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A Comprehensive Assessment of the Carbon Footprint of the Coal-to-Methanol Process Coupled with Carbon Capture-, Utilization-, and Storage-Enhanced Oil Recovery Technology

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Abstract: The process of coal-to-methanol conversion consumes a large amount of energy, and the use of the co-production method in conjunction with carbon capture, utilization, and storage (CCUS) technology can reduce its carbon footprint. However, little research has been devoted to comprehensively assessing the carbon footprint of the coal-to-methanol (CTM) co-production system coupled with CCUS-enhanced oil recovery technology (CCUS-EOR), and this hinders the scientific evaluation of its decarbonization-related performance. In this study, we used lifecycle assessment to introduce the coefficient of distribution of methanol and constructed a model to calculate the carbon footprint of the process of CTM co-production of liquefied natural gas (LNG) as well as CTM co-production coupled with CCUS-EOR. We used the proposed model to calculate the carbon footprint of the entire lifecycle of the process by using a case study. The results show that the carbon footprints of CTM co-production and CTM co-production coupled with CCUS-EOR are 2.63 t CO_2/tCH_3OH and 1.00 t CO_2/tCH_3OH, respectively, which is lower than that of the traditional CTM process, indicating their ability to achieve environmental sustainability. We also analyzed the composition of the carbon footprint of the coal-to-methanol process to identify the root causes of carbon emissions in it and pathways for reducing them. The work described here provided a reference for decision making and a basis for promoting the development of coal-to-methanol conversion and the CCUS industry in China.

Keywords: coal-to-methanol conversion; CCUS-EOR; carbon footprint; lifecycle assessment

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1. Introduction

Carbon emissions due to human activities and their effects on climate change constitute some of the most urgent and complex challenges facing the world today [1]. China has a distinctive energy structure that is characterized by "abundant coal, scarce oil, and limited gas". Coal has consistently been the primary fossil fuel consumed in China [2]. Its abundant coal resources have facilitated the rapid development of the country's coal chemical industry, with coal-to-methanol (CTM) conversion technology one of its key areas of focus [3]. Methanol is an important organic raw material, and China has been its largest producer since 2006 [4]. However, the traditional CTM process typically incurs a large amount of carbon emissions that have a negative environmental impact [5]. Co-production is a feasible method to reduce the carbon emissions of traditional CTM technology [6]. Traditional CTM technology involves several steps, including the gasification of coal, a water–gas shift reaction, the synthesis of methanol, and its rectification. In contrast, co-production technology uses the synthesized gas obtained from the gasification of coal to produce methanol, while the remaining gas is further processed to produce such chemical products as liquefied natural gas (LNG), olefins, urea, and synthetic fuels. The same raw materials can be transformed using co-production technology into products other than methanol, thereby enhancing the efficiency of the use of resources and energy [7]. Co-production technology reduces the loss of carbon in the CTM process, and it is a feasible solution for reducing carbon emissions. The use of carbon capture, utilization, and storage (CCUS) technologies at the end of the process is an important industrial approach to further reducing carbon emissions [8]. CCUS is a process that involves capturing carbon dioxide emissions from carbon-intensive industries, such as coal-fired power plants and chemical factories. After being subjected to purification and other forms of treatment, the captured CO_2 is transported to specific locations for either storage or utilization. This process aims to prevent CO_2 from entering the atmosphere and reduces greenhouse gas emissions [9–11]. Among various applications, CCUS-enhanced oil recovery (CCUS-EOR) is the most commonly used technology. By using CT images and flow pattern analysis to study the fluid flow mechanism and other properties of the reservoir [12–14], we can select a suitable reservoir and inject CO_2 into it to achieve the storage of CO_2 and obtain more oil, which benefits both environmental and economic aspects.

Co-production and CCUS-EOR are expected to reduce carbon dioxide emissions, thus achieving environmental sustainability in coal-to-methanol production. Researchers have investigated improving the coal chemical industry by integrating co-production technology with the CCUS method. Liu et al. [15] investigated the coal-based co-production of syngas/methanol, and the results showed that the co-production process reduced carbon emissions by approximately 7.9% while delivering the same production yield. Gu et al. [16] simulated the co-production of methanol and LNG and found that it could reduce annual CO_2 emissions by 130,000 tons. Li et al. [17] used lifecycle assessment (LCA) to evaluate the carbon footprint of coal-to-hydrogen production, and their results revealed that the use of CCUS technology resulted in a reduction of 81.72% of the carbon footprint of the lifecycle of coal-to-hydrogen production. Qin et al. [18] discussed the impact of CCUS on the lifecycle emissions of CTM technology and found that using CO_2 capture and compression in methanol plants reduced their carbon footprint by approximately 64.9%. Li et al. [19] used the LCA method to evaluate the impact of applying CCUS on the carbon footprint and cost of coal-to-hydrogen production. The results showed that the carbon footprint of hydrogen production with CCUS decreased by 52.34–74.59% to 4.92–10.90 CO_2 eq/kg H_2, which is comparable to the carbon footprint of hydrogen production from solar power.

