

Article

Evaluation of Industrial Urea Energy Consumption (EC) Based on Life Cycle Assessment (LCA)

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Abstract: With the increasingly prominent environmental problems and the decline of fossil fuel reserves, the reduction of energy consumption (EC) has become a common goal in the world. Urea industry is a typical energy-intensive chemical industry. However, studies just focus on the breakthrough of specific production technology or only consider the EC in the production stage. This results in a lack of evaluations of the life cycle of energy consumption (LcEC). In order to provide a systematic, scientific, and practical theoretical basis for the industrial upgrading and the energy transformation, LcEC of urea production and the greenhouse gas (GHG) emissions generated in the process of EC are studied in this paper. The results show that the average LcEC is about 30.1 GJ/t urea. The EC of the materials preparation stage, synthesis stage, and waste-treatment stage (EC_{RMP} , EC_{PP} , EC_{WD}) is about 0.388 GJ/t urea, 24.8 GJ/t urea, and 4.92 GJ/t urea, accounting for 1.3%, 82.4%, and 16.3% of LcEC, respectively. Thus, the synthesis stage is a dominant energy-consumer, in which 15.4 GJ/t urea of energy, accounting for 62.0% of EC_{PP} , supports steam consumption. According to the energy distribution analysis, it can be concluded that coal presents the primary energy in the process of urea production, which supports 94.4% of LcEC. The proportion of coal consumption is significantly higher than that of the average of 59% in China. Besides, the GHG emissions in the synthesis stage are obviously larger than that in the other stage, with an average of 2.18 t eq.CO₂/t urea, accounting for 81.3% of the life cycle of GHG (LcGHG) emissions. In detail, CO₂ is the dominant factor accounting for 90.0% of LcGHG emissions, followed by CH₄, while N₂O is negligible. Coal is the primary source of CO₂ emissions. The severe high proportion of coal consumption in the life cycle of urea production is responsible for this high CO₂ content of GHG emissions. Therefore, for industrial urea upgrading and energy transformation, reducing coal consumption will still be an important task for energy structure transformation. At the same time, the reformation of synthesis technologies, especially for steam energy-consuming technology, will mainly reduce the EC of the urea industry. Furthermore, the application of green energy will be conducive to a win-win situation for both economic and environmental benefits.

Keywords: energy consumption (EC); evaluation; urea industry; life cycle assessment (LCA); greenhouse gas (GHG) emissions

1. Introduction

Climate change has become a critical issue that restricts global sustainable development [1]. The greenhouse gas (GHG) emissions from fossil fuel consumption are world-widely considered as a crucial source of climate change [2]. Reducing energy consumption (EC) is believed effective to save energy, protect the environment, and achieve economic sustainability [3,4]. It is in line with the concept of global sustainability and has been gradually ratified by global decision-makers [5,6]. It has become one of the most critical topics in global economics [7].

The industrial sector provides an indispensable material foundation for the survival and development of human beings. It is a powerful driving force for future social development. However, the industrial sector is considered energy-intensive [8–10], accounting for 37% of total global EC in 2017 [11] and more than 50% of global end-use EC in 2018 [12]. According to the International Energy Outlook (IEO) 2019, the EC of the industrial sector will increase by more than 30% from 2018 to 2050 [12]. The industrial sector includes three distinct industry types: energy-intensive manufacturing, nonenergy-intensive manufacturing, and nonmanufacturing [13]. The ongoing long-term trend of increasing production in energy-intensive manufacturing drives the most rapid growth of EC in the industrial sector [11]. The chemical industry is one of the representatives and the largest energy consumer among energy-intensive industries. The share of energy use in the chemical industry accounts for 19% and 14% of the total delivered EC in the industrial sector of the Organization for Economic Cooperation and Development (OECD) countries and the non-OECD countries, respectively [13]. The share is estimated to rise to 20% in both regions in 2040 based on the IEO 2016 reference case [13]. Therefore, how to adjust the balance between economic development and the environment is a common issue for all countries to address the challenges related to energy, resources, and environment [14,15].

China's rapidly growing population and economy have driven the country to be the top energy producer and consumer [16] and CO₂ emitter [2] in the world. BP Energy Outlook 2018 estimates that China will still consume around one-quarter of world energy in 2040 despite the slowing growth of energy demand [17]. Moreover, as one of the largest chemical manufacturing countries in the world [18,19], China's share of industrial energy consumption will only decrease from 29% in 2018 to 24% in 2050, according to International Energy Outlook 2019 [12]. The study of the EC of the sector, especially the energy-intensive chemical industry in China, has important implications for the industrial upgrading and transformation of energy structure in the industrial sector worldwide.

Urea is not only a critical chemical fertilizer but also a widely used industrial raw materials. The urea industry is one of the representative chemical industrial sectors in the world. Urea production in China began in 1958 [20]. China is the world's largest producer and consumer of urea, producing 61.9 million tons of urea and consuming over 55% of total urea produced along with the Southwest Asian region in 2016 [21,22]. With the growing urea demand, the EC of the urea industry has increased. It is significant to analyze the EC in the production process, estimate the situation of energy use, and find the balance between the industrial economy and environmental improvement to achieve sustainable development.

The life cycle assessment (LCA) is a "cradle-to-grave" or "gate-to-gate" evaluation of the environmental costs associated with a given product [23,24]. It differs from traditional evaluation methods such as the single-factor energy efficiency evaluation method [25,26] and the total-factor energy efficiency evaluation method [27–29], in which the energy efficiency assessments are incomplete. The LCA offers a holistic view of environmental interactions that covers a range of activities from the extraction of raw materials to the production and distribution of energy, through the use, reuse, and final disposal of a product [24]. It is regarded as a common decision-support tool for both policymakers and industry experts in assessing the impacts of a product or process [24–31]. A combination of EC and GHG emissions analysis with the comparison of life cycle performance of production is conducive to the study of energy-saving and emissions reduction [32].

