and other electronic equipment	0.012	0.011	0.011	0.006
Information services	0.019	0.019	0.019	0.005
Research and development	0.029	0.029	0.029	0.004
All industries	0.075	0.073	0.059	0.028

Table 5. Average annual growth rates of energy input rates (%), by industry, 2011–2020.

Aligned Industry Name	CN Scope 3	US	Difference
Real estate	−6.027	3.192	9.219
Processing of petroleum, coal and other fuels	−1.707	7.297	9.003
Extraction of petroleum and natural gas	−9.862	−1.916	7.946

Table 5. *Cont.*

Aligned Industry Name	CN Scope 3	US	Difference
Leasing and business services	−7.714	−4.585	3.129
Health care and social assistance	−6.908	−4.409	2.498
Administrative management services	−4.644	−2.157	2.488
Information services	−6.464	−5.007	1.457
Agriculture, forestry and fishing	−5.929	−4.909	1.020
Wholesale and retail trade	−3.573	−4.222	−0.649
Mining, except oil and gas	−4.724	−5.445	−0.722
Public administration, social security and social organizations	−6.944	−7.876	−0.933
Finance	−7.123	−8.293	−1.170
Production and supply of water, electric, heat and gas	−3.264	−5.141	−1.877
Manufacture of chemical products	−3.550	−6.068	−2.518
Other manufacture	−5.961	−8.622	−2.661
Accommodation and food services	−2.284	−5.326	−3.042
Transport, warehousing and postal services	−6.001	−9.430	−3.429
Educational services	−4.828	−8.258	−3.430
Manufacture of foods and tobacco	−4.985	−8.433	−3.448
Research and development	−1.900	−5.517	−3.616
Manufacture of machinery and equipment	−3.687	−7.917	−4.231
Manufacture of metal products	−2.236	−6.961	−4.725
Manufacture of paper and paper products	−2.308	−7.706	−5.398
Processing of timber, manufacture of woods and furniture	−4.439	−10.282	−5.843
Manufacture of non-metallic mineral products	−4.020	−10.292	−6.273
Manufacture of transport equipment	−2.984	−9.549	−6.565
Smelting and pressing of metals	−1.978	−8.554	−6.576
Manufacture of textile	−1.474	−9.093	−7.619
Arts, entertainment, and recreation	0.070	−9.056	−9.126
Manufacture of textile, wearing apparel and accessories	−2.311	−11.723	−9.412
Construction	1.840	−7.955	−9.795
Manufacture of electrical machinery and devices	−0.551	−11.321	−10.770
Manufacture of communication, computers and other electronic equipment	−2.251	−16.959	−14.707
All industries	−4.828	−6.293	−1.465

Note: The difference represents the U.S. growth rate minus the Scope 3 growth rate.

3.3. Comparative Analysis by Industry Group

3.3.1. Comparison of Energy Dependence of Raw Materials Industries

The energy dependence of raw materials industries varies considerably between the United States and China. Raw materials industries are typically high-energy industries. China's raw materials industries are more energy-dependent in terms of their energy consumption compared to those in the United States. Even when excluding energy materials under Scope 3, China's raw materials industries are still more energy-dependent than those in the United States (see Figure 5). By 2020, China's energy dependence was higher than the that of the United States in all six raw material industries, of which the value-added and digitization levels were lower than the average level of all Chinese industries (This paper calculates direct consumption coefficients of each industry to digital economy industries based on the China Statistical Classification of the Digital Economy and Its Core Industries (2021) and the 2018 China Input-Output Table. The coefficients are used to reflect the digitization level of each industry. Scale and digitization level of raw material industries and high technology industries is presented in Appendix B Table A2 due to space constraints).