Although researchers have demonstrated the reduction in emissions through the use of co-production and CCUS in the coal chemical industry, prevalent research has mostly focused on assessing the reduction of carbon emissions by using individual improvements, while comprehensive assessments of the carbon footprint of CTM co-production and the use of CCUS technology in this context are lacking. Moreover, prevalent studies have ignored such factors as leakage in the subsequent storage and utilization when assessing the carbon footprint of CCUS. The processes of both co-production and CCUS may also yield by-products other than methanol, and research has not considered their impact on the carbon footprint. Therefore, the literature cannot provide a scientific and rational assessment of the decarbonization-related performance of the entire system when CTM co-production and CCUS technology are used together. In light of these shortcomings, our study made the following contributions:

(1) We considered CCUS-EOR technology as an example to systematically construct a model to calculate the carbon footprint of CTM co-production coupled with the CCUS-EOR process. The model aimed to provide a comprehensive and accurate reference for calculating the carbon footprint of these processes.
(2) We introduced a coefficient of methanol allocation to address the issue of multi-functionality caused by the by-products of the processes of coal-to-chemical conversion and CCUS-EOR, and this enabled the rational distribution of the contributions of different products in the multi-product system to the carbon footprint.
(3) We used case studies to systematically calculate the carbon footprint of the CTM process in different scenarios. We also examined the internal composition of the carbon footprint of CTM co-production coupled with CCUS-EOR technology, where

this provided an accurate and complete reference for reducing the carbon footprint of the CTM process.

2. Preliminary Details of Lifecycle Assessment and Carbon Footprint

2.1. Lifecycle Assessment

Lifecycle assessment (LCA) can be used to determine the environmental burden of a process or product throughout its lifecycle. It focuses on the whole lifecycle of a product, covering the whole process from the acquisition of raw materials needed to produce the product to manufacturing, use, and disposal after waste. It has been used to calculate the carbon footprint of the coal chemical industry and CCUS technology [5,20,21].

2.2. Calculation of the Carbon Footprint

In light of the availability of data and the operability of the calculations, we used a combination of the emission factor method and the material balance method to construct a model to calculate the carbon footprints of the CTM process and CTM coupled with the CCUS-EOR process. The emission factor method, which is recommended by the Intergovernmental Panel on Climate Change (IPCC), is the most common and simplest method of calculation to this end [22]. It involves converting activity data (such as the fuel consumption and electricity usage) into carbon dioxide emissions by using specific emission factors. The basic formula is shown in Equation (1). The material balance method is based on the law of the conservation of mass and focuses on the input of raw materials and the products obtained. It estimates carbon emissions by calculating the changes in carbon content. The basic formula is shown in Equation (2), where CF is the carbon footprint, AD represents activity data, EF is the emission factor, m is the type of raw material, p is the type of product, Q_m is the mass of the raw material m, Q_p is the mass of the product p, and CC is the carbon content.

$$CF = AD \times EF, \tag{1}$$

$$(CF = \sum_m Q_m \times CC_m - \sum_p Q_p \times CC_p) \times \frac{44}{12}, \tag{2}$$

2.3. Allocation

Multi-functionality is one of the most controversial aspects of the LCA. It refers to the inability to directly obtain the environmental impact of a single product when multiple products share a production process within the boundary of the system [23]. It is then necessary to allocate the generated environmental impact within the boundary to address the issues of multi-functionality arising during the process. Products other than methanol are generated in the processes of co-production and CCUS-EOR, and this necessitates the allocation of the carbon footprint during these processes to obtain accurate outcomes of the environmental cost of the production of a unit of methanol. ISO 14044 [24] provides methods for such allocation. Müller et al. summarized approaches to address issues of multi-functionality based on this standard, including the subdivision, system expansion, substitution, and allocation [25]. The differences among the four methods are illustrated in Figure 1 and Table 1.

Table 1. Differences between four methods of allocation.