Most studies focus on the breakthrough of a specific production technology [33,34], or only consider the EC in the production stage [35], resulting in the lack of the evaluations of the life cycle

energy consumption (LcEC). In this study, the LCA and the production process of the urea industry are carried out to establish a life cycle framework of industrial urea, which includes three stages: raw material production stage, production stage, and waste-treatment stage. Moreover, by using the inventory data from seven different real industrial urea operations, the LcEC of the urea industry from raw material extraction to disposal is evaluated the first time in this study. The GHG emissions generated throughout the LcEC of urea production are also estimated. This paper provides a systematic, valid, and realistic judgment on the EC and GHGs impacts of the chemical industry, which can be used as a scientific basis for future development strategies and policies to promote sustainability in the industrial sector.

2. Evaluation Methods and Data

2.1. Life Cycle Framework of the Urea Production

Urea (NH_2CONH_2) is an important nitrogen-rich organic compound, which was initially produced via the use of inorganics by Friedrich Wöhler in 1828 [36]. In the urea factory, urea is synthesized from synthetic ammonia, which is usually produced from coal or natural gas (NG) with other materials, and CO_2 [37]. The production routines mainly involve the ammonia synthesis process and urea synthesis process including air separation (likes grinding coal, industrial gasification, ash water treatment), desulfurization conversion, purification, ammonia synthesis, ammonia recovery, ammonia compression, urea synthesis, decomposition, concentration, and recovery, etc., the detailed information is available in the literature [38,39].

A life cycle framework of the urea production is established based on the International Standards ISO 14040:2006 and ISO 14044:2006 [40,41], and the analysis of material and energy flows in the production process. As shown in Figure 1, the life cycle of urea production is divided into three stages: the materials preparation stage, synthesis stage, and waste-treatment stage. In the materials preparation stage, natural resources are extracted and transported to the urea plant as raw materials. In the synthesis stage, the intermediate material ammonia is synthesized using coal or natural gas at first and then used to synthesis urea with CO_2 . In the waste-treatment stage, waste gas, water, and residues are disposed of in several ways.

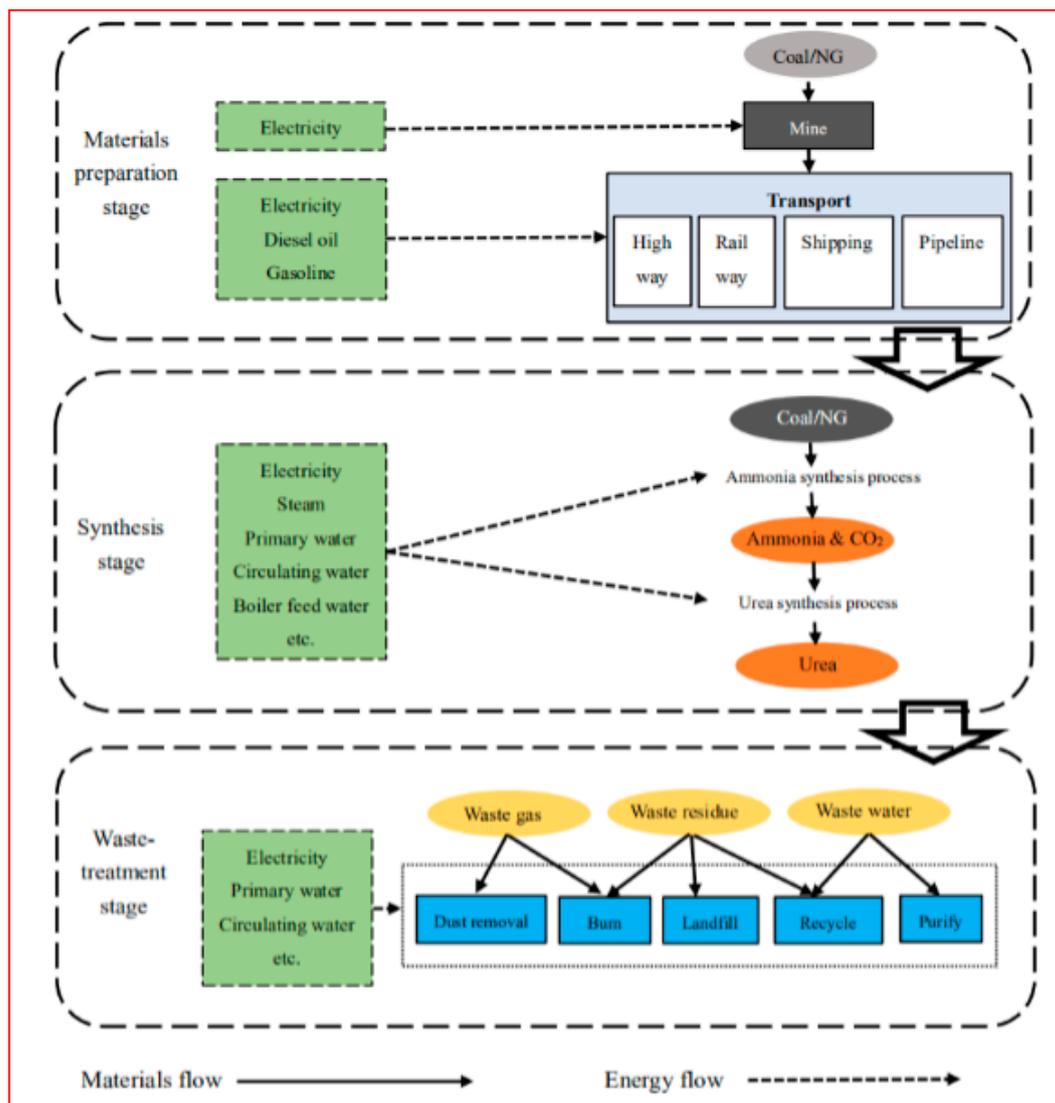


Figure 1. Life cycle framework of urea production.