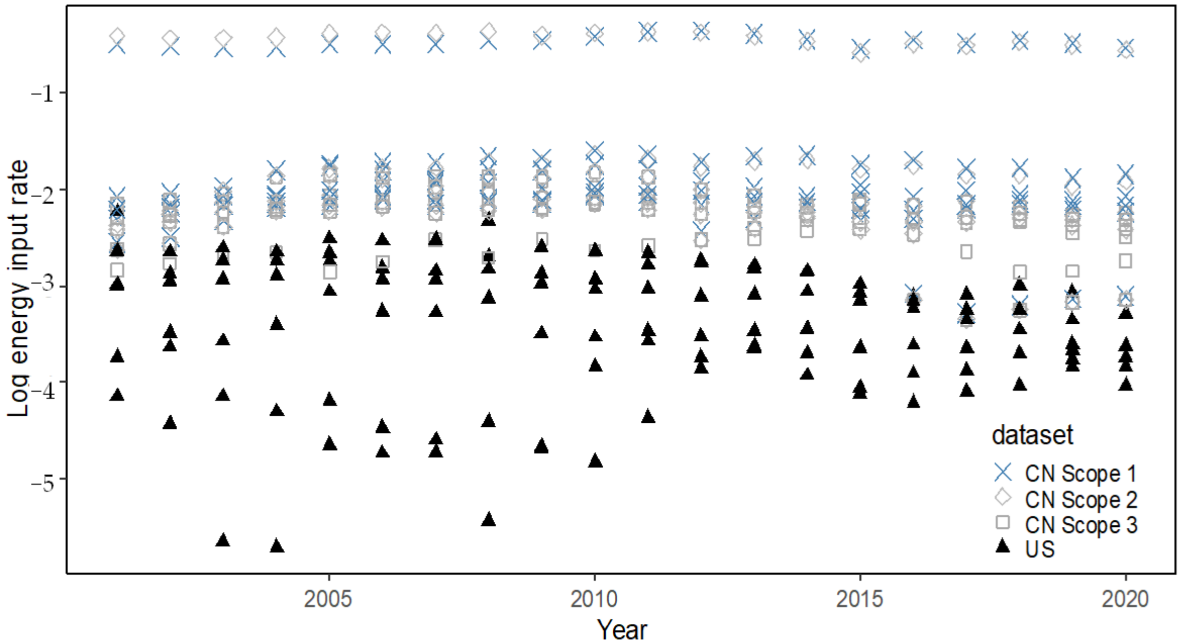

Figure 5. Comparison of energy input rates in raw materials industries between China and the U.S., 2001–2020.

As new energy substitution is a long-term process, improving energy efficiency and reducing energy dependence through digital technology is still an important way to achieve low-carbon and sustainable development. These high-energy-consuming industries should focus on increasing the industry's expenditure on technological transformation, eliminating outdated production capacity, and squeezing out investments in high-energy-consuming enterprises by encouraging enterprises to increase their investments in energy-saving technologies to improve their energy efficiency.

Due to the gaps in the energy dependence levels of industries caused by the differences in the scopes of energy consumption, China's raw materials industries face different pressures when adjusting their energy structure under different scopes. In this study, we projected the energy dependence level of each industry in China and the United States to the "peak carbon" goal in 2030. To better reflect the recent trend, data from 2021 to 2030 were projected based on 2020 data, assuming that the average energy input rate from 2021 to 2030 will maintain the respective maximum and average rates of decline from 2011 to 2020 for China and the United States. The fitting results are shown in Figure 6. (a) Under all three scopes, the energy input rate for the extraction of petroleum and natural gas will reach the United States level by 2030 by maintaining the same rate of decline from 2011 to 2020 (see Figure 6b). (b) The energy restructuring pressure that each industry faces under Scopes 2 and 3 is lower than under Scope 1. Under the three scopes, the energy input rates for the manufacture of non-metallic mineral products, mining (except oil and gas), and the processing of petroleum, coal, and other fuels can reach the projected level of the United States under Scopes 2 and 3, but is unable to do so under Scope 1 (see Figure 6a,c,e). (3) Chemical products and metal smelting and rolling processed products face greater pressure for energy restructuring. Under the three scopes, even if the maximum rate of decline is maintained, the energy input rates will still be 2 to 5 times those of the corresponding projected levels in the United States (see Figure 6d,f). As can be seen in Figure 6, China's raw materials industries are not only more energy-dependent than those in the United States, their decline of energy dependence is also significantly slower. China's raw materials industries have high potential for energy conservation if advanced energy-saving technologies and new sources of energy are quickly introduced to reduce the industries' dependence on traditional energy sources. Raw materials industries require a large amount of energy in their production process. Since coal still comprises a high proportion of China's energy mix, and some small- and medium-sized enterprises in China have relatively outdated technology and equipment, the raw materials industries in China have low energy efficiency and high energy dependency. Based on these problems, possible measures to reduce their energy dependence include promoting energy-saving technologies and equipment, using natural gas or clean energy to reduce dependence on coal, making full use of byproducts and waste materials, and encouraging the transfer and application of advanced technologies through international cooperation.