Methods		Functional Unit	System Boundary
Avoiding actual allocation	Subdivision	Remaining	Remaining
	System expansion	Extra by-product	Remaining
Actual allocation	Substitution Allocation	Remaining Remaining	Extra process Remaining

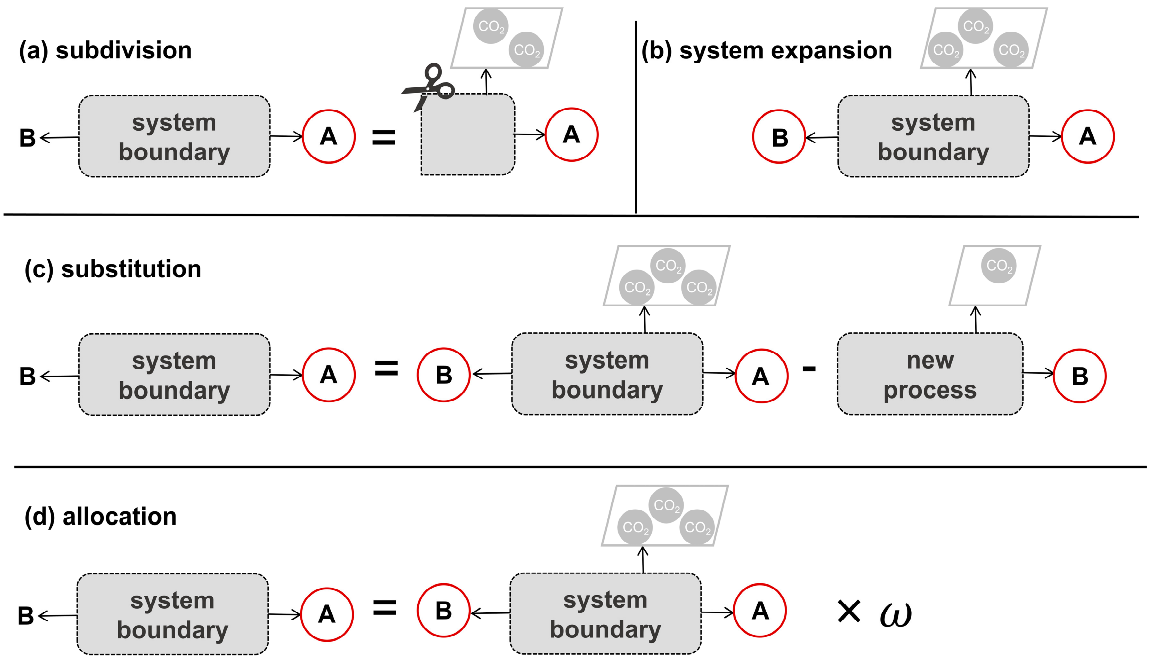

Figure 1. Schematic diagram of four methods of allocation (the red circle represents the functional unit).

3. Methodology

3.1. Overall Framework

Based on the typical process of CTM co-production of LNG and CCUS-EOR, we constructed LCA models of the carbon footprint of both the uncoupled CCUS-EOR and the coupled CCUS-EOR CTM co-production systems, referred to as "Scenario 1" and "Scenario 2", respectively. The CTM co-production portion includes coal gasification, the rectisol process, methane cryogenic separation, methanol synthesis, and methanol rectification. CCUS-EOR includes three parts: CO_2 capture, transportation, and EOR. The boundary of the system was defined as "cradle to gate", as shown in Figure 2. The "production of 1 ton of methanol" was chosen as the functional unit to calculate the carbon footprint in both scenarios.

Due to the involvement of numerous process units in the coal chemical and CCUS technology, it is unfeasible to directly use the subdivision method to allocate contributions to the carbon footprint. The system expansion method cannot maintain the original functional unit and thus cannot be used to calculate the carbon footprint of a unit of methanol. The substitution method adds process flows to render the problem complex and is thus not suitable for the allocation of the carbon footprint in the coal chemical industry. The allocation method distributes all inputs and outputs within the system according to certain relationships, such as the quality or energy of the product and its economic value. The criteria of allocation can be flexibly selected according to the different objects and purposes of research. We thus used this method for allocating the carbon footprint to solve the problem of the multi-functionality of the system.