2.2. Life Cycle Energy Consumption (LcEC)

In this study, the LcEC represents the total primary fossil fuel energy inputs in the life cycle of urea production, and the LcGHGs is calculated by the sum of GHGs (CO_2 , CH_4 , N_2O) generated by the EC of each stage.

According to the inventory analysis of LcEC in the chemical production process [40,41] and the three stages defined in Figure 1, the LcEC consists of the EC of raw material preparation (EC_{RMP}), product production (EC_{PP}) and waste disposal (EC_{WD}), which reflects the EC of the material preparation stage, synthesis stage, and waste-treatment stage, respectively. It is calculated by the sum of the product of process energy consumption (PEC) and the corresponding primary fossil consumption factor (PFCF) [32,42,43], as shown in Equation (1).

$$LcEC = EC_{RMP} + EC_{PP} + EC_{WD} = \sum_f \sum_i \sum_j PEC_{f,i} \times PFCF_{i,j} \quad (1)$$

where f represents sub-stage of raw materials preparation stage, synthesis stage, and waste-treatment stage; i represents the type of process energy; j represents the type of primary fossil energy input; $PEC_{f,i}$

represents the PEC of unit urea in the sub-stage f ; and $PF_{CF_{ij}}$ represents the consumption of primary fossil j to obtain 1 MJ process energy i , as shown in Table 1.

The sub-stage of synthesis stage includes the whole process of material from various physical and chemical reactions to completion of chemical products, that is, processing of gasification, intermediate material synthesis, urea synthesis, and storage with process energy (e.g., circulating water, condensate consumed by energy-used medium). The energy coefficient of the energy-consumed medium is shown in Table 2.

Table 1. Primary fossil consumption factors [32,42–44].

Process Energy	Coal (MJ/MJ)	NG (MJ/MJ)	Oil (MJ/MJ)
Coal	1.06	0.00	0.11
Electricity	2.86	0.03	0.37
Steam	1.38	0.00	0.01
Diesel	0.18	0.03	1.12
Gasoline	0.18	0.03	1.12

Table 2. Energy coefficient of the energy-consumed medium [45].

Types	Unit	Average Calorific Value (MJ)
Circulating water	t	4.19
Softened water	t	10.47
Heating equipment condensate	t	320.3
Steam turbine condensate water	t	152.8
Desalted water	t	96.3
Deoxygenated water	t	385.2
Compressed air (purified)	m ³	1.59
Compressed air (Non-purified)	m ³	1.17
Steam (10.0 MPa)	t	3852
Steam (4.9 MPa)	t	3768
Steam (3.5 MPa)	t	3684
Steam (3.0 MPa)	t	3681
Steam (2.5 MPa)	t	3559
Steam (1.3 MPa)	t	3349
Steam (1.0 MPa)	t	3182
Steam (0.6 Mpa)	t	3011
Steam (0.5 MPa)	t	2763
Steam (0.3 MPa)	t	2763
Steam (<0.3 MPa)	t	2303

Process Energy Consumption of Raw Material Preparation (PEC_{RMP})

The materials preparation stage includes two sub-stages: raw material extraction and transportation. The PEC_{RMP} consists of process energy consumption of material preparation (PEC_{MP}) and process energy consumption of material transportation (PEC_{MT}) of unit urea production, as Equation (2).

$$PEC_{RMP} = PEC_{MP} + PEC_{MT} \quad (2)$$

where, the EC_{MP} and EC_{MT} can be determined by Equations (3) and (4), respectively.

$$PEC_{MP} = \sum RM_x \times EC_{x,i} \quad (3)$$

$$PEC_{MT} = \sum EI_{x,i,y} \times L_x \times RM_x \quad (4)$$

where x presents raw material coal; y represents the transportation mode; i represents the process energy; $PEC_{x,i}$ represents the EC of coal extraction by using process energy i , based on The Norm of

The Energy Consumption Per Unit Production of Coal Underground Mining GB29444-2012 [46], with $EC_{\text{Coal, electrical}}$ set as 345.65 MJ/t; L_x represents the transport distance of raw material x (km); and $EI_{x,i,y}$ represents the energy intensity by process energy i in mode y (MJ/t.km), and the energy intensity of transportation mode refer to the literature [32,47,48].

2.3. GHG Emissions from LcEC

The LCA is an essential tool for assessing the environmental impact in material, products, process, and service [31,49]. It is widely recognized as a quantitative evaluation method of environmental load internationally [50]. Based on global-warming potential (GWP) [51], the GHGs (CO_2 , CH_4 , N_2O) generated from the PEC in each sub-stage f are determined by Equations (5)–(6).

$$GHG_p = \sum_f \sum_i PEC_{f,i} \times EF_{f,i,p} \quad (5)$$

$$LcGHG = \sum GHG_{\text{CO}_2} + 25 \sum GHG_{\text{CH}_4} + 298 \sum GHG_{\text{N}_2\text{O}} \quad (6)$$

where $PEC_{f,i}$ represents the consumption of process energy i in sub-stage f , and $EF_{f,i,p}$ represents the emission factor of gas p by process energy i in the sub-stage f , $p \in \{\text{CO}_2, \text{CH}_4, \text{N}_2\text{O}\}$.