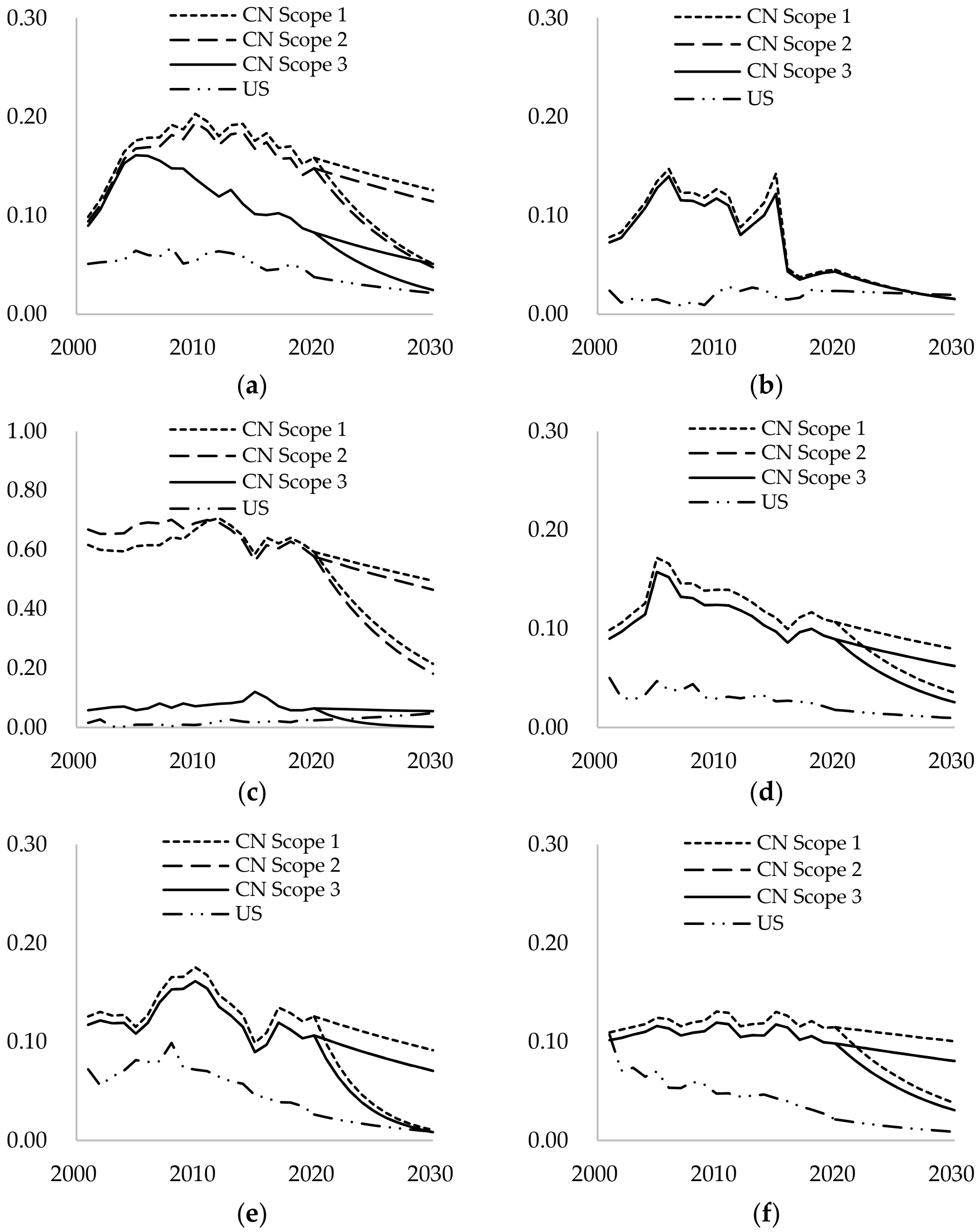

Figure 6. Comparison of energy input rates in raw materials industries between China and the U.S., 2001–2020. (**a**) Mining, except oil and gas. (**b**) Extraction of petroleum and natural gas. (**c**) Processing of petroleum, coal, and other fuels. (**d**) Manufacture of chemical products. (**e**) Manufacture of non-metallic mineral products. (**f**) Smelting and pressing of metals.

3.3.2. Comparison of Energy Dependence in High-Tech Industries

The high-tech industry's dependence on energy is relatively low. However, China's high-tech industry's energy dependence is still higher than in the United States, even when excluding energy materials. China's high-tech industry's energy dependence shows a fluctuating downward trend, while the high-tech industry's declining trend of energy dependence is more pronounced in the United States (see Figure 7). Under the three energy consumption scopes, China's high-tech industry's average energy input rates from 2001 to 2020 were 0.020, 0.019, and 0.019 respectively, which are about three times the United States' average of 0.006. China's high-tech industry has a higher degree of digitization than other industries in China. However, compared to the United States, China's high-tech industry has significant potential for enhancing its energy efficiency through the advancement of industrial digitalization.