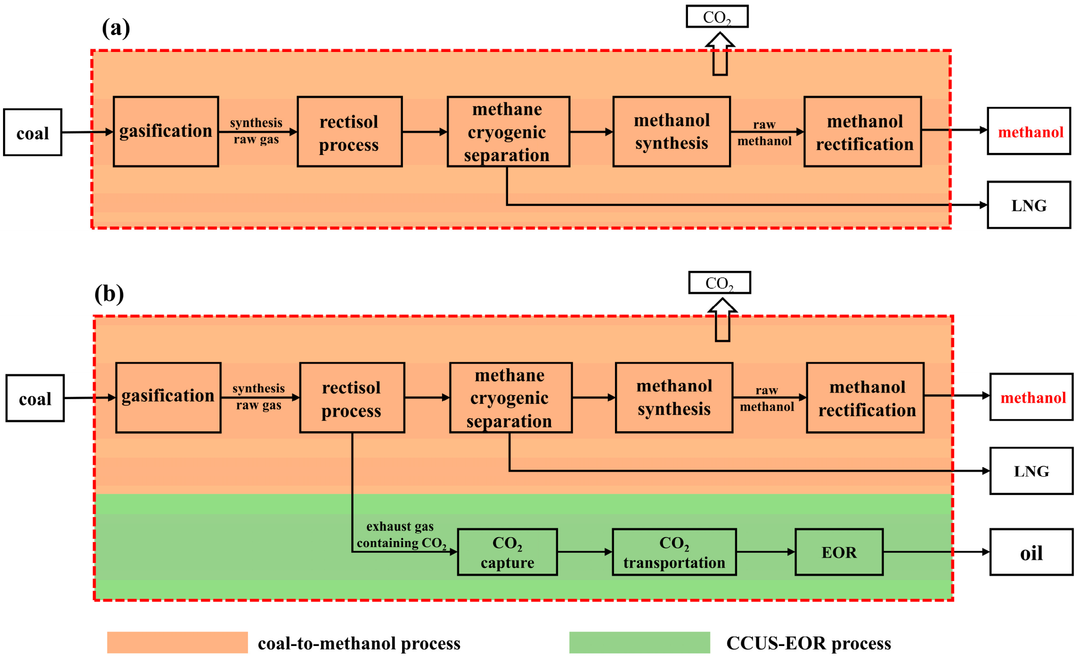

Figure 2. Boundary of the system to calculate the carbon footprint. (**a**) Scenario 1: not coupled with CCUS-EOR. (**b**) Scenario 2: coupled with CCUS-EOR.

The efficiency of the use of carbon is a key factor influencing the carbon footprint of the CTM process. The two scenarios examined here primarily involved carbon among the generated products. We thus used the carbon contents of different products as the criterion to allocate the carbon footprint. The calculation of the coefficient of methanol allocation is as follows:

$$\omega_i = \left(m_{CH_3OH} \times CC_{CH_3OH}\right) / \left(\sum_p Q_p \times CC_p\right), \tag{3}$$

where i represents a scenario of coal-to-methanol production, ω_i is the coefficient of methanol allocation under scenario i, m_{CH3OH} is the quality of the methanol products, and CC_{CH_3OH} is the carbon content of methanol.

3.2. Construction of the Model to Calculate the Carbon Footprint

We used the abovementioned methods to construct two models to calculate the carbon footprint of methanol production under two scenarios. To simplify the calculations, we considered only CO_2, which is one type of greenhouse gas, in the models. Furthermore, the wastewater and solid waste generated by the system were considered to have been transported beyond the boundaries of the factory and were thus not included in the scope of this study. We also did not consider the consumption of materials that were recycled within the system.

The model to calculate the carbon footprint included a CTM co-production sector and a CCUS-EOR sector

$$CF_i = \left(CF_{CTMi} + CF_{CCUS} \times S_i\right) \times \omega_i, \tag{4}$$

where CF_i is the carbon footprint of the methanol functional unit in scenario i, CF_{CTMi} is that of coal-to-methanol production in scenario i, CF_{CCUS} is the carbon footprint of the CCUS-EOR sector in Scenario 2, and S_i is a variable, with i = 1 when S_i = 0 and i = 2 when S_i = 1.

3.2.1. CTM Co-Production

The total carbon emissions generated in the CTM co-production process consisted of direct carbon emissions generated by the chemical processes and indirect emissions generated by energy consumption due to electricity and steam. Due to the involvement of multiple processes in methanol production, we constructed a model to calculate the direct carbon emissions by using the material balance method. It calculated the difference between the potential carbon emissions when using coal as the raw material and those of the product as the volume of direct carbon emissions in the CTM process. The indirect carbon footprint was calculated by using the emission factor method. The total carbon footprint of methanol production was then expressed as:

$$\begin{cases} CF_{CTMi} = DE_i + IE_i \\ DE_i = \left(Q_{coali} \times CC_{coal} - \sum_p Q_{pi} \times CC_p\right) \times \frac{44}{12} \\ IE_i = (AD_{eleci} \times EF_{elec} + AD_{steami} \times EF_{steam}) \end{cases} \tag{5}$$

where CF_{CTMi} is the carbon footprint of methanol production in scenario i, DE_i represents direct emissions due to methanol production in scenario i, IE_i represents indirect emissions due to methanol production in scenario i, Q_{coali} is the amount of raw coal used in scenario i, CC_{coal} is the carbon content of raw coal, Q_{pi} is the yield of p in scenario i, AD_{eleci} is the electricity consumed during production in scenario i, EF_{elec} is the electricity emission factor, AD_{steami} is the steam consumed during production in scenario I, and EF_{steam} is the steam emission factor.