The EF consists of direct emission and indirect emission factors [32,43]. In this study, the direct emission factor relates to the exhaust gas produced by process energy use and combustion, whereas the indirect emission factor caused by the LcEC [43,44,52]. Based on the literature [32,42,43,53], the emission factors are demonstrated in Table 3.

Table 3. Direct and indirect emission factors of energy used [32,42,43,53].

Classes	Energy Type	Direct Emission Factors			Indirect Emission Factors		
		CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (mg/MJ)	CO_2 (g/MJ)	CH_4 (g/MJ)	N_2O (mg/MJ)
Industrial	Coal	81.6	0.001	0.001	5.73	0.43	0.17
	Electricity	0	0	0	248	2.16	0.62
	Steam	0	0	0	114	0.29	1.79
Highway	Gasoline	67.9	0.08	0.002	28.8	0.09	0.47
	Diesel	72.6	0.004	0.028	27.9	0.08	0.44
Railway	Diesel	72.6	0.004	0.028	27.9	0.08	0.44

2.4. Inventory Data

In this study, the PEC data of each stage is gathered from 7 different urea plants, referred to as A, B, C, D, E, F, G, and H, respectively. Table 4 shows the distances and mode of raw material transportation. The process energy from the energy-consumed medium measured RM_{coal} (e.g., circulating water, condensate, etc.). Table 5 summarizes the PEC data of the synthesis stage and the waste-treatment stage. The specific information about the 7 urea plants are shown in Table 6.

Table 4. The inventory data of process energy used in the materials preparation stage.

Objects	Transportation	Energy	RM _{coal} (t/t Urea)	EC _{Coal,electrical} [46]	Distances (km)	Energy Intensity (MJ/t km) [32,48]
A	Highway	Gasoline	0.68		30	2.58
B	Railway	Diesel	0.62		650	0.11
C	Highway	Gasoline	0.85		30	2.58
D	Railway	Diesel	0.98	345.65 MJ/t	30	0.11
E	Highway	Diesel	0.78		30	2.35
F	Railway	Diesel	0.66		760	0.11
G	Railway	Diesel	1.04		500	0.11

Table 5. The inventory data of process energy used in the synthesis stage and waste-treatment stage (MJ/t urea).

Items	Synthesis Stage			Total	Waste-Treatment Stage			Total
	Electricity	Steam	RM _{coal}		Exhaust Gas	Wastewater	Solid Waste	
					Coal	Coal	Coal	
A	1120	9630	2100	12,850	2210	16.7	5.22	2231.92
B	3200	6520	961	10,681	2240	21.3	3.73	2265.03
C	353	12,080	1540	13,973	6430	14.8	6.71	6451.51
D	2980	9180	1360	13,520	1180	6.65	24.2	1210.85
E	1210	16,300	21,500	39,010	6760	6.06	8.94	6775
F	585	10,300	2130	13,015	5206	102	18.3	5326.3
G	360	13,400	873	14,633	5130	16.8	9.31	5156.11

Table 6. The specific information about 7 urea production processes.

Project	Materials Preparation Stage		Synthesis Stage			Urea quality
	Raw Materials	Transport	Ammonia Synthesis	Urea Synthesis		
			Gasification Technology	Process	Equipment	
A	Coal	Highway	Hangtian pulverized coal pressure gasification technology (HT-L)	CO ₂ stripping	Fluid bed big granular urea unit (Hydro)	TN ≥ 46.5
B	Coal	Railway	Continuously gasification	The improved water cycle process	Modified water cycle urea plant	TN ≥ 46.4
C	Coal	Highway	Shell coal gasification process	Improved CO ₂ stripping	Modified CO ₂ stripping method urea plant	TN ≥ 46.4
D	Coal	Railway	Intermittent fixed-bed gasification	Water cycle process	Water cycle urea plant	TN ≥ 46.3
E	Coal	Highway	Intermittent fixed-bed gasification	CO ₂ stripping	CO ₂ stripping method urea plant	TN ≥ 46.2
F	Coal	Railway	Continuous coal gasification	New CO ₂ stripping	CO ₂ stripping method urea plant	TN ≥ 46.4
G	Coal	Highway	Pulverized coal pressure gasification process	CO ₂ stripping	CO ₂ stripping method urea plant	TN ≥ 46.3

3. Results and Discussion

3.1. LcEC

The LcEC of 7 urea plants was calculated by Equations (1)–(4) using data in Tables 1, 5 and 6. As shown in Figure 2, the LcEC of the 7 industry operations is 22.5 GJ/t urea, 23.6 GJ/t urea, 26.1 GJ/t urea, 25.9 GJ/t urea, 60.0 GJ/t urea, 25.3 GJ/t urea, 27.4 GJ/t urea, respectively. Because of the significant EC_{pp} , industry E presented the highest EC. However, since the production equipment in the urea industry has different service life and different loss degree, this study focuses on the comparison of the EC and GHG emissions in different stages of urea production. The purpose of collecting and evaluating the EC of 7 urea plants is to demonstrate the commonality of EC characteristics in the life cycle of urea production. Therefore, according to Figure 2, the life cycle performance of urea EC presented a significant EC in the synthesis stage and the lowest EC in the material preparation stage, where the average EC_{RMP} , EC_{PP} , EC_{WD} accounted for 1.3%, 82.4%, and 16.3% of LcEC, respectively.

