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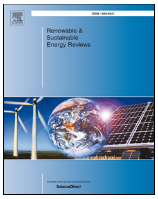

Low-carbon roadmap of chemical production: A case study of ethylene in China

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ABSTRACT

The increasing emissions of carbon dioxide (CO_2) are primarily driven by the rapid expansion of energy-intensive sectors such as the chemical industry. This work selects ethylene, one of the most important chemicals, as a model study to represent the low-carbon roadmap of chemical production. Four strategies improving the efficiency of fossil resource usage, developing the technology for carbon capture and storage (CCS), CO_2 chemical conversion, and converting biomass resources into chemicals, are used to reduce CO_2 emissions. A comprehensive analysis of the life cycle CO_2 emissions of different ethylene production routes has been performed to compare their emission reduction potential. The results indicate that the BMTO (biomass to olefins via methanol-to-olefins) pathway releases the least CO_2 (− 1.3 t CO_2/t ethylene), while the CFTO (coal to olefins via Fischer-Tropsch synthesis) possesses the highest CO_2 emissions. Combining CCS with BMTO results in CO_2 emissions of – 8.2 t per t ethylene. Furthermore, we analysed the annual production and CO_2 emissions of ethylene in the last 17 years and integrated this real-time change with different pathways. The CO_2 emissions have decreased by 29.4% per t ethylene from 2000 to 2016 in China. However, the total amount of CO_2 emissions continuously increases in ethylene production industry. Given that China has promised to hit peak CO_2 emissions by 2030, a scenario analysis was performed. To achieve this goal, the ratios of BMTO, CO2MTO (CO_2 to olefins via methanol-to-olefins) or BETE (ethanol to ethylene pathway originating from biomass) pathways should increase by 1.0%, 1.2% and 1.1% annually from 2020, respectively. Then more than 500 million metric tons of CO_2 will be eliminated from 2020 to 2040. The results highlight the pivotal role that regulation and policy administration can play in controlling CO_2 emissions by increasing average technological level and turning to low-carbon routes in the chemical industry in China.

1. Introduction

Carbon dioxide (CO_2) has become the focus of world attention due to its impact on climate change [1,2]. It has been reported that atmospheric CO_2 concentration has increased from approximately 280 ppm in 1750, at the beginning of the industrial era, to a level of 404 ppm in February of 2017 [3,4]. The chemical industry, as one of the most energy-intensive sectors, is responsible for 16% of direct global CO_2 emissions [5]. Without decisive action, energy-related CO_2 emissions will keep increasing due to rapid development. For example, an annual average CO_2 growth rate for the chemical industry is 3.37% in China during the period 1980–2010 [6]. Therefore, a low-carbon roadmap for the chemical industry is essential to make the right decisions for reducing CO_2 emissions.

Abbreviations: AGR, acid gas removal; AS, air separation; BETE, biomass to ethylene via ethanol to ethylene pathway; BG, biomass gasification; BMTO, biomass to olefins via methanol-to-olefins pathway; CCS, carbon capture and storage; CFTO, coal to olefins via Fischer-Tropsch to olefins pathway; CG, coal gasification; CMTO, coal to olefins via methanol-to-olefins pathway; CO_2, carbon dioxide; CPP, catalytic pyrolytic process; CO2MTO, CO_2 to olefins via methanol-to-olefins pathway; ETE, ethanol to ethylene; FTO, Fischer-Tropsch to olefins; GHG, greenhouse gas; LCA, life cycle assessment; MEA, monoethanolamine; MTO, methanol-to-olefins; MS, methanol synthesis; NG, natural gas; NGLs, natural gas liquids; NMTO, natural gas to olefins via methanol-to-olefins pathway; NSC, steam cracking of conventional natural gas; PSC, steam cracking of mixed petroleum; SC, steam cracking; SSC, steam cracking of shale gas; TEA, techno-economic analysis; WGS, water gas shift

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Table 1
Variability in GHG emission results for different ethylene production pathways.

	Location	Study year	Functional unit (FU)	Allocation method	Results (t CO_2eq/FU)	System boundary	Ref.
SC of mixed oil	China	2015	t Olefins (ethylene, propylene)	-	4–5	Oil extraction and processing, transportation, refining, steam cracking	[19]
	China	2017	t Ethylene	Mass	2.2		[20]
	U.S.A.	2014	t Ethylene	Energy	1.1		[26]
CMTO	China	2015	t Olefins (ethylene, propylene)	-	11.5	Coal extraction and processing, transportation, gasification, methanol synthesis, (CCS,) MTO	[19]
	China	2017	t Ethylene	Mass	5.2		[20]
CMTOwCCS	China	2015	t Olefins (ethylene, propylene)	-	7–8		[19]
NGMTO	China	2015	t Olefins (ethylene, propylene)	-	4–5	NG extraction and processing, transportation, methanol synthesis, MTO	[19]
	China	2017	t Ethylene	Mass	2.1		[20]
NSC	U.S.A.	2015	t HVC	-	1.8–2.2	NG recovery, NG processing, transportation, ethylene production	[8]
	U.S.A.	2014	t Ethylene	Energy	0.8		[26]
SSC	U.S.A.	2015	t HVC	-	2.0–3.4	SG recovery, SG processing, transportation, ethylene production	[8]
	U.S.A.	2016	t Ethylene	Mass	0.75–1.05		[21]
	U.S.A.	2016	t Ethylene	Economic	1.24–2.13		[21]
Corn-based ETE	China	2014	t Ethylene	Mass	2.7–4.1	Corn production, transportation, ethanol production, ETE, waste treatment	[9]
Cassava-based ETE	China	2014	t Ethylene	Mass	4.3–7.4	Cassava production, transportation,ethanol production, ETE, waste treatment	[9]
Wood-based MTO	Sweden	2015	t Ethylene	Economic	0.28–0.3	Biomass acquisition, transportation, gasification, methanol synthesis, MTO	[25]
Wood-based ETE	Sweden	2013	t Ethylene	-	5.2–5.6	Biomass acquisition, transportation, ethanol production, enzyme production, ETE	[31]
	Sweden	2013	t Ethylene	-	3.2–3.6		[31]