3.2.2. CCUS-EOR

The carbon footprint of the CCUS-EOR sector was divided into two parts: the positive carbon footprint generated by the consumption of energy and material from related facilities, including carbon emissions from leaks, and the negative carbon footprint resulting from carbon capture. The positive carbon footprint was further divided into three units: those due to capture, transportation, and oil recovery. All of them were calculated by using the emission factor method

$$CF_{CCUS} = CF_{cap} + CF_{tran} + CF_{EOR} + CF_{leak} - Q_{cap}, \tag{6}$$

where CF_{cap} is the carbon footprint generated by carbon capture due to energy consumption, CF_{tran} is the carbon footprint generated by the transportation of CO_2 products, CF_{EOR} is the carbon footprint generated by oil recovery, CF_{leak} is that generated by CO_2 leakage, and Q_{cap} is the CO_2 in exhaust gas that is directly captured.

- CO_2 capture

Due to its varying sources, the concentration of CO_2 in the gas captured as raw material by different methods differs, which in turn influences the energy required for carbon capture. In general, the concentration of CO_2 is inversely proportional to the energy consumed for carbon capture. Prevalent methods for CO_2 capture include chemical absorption, adsorption, cryogenic separation, and membrane separation. We considered the rectisol process as an example to construct the model to calculate the carbon footprint. The process of capture was composed of two parts: the positive carbon footprint due to the consumption of electricity for carbon capture, and the negative carbon footprint due to the capture of directly emitted exhaust gas

$$CF_{cap} = AD_{elec-cap} \times EF_{elec}, \tag{7}$$

$$Q_{cap} = DE_2 \times \varphi, \tag{8}$$

where $AD_{elec\text{-}cap}$ is the electricity consumed per unit of captured carbon dioxide and φ is the rate of capture of carbon dioxide.

- CO_2 transportation

Methods for the transportation of CO_2 include pipelines, railway, tankers on the road, and ships [26]. Pipeline transportation is the most commonly used means of transportation. CO_2 is mainly transported through pipelines in the United States, but not in China, where tankers on the road are the major means of its transport [27]. We used a diesel tanker as an example to construct the carbon footprint of the transportation of CO_2. The carbon emission factor of diesel was calculated according to the "Guidelines for Corporate Greenhouse Gas Accounting and Reporting for Power Generation Facilities":

$$\begin{cases} CF_{tran} = AD_{diesel} \times EF_{diesel} \times d \\ EF_{diesel} = NCV_{diesel} \times CC_{diesel} \times OF_{diesel} \times \frac{44}{12} \end{cases} \tag{9}$$

where AD_{diesel} is the diesel consumed during transport, EF_{diesel} is the emission factor of diesel, d is the distance traveled, NCV_{diesel} is the net calorific value of diesel, CC_{diesel} is its carbon content, and OF_{diesel} is its rate of oxidation of carbon.

- CO_2 utilization and leakage

Compared with traditional flooding using water, CO_2 can better displace crude oil. The carbon footprint of this unit is mainly composed of the indirect carbon footprint generated by the consumption of electricity during the displacement of oil and the direct carbon footprint generated by leaks caused by fractures in the formation and corrosion of the wellbore:

$$CF_{EOR} = AD_{elec-EOR} \times EF_{elec}, \tag{10}$$

$$CF_{leak} = Q_{cap} \times \sigma, \tag{11}$$

where $AD_{elec\text{-}EOR}$ is the electricity consumed per unit of oil displaced and σ is the rate of storage.

4. Case Study

4.1. Introduction to the Case

We used the CCUS project of a coal-based methanol production company in the Xinjiang Autonomous Region of China to verify our model. The project is a demonstration project, with a capacity of 100,000 tons/year for carbon dioxide capture and use. The source of carbon dioxide was highly concentrated flue gas obtained from the acid treatment of low-temperature methanol scrubbing in coal-based methanol and LNG. After compression, purification, liquefaction, and distillation, liquid carbon dioxide was produced and transported to the Santang Lake oilfield by diesel tankers for enhanced oil recovery.

4.2. Data

The data used for the case were mainly taken from three sources: on-site field investigation, national statistical data, and the literature. Liu et al. [28] sampled raw coal from 602 locations in the 100 largest coal-mining areas in China, which accounted for approximately 99% of the country's coal production. The average low-heating value of the coal samples was determined to be 20.95 MJ/kg, while the average carbon content per unit of heating value was 26.59 kg/GJ. If the average low-heating value and carbon content per unit of heating value of the coal used for methanol production were equal to the above averages, the carbon content of the raw coal used as feedstock was 59.91%. The electricity emission factor was set as the average emission factor of the Chinese national grid in 2022, which was 0.5703 t CO_2/MWh. The steam emission factor was taken from the default value published by the Ministry of Ecology and Environment of China, which was 0.11 t CO_2/GJ [29].