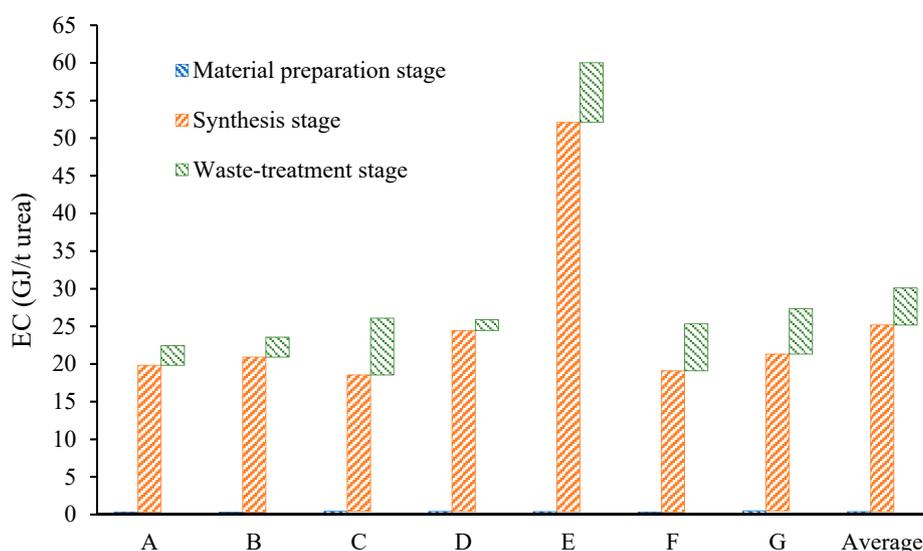


Figure 2. Distribution of life cycle of energy consumption (LcEC) by stages from 7 urea industries.

In order to reveal the dominant primary fossil energy in the life cycle of urea production, the primary fossil energy consumption was analyzed and is shown in Figure 3. It presents that coal is the dominating energy inputs of the urea industry, accounting for 94.4% of LcEC. In contrast, oil and NG are a tiny fraction of LcEC, accounting for 0.144% and 5.42% of LcEC, respectively. According to the China Statistical Yearbook 2019, coal is the primary source of energy in China; coal, oil, NG, primary electricity, and other energy sources account for 59.0%, 18.9%, 7.8%, and 14.3% of total EC in 2019, respectively [54]. Thus, the proportion of coal consumption of the urea industry is higher than that of coal in the whole country. Driven by resource and environmental constraints, as well as pressure to reduce GHG emissions, China's primary energy consumption structure is expected to shift in the coming decades [55]. Reducing coal consumption in the urea industry is an effective way to help achieve this goal.

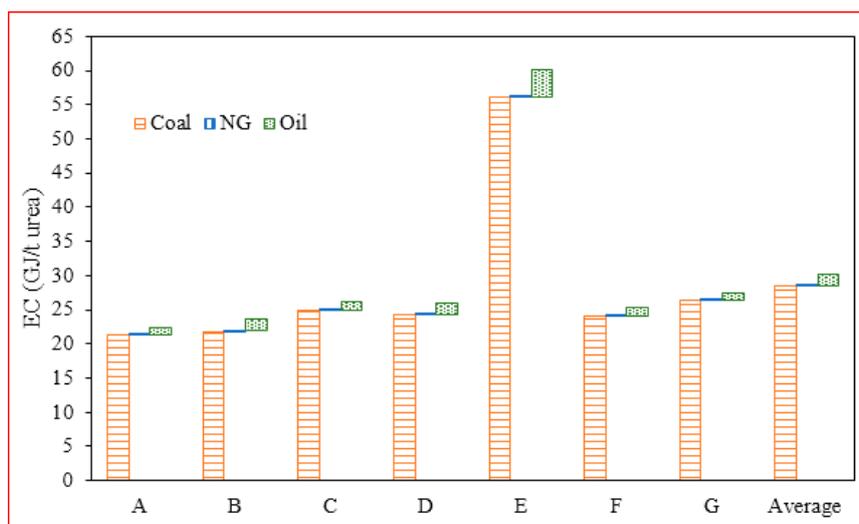


Figure 3. Distribution of LcEC for urea production.

Based on the analysis of the average LcEC of 7 urea industries, the distribution of primary fossil energy consumption by stage is shown in Figure 4. The results suggest that the average LcEC is about 30.1 GJ/t urea, where the materials preparation stage, synthesis stage, and waste-treatment stage consuming about 0.388 GJ/t urea, 24.8 GJ/t urea, and 4.92 GJ/t urea of energy, respectively. As mentioned before (Figure 3), coal is the dominant primary fossil fuel energy in the life cycle of urea production. Figure 4 reveals that in the life cycle of urea production, about 1.06% of coal is consumed by the material preparation stage, 83.3% of coal is used in the synthesis stage, and 15.7% of coal is consumed in the waste-treatment stage. Additionally, the consumption of coal in the material preparation stage, the synthesis stage, and the waste-treatment stage account for about 77.9%, 95.5%, and 90.6% of the total energy consumed in each stage, respectively. Undoubtedly, the synthesis stage is an energy-intensive stage in the life cycle of the urea production process. An in-depth analysis of the EC performance of the synthesis stage helps provides a robust scientific basis for adjusting EC in the urea industry, as shown in Figure 5.