* - means no allocation method.

Given that the chemical industry is diverse and complex, the analysis has to be restricted to individual products [7]. Herein, ethylene is taken as an example because ethylene is one of the most important chemicals and its production process contributes 30% of energy to the chemical industry [8,9]. Ethylene can be used to produce polyethylene, polystyrene, polyethylene terephthalate and polyvinyl chloride [10]. In China, the ethylene industry has expanded dramatically from an annual production of 4.7 million metric tons in 2000 to 19.5 million metric tons in 2015 [11,12]. However, a gap between supply and demand of ethylene still exists. Annual production of ethylene only reached 51.9% of the ethylene equivalent consumption in 2015 [12]. Therefore, the demand for ethylene will continue to show an increasing trend in the short term. To tackle high environmental impact and booming expansion associated with ethylene production site, Chinese government and researchers have paid significant attention to upgrading and restructuring of ethylene plants [13,14].

Ethylene is conventionally produced by steam cracking (SC), the feedstocks for which can be a broad range of hydrocarbon feedstocks [15]. Ethylene is predominantly from SC of mixed petroleum (PSC) in Europe and Asia, while North America and the Middle East adopt light hydrocarbons as feedstocks for SC [7,15]. This process is crucially dependent on petroleum and emits considerable CO_2, which conflicts with the growing pressure for fossil fuel reduction and climate change mitigation. Therefore, alternative routes and feedstocks are explored and developed to adapt to the sustainable development of the olefins industry [15]. For example, China, with large coal reserves, focuses on the conversion of coal-based methanol-to-olefins (CMTO) in an attempt to reduce reliance on imported petroleum [16]. By techno-economic analysis (TEA) and life cycle assessment (LCA), Xiang et al. [17] found that CMTO is economically competitive and independent of petroleum, however, controversies have accompanied this route because CMTO has higher energy consumption and generates more greenhouse gas (GHG) emissions than the oil route [18,19]. Furthermore, Chen et al. [20] found CMTO leads to about 2.5 times GHG emissions of PSC and NG-based methanol-to-olefins (NMTO), and the eco-efficiency of NMTO is the highest among the three production routes.

Different from China, the U.S.A. has developed SC of natural gas liquids (NGLs) to ethylene due to its vast shale gas reserves. He et al. [21] conducted a techno-economic-environmental analysis of SC of shale gas (SSC) to olefin in the U.S.A. and found that shale regions of the U.S.A. could supply feedstocks for ethylene for more than 130 years. SSC has a little higher GHG emissions in comparison with SC of conventional natural gas (NSC) [8,21].

SC and methanol-to-olefins (MTO) based on natural gas, shale gas, and coal can reduce dependence on petroleum. However, these technologies still emit CO_2. CO_2 emissions in CMTO pathway are even higher than that of the PSC pathway. Carbon capture and storage (CCS) was used to reduce CO_2 emissions. By LCA, Xiang et al. [19,22] found that CMTO process with CCS is competitive in product cost as well as low GHG emissions. However, the eco-efficiency of integration of CCS with CMTO is lower than PSC and NMTO routes [20].

Switching from fossil sources to the renewable resources such as CO_2 and biomass, particularly bio-waste, is attractive since it can establish a sustainable and low carbon centre to produce chemicals [23,24]. Some researchers have developed work associated with ethylene production adopting biomass as raw material. Hong et al. [9] performed a LCA to estimate corn- and cassava-based ethylene production. Liptow et al. [25] evaluated the environmental burden of biomass-based ethylene production routes via gasification and fermentation. Ghanta et al. [26] estimated environmental impacts of ethylene production from naphtha, ethane, and ethanol. These work focused on varietal environmental impacts of ethylene production, which makes a limited focus on CO_2 or GHG emissions.

By LCA and TEA, the previous work assessed CO_2 emissions of specific pathways for ethylene production. However, it is not appropriate to directly compare CO_2 emissions among these pathways due to different system boundary, functional unit, location, allocation method and study time, as shown in Table 1. Given this, Ren et al. [27,28] have made an extensive comparison of different olefins production routes in terms of energy use and CO_2 emissions by a simplified method of LCA. Some processes, such as transportation, are excluded in the study. Inaccuracy will be inevitable without regard to the uniform functional unit and appropriate system boundary. Also, some technologies, such as catalytic pyrolytic process (CPP), Fischer-Tropsch-to-olefins (FTO), and