Based on the actual production situation on site, the lifecycle inventory for the calculation of the carbon footprints of the CTM process under the two scenarios is presented in Table 2. The key process parameters of CCUS-EOR are shown in Table 3.

Table 2. Lifecycle inventory of methanol in two scenarios.

Scenarios	Allocation Coefficient	Items		Values	Units
Scenario 1	59.91%	Inputs	Coal	2.93	t/t
			Steam	3.20	GJ/t
			Electricity	0.61	MWh/t
		Outputs	Methanol	1	t/t
			LNG	0.33	t/t
Scenario 2	33.10%	Inputs	Coal	2.93	t/t
			Steam	3.20	GJ/t
			Electricity	1.37	MWh/t
			Diesel	3.16	kg/t
		Outputs	Methanol	1	t/t
			LNG	0.33	t/t
			Oil	0.60	t/t

Table 3. The main parameters used to calculate the carbon footprint of CCUS-EOR.

Units	Items	Symbols	Values	Units	Resources
Capture	Capture rate	φ	70%	/	Field research
	Electricity consumption	$AD_{elec-cap}$	0.29	MWh/t	Field research
Transportation	Diesel net calorific value	NCV_{diesel}	42.652	GJ/t	[30]
	Diesel carbon content	CC_{diesel}	0.0202	tC/GJ	[31]
	Diesel carbon oxidation rate	OF_{diesel}	98%	/	[31]
	Diesel consumption	AD_{diesel}	0.0029	t/km·t	Field research
	Distance	d	107	km	[32]
EOR	Displacement ratio	/	3:1	/	Field research
	Storage rate	σ	70%	/	Field research
	Electricity consumption	$AD_{elec-EOR}$	10	kWh/t	Field research

4.3. Results

Figure 3 shows that when CCUS-EOR technology was not considered, the carbon footprint of CTM co-production in Scenario 1 was 2.63 t CO_2/tCH_3OH. When this was coupled with CCUS-EOR technology, i.e., Scenario 2, the overall carbon footprint decreased to 1 t CO_2/tCH_3OH, a reduction of approximately 61.8%. Figure 4 shows that the total carbon footprint of the CCUS-EOR sector was −0.45 t CO_2/tCH_3OH, while the direct negative carbon footprint resulting from carbon capture was −0.86 t CO_2/tCH_3OH. The two largest sources of additional emissions were direct fugitive emissions during the storage process and indirect emissions caused by electricity consumption during the carbon capture process, with carbon footprints of 0.26 t CO_2/tCH_3OH and 0.14 t CO_2/tCH_3OH, respectively.

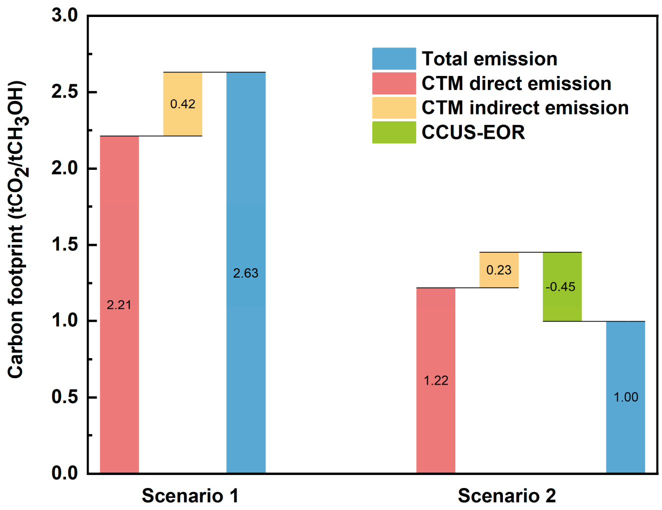

Figure 3. Carbon footprints of CTM production in different scenarios.