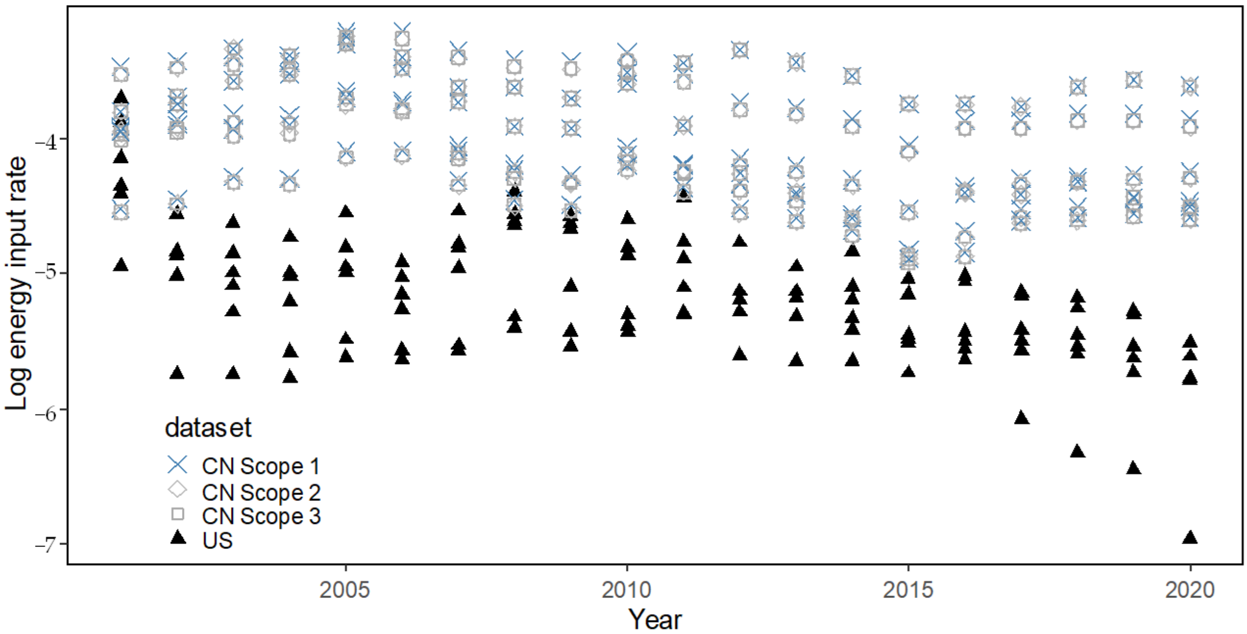

Figure 7. Comparison of energy input rates for high-tech industries in China and the U.S., 2001–2020.

As of 2020, the energy dependence of all six high-tech industries in China was higher than in the United States. Since energy consumption scopes have a smaller impact on high-tech industries, the energy restructuring pressure that each industry faces is close under the different energy consumption scopes. In this study, we also projected the energy dependence levels of high-tech industries in both countries from 2021 to 2030 under the current trends of their energy input rate (see Figure 8). By maintaining the maximum rate of decline from 2011 to 2020, the energy input rates for information services and the manufacture of transport equipment would fall below the United States level by 2030 (see Figure 8b,e). The manufacture of machinery and equipment, the manufacture of electrical machinery and devices, and research and development would reach 1.43, 1.45 and 1.59 times the projected levels of the United States projected in 2030 (see Figure 8a,c,f). The energy input rates of the manufacture of communication, computers, and other electronic equipment would remain at 9.15 times the projected level in the U.S. in 2030 under Scope 3 (see Figure 8d). As can be seen in Figure 8, although there was a gap between the current level of energy dependence in China's high-tech industry and the United States, high-tech development has accelerated the industry's energy conservation and efficiency, providing high potential for energy conservation.