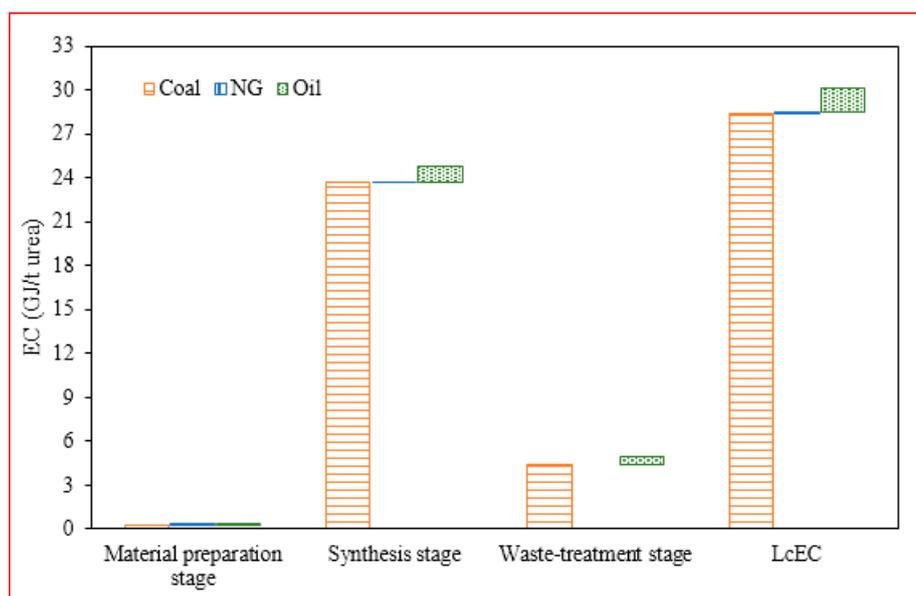


Figure 4. Distribution of average primary fossil energy consumption by stages.

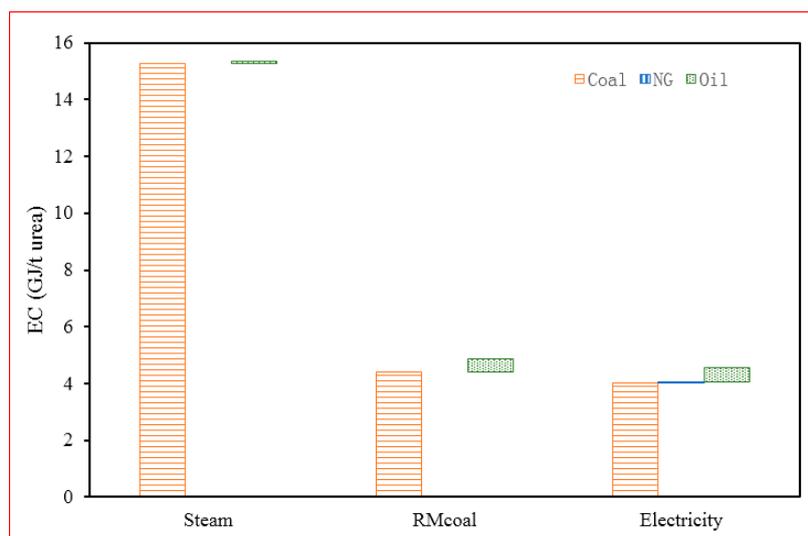


Figure 5. Distribution of average primary fossil energy consumption by the process energy used in the synthesis stage.

In the synthesis stage, the distribution of average primary fossil energy consumption by process energy used is shown in Figure 5. The results reveal that in the synthesis stage, steam is the dominating source of primary fossil energy consumption, which accounts for about 62.0% of EC_{PP} . Besides, coal plays a vital role in the generation of process energy. Based on Figures 4 and 5, 95.5% of process energy in the synthesis stage is supported by coal, where 15.3 GJ/t urea of coal is used to support steam generation, about 4.40 GJ/t urea of coal is used to support the RM_{coal} consumption (which replaces the process energy used by energy-used mediums), and about 4.01 GJ/t urea of coal is used to support the electricity. In other words, nearly 99.3%, 90.6%, and 87.7% of steam, RM_{coal} , and electricity come from coal consumption, respectively. The proportion of coal consumption in the generation of process energy in the synthesis stage is significantly higher than that of coal in the whole country. Thus, how to decline steam consumption or use clean energy instead is a question worth considering in the transformation of the urea industry. According to the study of LcEC performance of urea production, there is an urge to transform the industrial energy mix, including the improvement of energy efficiency in energy-intensive processes and the use of clean energy to accelerate the transformation of China's energy structure and improve energy security.

3.2. LcGHGs

Based on Tables 2–5, the LcGHGs is calculated by Equations (5) and (6). The results shown in Figure 6 suggest that the 7 urea industries generate 2.01 t eq. CO_2 /t urea, 2.15 t eq. CO_2 /t urea, 2.32 t eq. CO_2 /t urea, 2.37 t eq. CO_2 /t urea, 5.21 t eq. CO_2 /t urea, 2.24 t eq. CO_2 /t urea, and 2.45 t eq. CO_2 /t urea of LcGHGs by consuming energy, respectively. The average LcGHGs is about 2.68 t eq. CO_2 /t urea. The distribution of GHG emissions by stage presents a similar trend with EC in urea production (Figure 2). In the life cycle of urea production, the GHG emissions generated by EC in the synthesis stage are significantly larger than that in the other stage, with an average of about 2.18 t eq. CO_2 /t urea, accounting for 81.3% of the LcGHG emissions. The emission of GHGs in the material preparation stage and waste-treatment stage is about 0.09 t eq. CO_2 /t urea and 0.41 t eq. CO_2 /t urea which accounts for 3.31% and 15.4% of LcGHGs, respectively. Therefore, the synthesis stage is not merely a stage with intensive EC, but also a step with high-intensity GHG emissions. This phenomenon is in line with the fact that EC is proportional to GHG emissions.