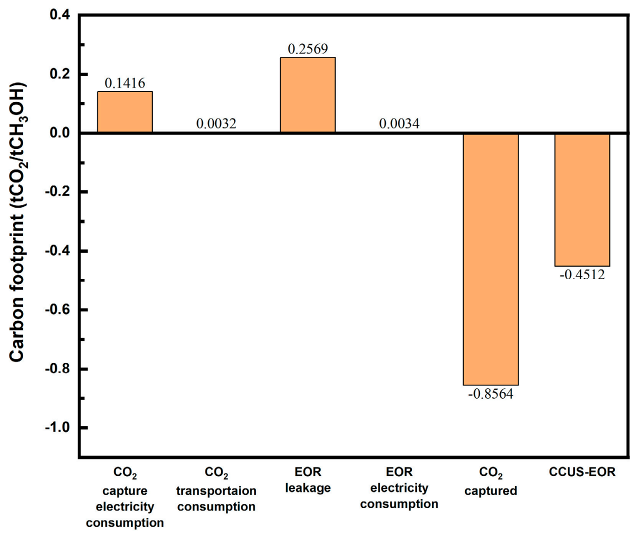

Figure 4. Composition of the carbon footprint of the CCUS-EOR sector.

The results of the case study showed that regardless of whether the CCUS-EOR process was coupled with the CTM process, the direct emissions resulting from the chemical processes were the main source of the carbon footprint in both Scenarios 1 and 2. The carbon footprints associated with these emissions were 2.21 t CO_2/tCH_3OH and 1.22 t CO_2/tCH_3OH, accounting for 84.1% and 65.8% of the total carbon footprint, respectively. While coupling the CTM process with CCUS-EOR technology reduced the carbon footprint of the former, the direct emissions from chemical production persisted as the major contributor to the carbon footprint. Therefore, measures should be taken to reduce the carbon footprint of this process to improve the efficiency of the use of carbon and to reduce the carbon footprint. Figure 4 shows that the carbon footprint due to leakage was the largest component of the positive carbon footprint of CCUS-EOR, followed by the indirect carbon footprint caused by the electricity consumed for carbon capture. Therefore, improving the efficiency of storage and reducing energy consumption during carbon capture were crucial for emission reduction in CCUS-EOR.

5. Discussion

We used the concept of LCA to develop a model to calculate the carbon footprint for CTM co-production and CTM co-production coupled with CCUS-EOR technology. The model considered the consumption of energy and materials in each process and provided a method to calculate carbon capture, transportation, and oil recovery for the CCUS sector. We constructed the model from a holistic perspective to address the shortcomings of previous work and to provide a theoretical method to calculate the carbon footprint of the CTM process coupled with CCUS-EOR technology.

To verify the reliability of the proposed model, we compared its results with those of representative methods in the literature (Figure 5). Qin [18] simulated the process of CTM production by using Aspen Plus and constructed a model to calculate the carbon footprint of the conventional process of CTM conversion based on the emission factor method. They calculated the carbon footprint of conventional CTM production to be 2.971 t CO_2/tCH_3OH. Zhu [33] used the emission factor method to calculate the average carbon footprint of the coal-to-methanol industry and obtained a value of 2.661–3.355 t CO_2/tCH_3OH under different rates of technological improvement. The carbon footprint of Scenario 1 in our study, which did not consider CCUS-EOR, was 2.63 t CO_2/tCH_3OH, which was lower than the results reported in the literature. This was because the co-production process in the case study improved the efficiency of the use of carbon in raw coal and reduced emissions during production. Moreover, the process generated LNG as a by-product to partially offset the carbon footprint of the system.

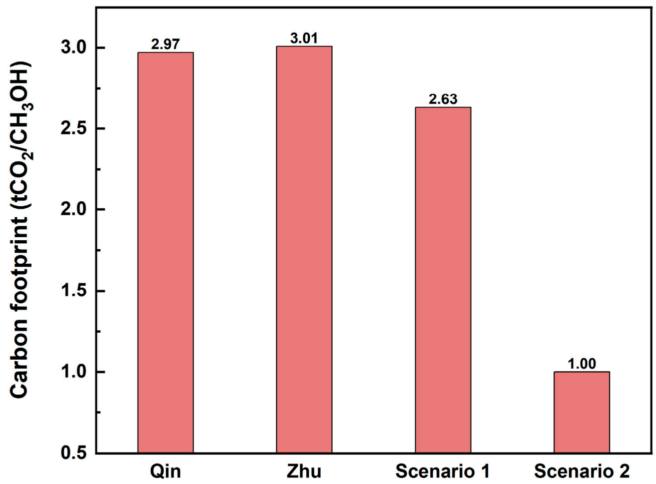

Figure 5. Carbon footprint of CTM production in different processes [15,29].