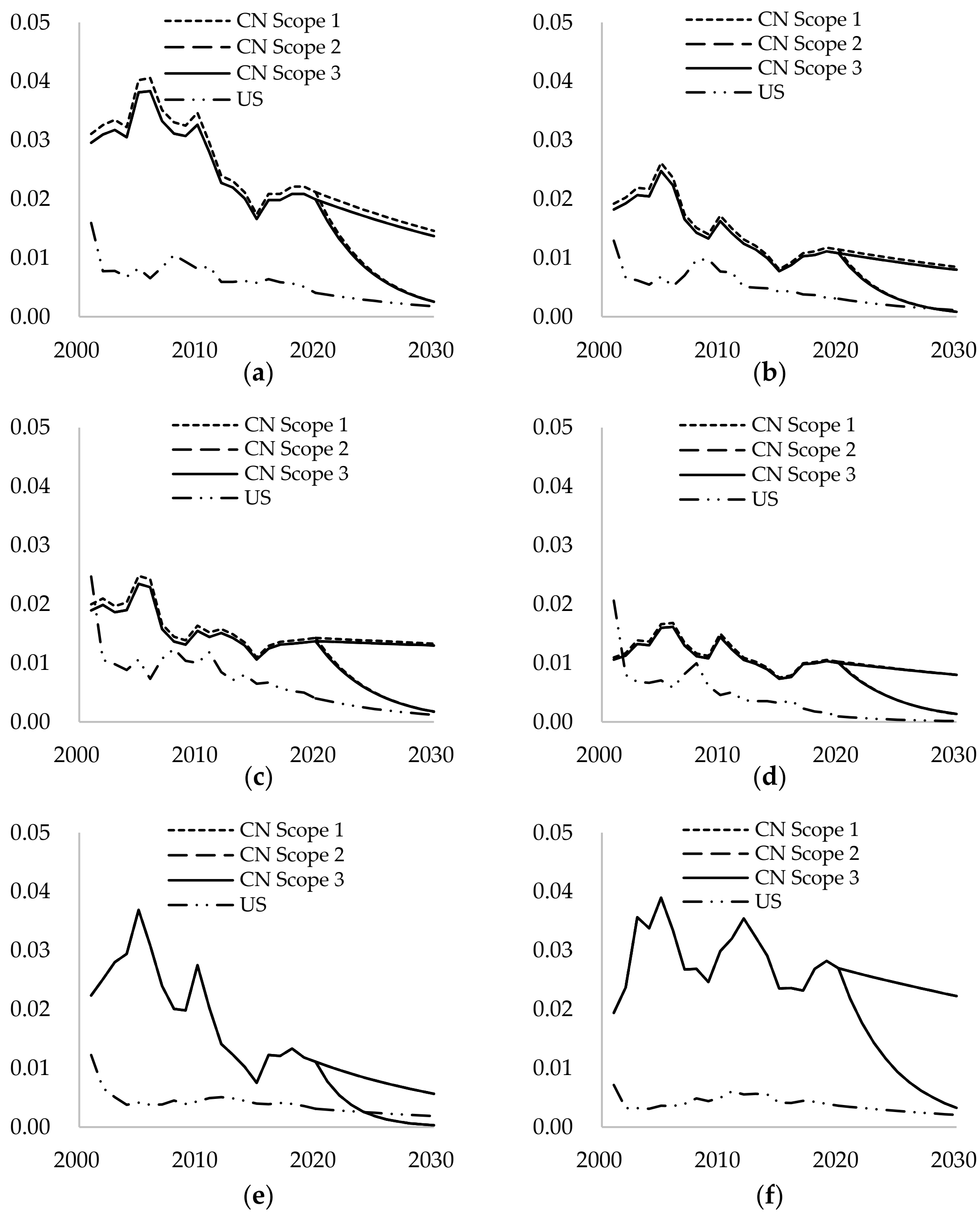

Figure 8. Comparison of energy input rates for high-tech industries in China and the U.S., 2001–2020. (**a**) Manufacture of machinery and equipment. (**b**) Manufacture of transport equipment. (**c**) Manufacture of electrical machinery and devices. (**d**) Manufacture of communication, computers, and other electronic equipment. (**e**) Information services. (**f**) Research and development.

3.3.3. Comparison of Energy Dependence of Other Selected Sectors

The energy input rates for the production and supply of water, electric, heat, and gas in the United States are lower than those for China under the three scopes. The main source of the gap is the difference in the value-added rates, which are significantly higher in the United States than in China (see Figure 9).

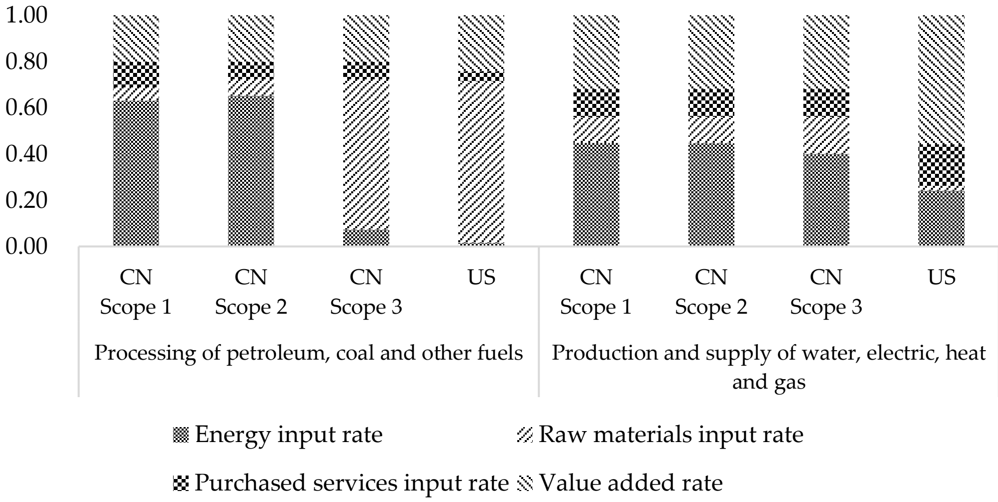

Figure 9. Comparison of input structure, 2001–2020 average.