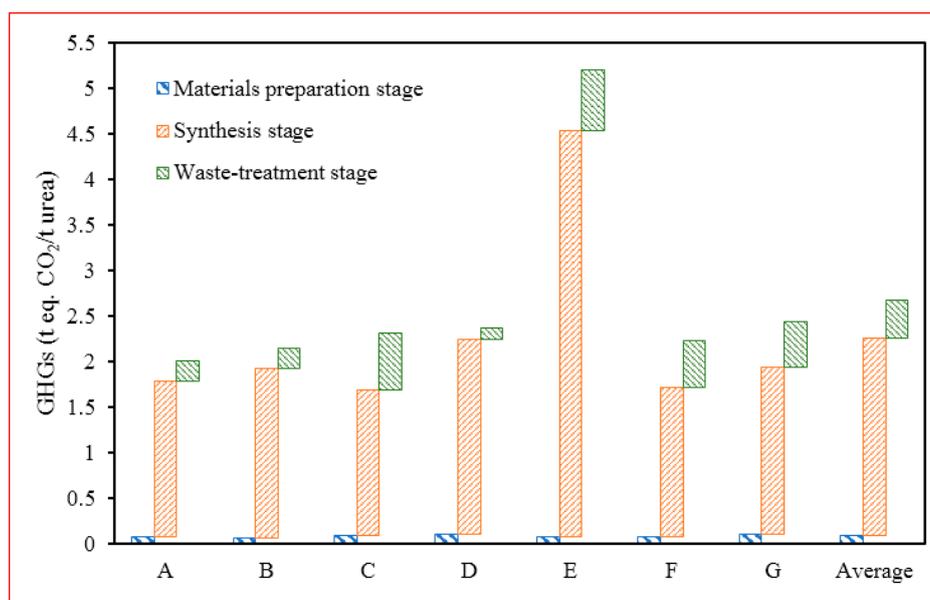


Figure 6. The life cycle of GHG (LcGHG) emissions from 7 urea industries.

The distribution of LcGHG emissions, shown in Figure 7, reveals that CO₂ is the dominant GHGs emission, accounting for 90.0% of LcGHG emissions, followed by CH₄. N₂O is negligible for the GHG emissions of the LcEC. In detail, the CO₂ equivalent emission is 2.41 t eq. CO₂/t urea, in which 81.7% is from the synthesis stage, 15.2% comes from the waste-treatment stage, and 3.05% comes from the material preparation stage. CO₂ equivalent emissions of the material preparation stage, synthesis stage, and waste-treatment stage account for 82.9%, 90.5%, and 89.0% of GHG emissions, and the corresponding CH₄ equivalent emissions account for 17.0%, 9.22%, and 11.0% of GHG emissions, respectively. The distribution of LcGHG in Figure 7 presents a similar trend with LcEC in Figure 4. Coal is the primary source of CO₂ emission. A great deal of coal consumption in each stage is responsible for the emission of high CO₂ concentration. Therefore, reducing coal's share in EC is the most direct way to reduce GHG emissions in the urea plant.

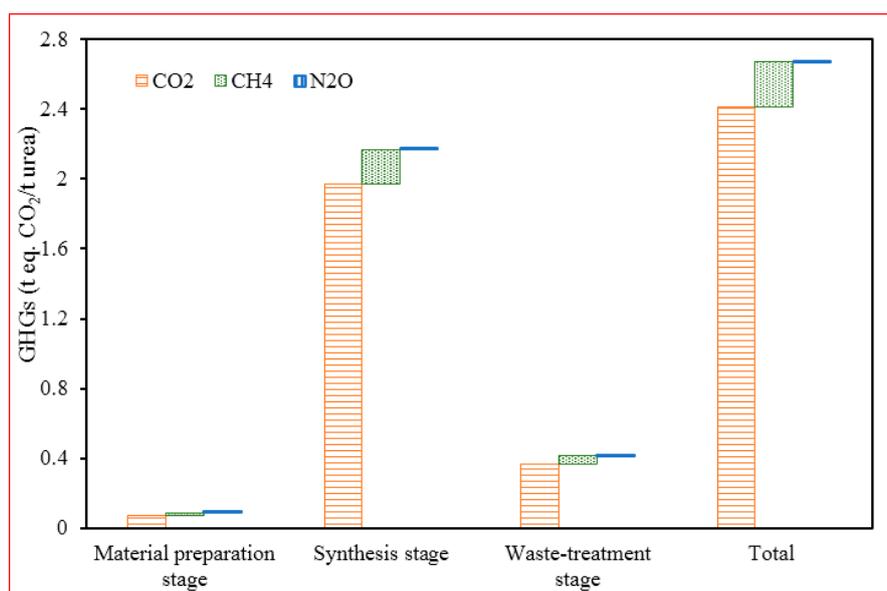


Figure 7. Distribution of LcGHG emissions.

Figure 8 shows the GHG emissions from different process energy inputs in the synthesis stage. The consumption of electricity, steam, and RM_{coal} produces GHGs of about 0.42 t eq. CO_2/t urea, 1.35 t eq. CO_2/t urea, and 0.41 t eq. CO_2/t urea, respectively. The GHGs produced by steam consumption account for 61.8.0% of the total GHG emissions in the synthesis stage. From the perspective of distribution, the generation of CO_2 equivalent emissions by electricity, steam, and RM_{coal} consumption account for 82.1%, 93.6%, and 89.0% of GHG emissions, and the corresponding CH_4 equivalent emissions account for 17.9%, 5.96%, and 11.0%, respectively. Therefore, steam is the main reason for GHG emissions with high CO_2 concentration. As shown in Figure 5 and Table 5, steam consumes about 15.3 GJ/t urea of coal, and accounts for over 64% of total coal consumption (23.7 GJ/t urea). The relatively higher proportion of coal consumed may be responsible for the higher CO_2 content of the GHGs during the synthesis stage. Thus, combined with the result from Figure 5, it is useful to replace coal with green energy or to increase the energy efficiency of steam-consuming substage in the synthesis stage in order to reduce EC and GHG emissions in the life cycle of urea production.