Some scholars have studied the decarbonization-related performance of CCUS technology in coal chemical processes, but a complete assessment of the carbon footprint of CCUS has thus far been lacking. Burmistrz [20] considered only the carbon footprint generated during the capture and transportation processes. Although Xie [21] considered the electricity consumed during carbon storage, he neglected the impact of leaks during the sealing process on the carbon footprint. The efficiency of storage of CCUS is approximately 60–70% [34]. The unsealed portion of CO_2 escapes into the atmosphere, leading to an increase in carbon emissions in the system. The field research for the case study considered in this article showed that the rate of storage of carbon dioxide was approximately 70%. Under these operating conditions, the ratio of the carbon footprint caused by leakage was the largest among the additional sources of carbon generated by the CCUS-EOR process (Figure 6). Therefore, it is clearly unreasonable to ignore the carbon footprint due to storage and leakage in CCUS when describing its decarbonization-related performance. It is necessary to comprehensively consider the system for each step of CCUS to avoid exaggerating its decarbonization-related performance.

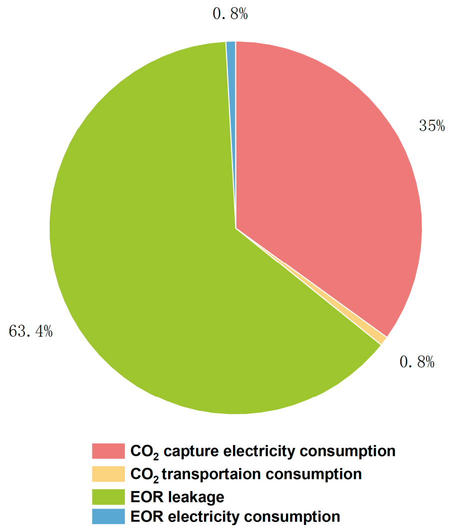

Figure 6. Composition of the positive carbon footprint contributions of CCUS-EOR.

Furthermore, the decision regarding whether to allocate the products generated during the subsequent use of CO_2 also influences the carbon footprint of the final functional unit. Consider CCUS-EOR as an example. Due to the displacement of crude oil by CO_2, a new by-product is generated within the system. The environmental impact on the boundary of the system needs to be allocated to all products according to certain ratios, because of which crude oil contributes to the carbon footprint of the system. Figure 7 shows that if the allocation of additional crude oil products was not considered, the carbon footprint of methanol was 1.82 t CO_2/tCH_3OH, which was much higher than that obtained by considering crude oil. Whether the allocation of crude oil was considered thus significantly influences the carbon footprint of the methanol functional unit. The impact of new products within the system on the carbon footprint of the functional unit thus could not be ignored. Similarly, if derivative by-products were generated within the designated boundary of the system in other methods for using CCUS, appropriate principles of allocation should be used based on the actual conditions to divide the carbon footprint.

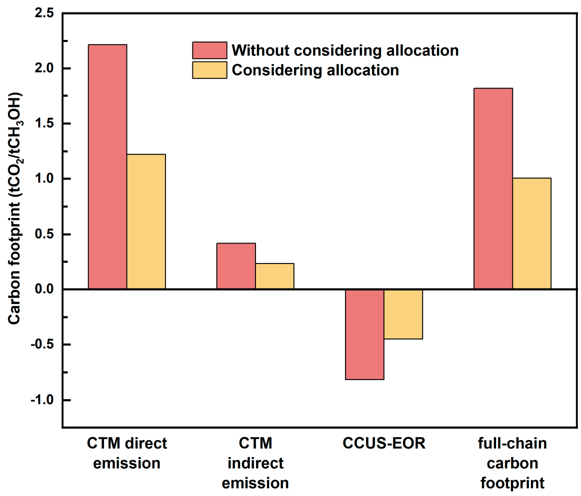

Figure 7. Carbon footprint of Scenario 2.

6. Conclusions

In this study, we constructed a comprehensive model to calculate the carbon footprint of the CTM co-production process and CTM co-production coupled with CCUS-EOR technology in order to overcome the shortcomings of prevalent models. The introduction of the emission factor of methanol addressed the issue of multi-functionality associated with the co-production process and CCUS-EOR technology. The carbon footprint of methanol was then calculated by using a case study. The results demonstrated that CCUS-EOR technology significantly reduced CO_2 emissions in the CTM process to promote the green transformation of industrial production. The case study revealed that direct emissions from chemical production contributed significantly to the carbon footprint, highlighting the need for the further optimization of the efficiency of the use of carbon in CTM production. Moreover, increasing the efficiency of storage and reducing the energy consumed for carbon capture were key to making CCUS greener and more efficient. With further technological advancement and policy support in the future, the application of the co-production process and CCUS technology is expected to become a key means for promoting the sustainable development of the coal chemical industry. To implement these technologies, such factors as system optimization, reduction in energy consumption, and the management and monitoring of leakage need to be considered. Finally, attention should be paid to technological progress and changes in market demand to ensure that measures for reducing carbon emissions align with the goals of industrial development. The transition to green energy and environmental protection should also be promoted to contribute to the goal of carbon neutrality.

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