The energy input rates of 21 other industries show consistent results under the three scopes. The average energy input rates of these industries from 2001 to 2020 are shown in Figure 10. According to the figure, 13 industries in China have higher energy input rates than in the United States. Influenced by the nature of their industries' production, transport, warehousing, and postal services have higher energy dependence compared to other industries in both China and the United States.

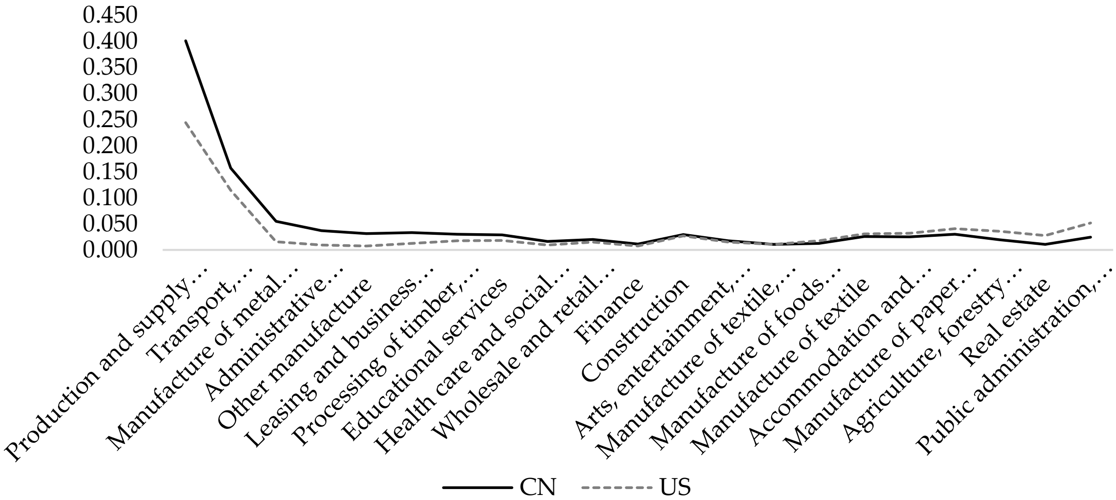

Figure 10. Comparison of energy input rates of other industries, 2001–2020 average.

4. Conclusions and Recommendations

This study distinguished between the energy products used as raw materials and those used as other intermediate inputs based on China's annual input–output table from 2001 to 2020. In this paper, the energy consumption and energy conservation potential of 33 industries in both China and the United States were compared under the following three different energy consumption scopes: not excluding energy resources used as raw materials, excluding energy resources used as raw materials for the production of non-energy products, and excluding energy resources used as raw materials for the production of non-energy products or the production of energy products through non-combustion processes. This study also compared the energy dependence characteristics of these industries. The use of monetary energy consumption and the energy ratio links industrial energy consumption with other value-based indicators under the national accounting system, providing a new perspective on industries' energy dependency.

The main findings are as follows:

(1) There are differences in China's energy consumption under the three accounting scopes. The energy consumption characteristics are close for Scopes 1 and 2, which differ significantly from Scope 3. Scope 3 is not only closer to the BEA KLEMS account as a representative of the international standard but also aligned with GHG Scope 1. Using the Scope 3 energy consumption measure is conducive to improving the groundwork for international negotiations on energy, climate, and other related issues.

(2) Comparing the average annual growth rates of the energy input rates of industries in China and the U.S. from 2011 to 2020, the tech progress of the high-tech industries in the U.S. has decreased their energy dependence. The energy dependence of China's petroleum-related industries has declined rapidly with policy support, while in the U.S., it has declined slowly or even increased.

(3) The efforts to save energy in China's raw materials sector have begun to bear fruit, but the task remains daunting. The gap between China's six raw materials industries and those in the United States is narrowing. Under Scope 3, if the energy input rates maintain the 2011–2020 maximum decline rate, four of the raw materials industries can reach or approach the projected level of the United States in 2030, while the manufacture of chemical products and the smelting and pressing of metals still face higher pressure for energy restructuring.