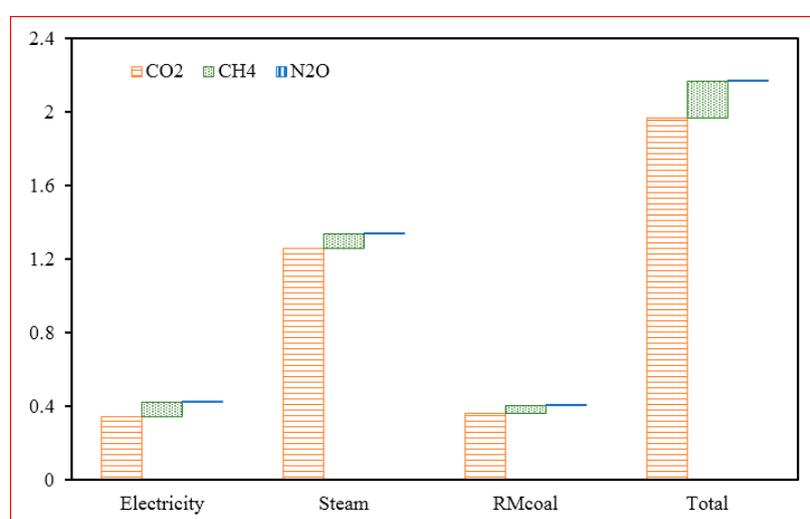


Figure 8. Distribution of GHG emissions by process energy used in the synthesis stage.

3.3. Implications of the Results

The LcEC analysis illustrates the following: (1) The synthesis stage is the leading energy-consuming stage in life cycle urea production, accounting for 82.4% of LcEC. Steam, electricity, and RM_{coal} are the primary process energies used in the synthesis stage. The supply of steam consumes 62.0% of EC_{pp} . The steam-consuming equipment is responsible for the high EC of urea production. (2) Coal is the dominant primary fossil energy in each stage, accounting for 94.4% of LcEC. Based on the China Statistical Yearbook 2019, coal accounts for 59.0% of the total primary energy consumption in China [54]. The proportion of coal consumption in the urea industry is higher than that of coal consumption generally in China. Therefore, the urea industry has excellent potential for coal energy-saving. Besides, improving the energy efficiency of steam-consuming equipment or replacing coal with green energy is an effective way to reduce coal consumption in the urea industry.

GHG emissions are closely related to the amount of energy used and the type of energy consumed. Due to the life cycle performance of EC in the urea industry, LcGHG emissions present a similar trend with LcEC. In detail, CO_2 equivalent emissions of the material preparation stage, synthesis stage, and waste-treatment stage account for 82.9%, 90.5%, and 89.0% of GHG emissions of each stage. Coal is the primary source of CO_2 emission. As shown in Figure 4, the higher proportion of coal consumed during the synthesis stage may be responsible for the higher CO_2 content of the GHGs during this phase. Applying renewable energies, such as low-carbon and renewable biomass provided by biorefinery [56], is critical toward a more sustainable energy system [57,58]. Therefore, the utilization of renewable energy is the right approach to change the situation of high GHG emissions.

4. Conclusions

In this study, the LCA is applied to establish a life cycle framework of urea production, which divides the life cycle into three stages: the material preparation stage, synthesis stage, and waste-treatment stage. Based on the inventory data onto 7 real urea industries, LcEC of urea production, and LcGHG emissions generated by the process of EC are studied in this paper. The results show that the average LcEC is about 30.1 GJ/t urea. The EC_{RMP} , EC_{PP} , and EC_{WD} is about 0.388 GJ/t urea, 24.8 GJ/t urea, and 4.92 GJ/t urea, accounting for 1.3%, 82.4%, and 16.3% of average LcEC, respectively (Figure 2). Coal plays the primary energy in the urea production, which supports 94.4% of LcEC (Figure 3), and 77.9% of EC_{RMP} , 95.5% of EC_{PP} , and 90.6% of EC_{WD} (Figure 4). Therefore, the synthesis stage is the dominant energy consumer, in which the supplying of steam consumes 62.0% of EC_{PP} , where 99.3% comes from coal consumption (Figure 5). It reveals that the proportion of coal consumption in the life cycle of the urea industry is higher than that of coal consumption generally in China. Besides, due to the life cycle performance of EC in the urea industry, LcGHG emissions present a similar trend with LcEC (Figure 6). In detail, CO₂ equivalent emissions of the material preparation stage, synthesis stage, and waste-treatment stage account for 82.9%, 90.5%, and 89.0% of GHG emissions of each stage (Figure 7). Finally, the steam-consuming produces 1.35 t eq.CO₂/t urea GHG emissions, accounting for 61.8% of the total GHG emissions from the synthesis stage; in detail, the generation of CO₂ equivalent emissions by steam account for 93.6% of GHG emissions (Figure 8).

Urea production technologies and processes have been widely studied, and the results have been visible progress. The performance of EC and GHG emissions in the life cycle of urea production illustrates that whatever process or technique used in the urea factory nowadays, the reduction of coal consumption will still be a crucial task for the urea industry. Improving the energy efficiency of steam-consuming equipment or replacing coal with green energy is an effective way to reduce coal consumption. Besides, the promotion of the application of green energy, such as renewable energy, will contribute to the reform of industrial energy consumption structure, reduce the consumption of primary energy, and relieve GHG emissions. This is a powerful driving force for the realization of sustainable industrial development in the future.

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