(4) China's high-tech industries are highly digitized and have more room for improvement in energy efficiency. If the energy input rate maintains the 2011–2020 maximum decline rate, five of the high-technology industries (the manufacture of communication, computers, and other electronic equipment not included) can reach or approach the projected level of the United States in 2030. Compared to those in China, the high-tech industries in the U.S. have significant technological advancements and are shifting toward the miniaturization and integration of components, leading to more energy-efficient production processes and a rapid decline in energy dependence.

(5) The production and supply of water, electric, heat, and gas and raw materials industries have higher dependence on energy and are the key industries for China's energy conservation and emission reduction. There are obvious differences in the energy conservation potential among the raw materials industries, so specific policy implications need to be applied to each industry.

Based on the above findings, some policy recommendations are as follows:

(1) In the process of improving its energy statistics system, it is necessary for China to further strengthen its exchanges and cooperation with international organizations and other national statistical agencies. The authors of this paper advocate for taking international comparability into account, exploring different scopes of China's energy consumption and releasing different scopes of energy consumption data to fit different analytical needs. For example, China could actively participate in international energy statistics projects and joint research initiatives to conduct in-depth studies on energy consumption accounting methods that are applicable to both developed and developing countries. Countries should also establish a bilateral or multilateral energy statistics cooperation network. Through this network, countries can regularly exchange data with other countries, conduct comparative analyses, and jointly develop energy consumption benchmarks for different industries.

(2) Targeted strategies are necessary for energy-intensive industry transformation in both China and the U.S. For energy-intensive industries in China, the manufacture of chemical products, the manufacture of non-metallic mineral products, and the smelting and pressing of metals have high energy dependence and high carbon emissions and comprise low proportions of the country's total added value; thus, they have high potential for energy conservation. On the one hand, energy-intensive industries should be targeted to increase investments in the research and development of energy-saving technologies, improve the efficiency of carbon emission technologies, accelerate the promotion of new energy substitution, and adjust the energy structure. The government could offer tax incentives and subsidies for companies that invest in energy-saving technology research

and development and support the development of energy service companies (ESCOs) that provide comprehensive energy management solutions for energy-intensive industries. On the other hand, these industries should be shifted from rough processing to finishing, accelerating industrial chain upgrading and industrial restructuring and lowering energy dependence to reduce China's overall carbon emissions. For the U.S. petroleum industry, the U.S. government should continue conducting in-depth research on a carbon tax for the petroleum industry. The revenue generated from this tax could be used to fund the research and development of clean energy technologies, but it may also increase the price of petroleum, thus increasing the monetary energy dependence. The U.S. government may learn from China, providing incentives for the development and deployment of low-carbon alternatives to petroleum and strengthening environmental regulations and enforcements on the petroleum industry.

(3) Digital technology is still an effective method for industries to achieve low-carbon and sustainable development. The potential of cutting-edge information technology, such as 5G, industrial internet, and big data, should be further developed and utilized in various industries to enhance their management efficiency, production efficiency, and energy use efficiency. The U.S. should maintain its advantages in high-tech industries, while China can learn from the U.S., further improving energy efficiency through the following measures: First, increase the investments in smart grids, 5G networks, and the industrial internet to improve data transmission speed and stability and enhance the flexibility and reliability of power systems. Second, utilize big data analytics and artificial intelligence (AI) to optimize production processes, manage energy use, and reduce energy waste. Third, introduce policy incentives, such as tax subsidies, to encourage corporate investments in high-efficiency technologies.

(4) In this study, we constructed a monetary energy consumption database for China that corresponds to GHG Scope 1, but we were unable to add additional energetic sustainability costs, which is a significant part of GHG Scopes 2 and 3, due to data limitations. Accurately measuring the costs and energy consumption in the sustainable energy production industry is crucial for sustainable development and energy policy formulation. Governments should conduct comprehensive surveys to collect data on the inputs and outputs of sustainable energy production companies and establish comprehensive energy statistical systems that cover the entire supply chain, ensuring transparency and accuracy of the data for sustainable development purposes.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. China–US industry alignment table.

No.	Aligned Industry Name	China Industry Name	The United States Industry Name
1	Agriculture, forestry and fishing	Agriculture, forestry and fishing products and services	Agriculture, forestry, fishing, and hunting
2	Mining, except oil and gas	Mining and washing of coal	Mining, except oil and gas
		Mining and processing of metal ores	Support activities for mining
		Mining and processing of nonmetal ores	
3	Extraction of petroleum and natural gas	Extraction of petroleum and natural gas	Oil and gas extraction
4	Manufacture of foods and tobacco	Manufacture of foods and tobacco	Food and beverage and tobacco products
5	Manufacture of textile	Manufacture of textile	Textile mills and textile product mills
6	Manufacture of textile, wearing apparel and accessories	Manufacture of textile, wearing apparel and accessories	Apparel and leather and allied products
7	Processing of timber, manufacture of woods and furniture	Processing of timber, manufacture of woods and furniture	Wood products
8	Manufacture of paper and paper products	Manufacture of paper and paper products	Paper products
			Printing and related support activities
9	Processing of petroleum, coal and other fuels	Processing of petroleum, coal and other fuels	Petroleum and coal products
10	Manufacture of chemical products	Manufacture of chemical products	Chemical products
			Plastics and rubber products
11	Manufacture of non-metallic mineral products	Manufacture of non-metallic mineral products	Nonmetallic mineral products
12	Smelting and pressing of metals	Smelting and pressing of metals	Primary metals
13	Manufacture of metal products	Manufacture of metal products	Fabricated metal products
14	Manufacture of machinery and equipment	Manufacture of general purpose machinery	Machinery
		Manufacture of special purpose machinery	
		Manufacture of measuring instruments and machinery	
15	Manufacture of transport equipment	Manufacture of transport equipment	Motor vehicles, bodies and trailers, and parts
			Other transportation equipment
16	Manufacture of electrical machinery and devices	Manufacture of electrical machinery and devices	Electrical equipment, appliances, and components
17	Manufacture of communication, computers and other electronic equipment	Manufacture of communication, computers and other electronic equipment	Computer and electronic products
18	Other manufacture	Other manufacture and utilization of waste resources	Miscellaneous manufacturing
		Repair service of metal products, machinery and equipment	

Table A1. *Cont.*

No.	Aligned Industry Name	China Industry Name	The United States Industry Name
19	Production and supply of water, electric, heat and gas	Production and supply of electric power and heat power	Utilities
		Production and supply of gas	
		Production and supply of water	
20	Construction	Construction	Construction
21	Wholesale and retail trade	Wholesale and retail trade	Wholesale trade
			Retail trade
22	Transport, warehousing and postal services	Transport, warehousing and postal services	Transportation and warehousing
23	Accommodation and food services	Accommodation and food services	Accommodation and food services
24	Information services	Information transmission, software and information technology services	Information
			Computer systems design and related services
25	Finance	Finance	Finance and insurance
			Federal reserve banks, credit intermediation, and related activities
			Securities, commodity contracts, and investments
			Insurance carriers and related activities
			Funds, trusts, and other financial vehicles
26	Real estate	Real estate	Real estate
27	Leasing and business services	Leasing and business services	Rental and leasing services and lessors of intangible assets
			Legal services
			Management of companies and enterprises
28	Research and development	Research and experimental development	Professional, scientific, and technical services
		Integrated technical services	Miscellaneous professional, scientific, and technical services
29	Administrative management services	Water, environment and utilities management	Administrative and waste management services
		Residential services, repairs and other services	
30	Educational services	Educational services	Educational services
31	Health care and social assistance	Health care and social assistance	Health care and social assistance
32	Arts, entertainment, and recreation	Arts, entertainment, and recreation	Arts, entertainment, and recreation
33	Public administration, social security and social organizations	Public administration, social security and social organizations	Government

Appendix B

Table A2. Scale and digitization levels of raw materials and high-technology industries.

Industry Group	Aligned Industry Name	Value-Added Ratio (%) *		Digitization Level **
		CN	US	CN
Raw material industries	Mining, except oil and gas	2.87	0.75	0.015
	Extraction of petroleum and natural gas	1.45	1.50	0.009
	Processing of petroleum, coal and other fuels	1.23	1.36	0.004
	Manufacture of chemical products	4.27	2.46	0.015
	Manufacture of non-metallic mineral products	2.27	0.29	0.011
	Smelting and pressing of metals	3.27	0.39	0.007
High technology industries	Manufacture of machinery and equipment	3.15	0.83	0.104
	Manufacture of transport equipment	2.27	1.47	0.045
	Manufacture of electrical machinery and devices	1.59	0.35	0.129
	Manufacture of communication, computers and other electronic equipment	2.15	1.32	0.565
	Information services	2.69	6.42	0.261
	Research and development	1.59	11.68	0.103

* Note 1: Using 2012 constant prices. Due to the non-additivity of chained price indices, a deviation in the industry value-added exists as a percentage of the whole country. ** Note 2: The mean value of the digitization level of 33 industries in China was 0.058 and the median was 0.029.

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