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Energy technology roadmap for ethylene industry in China

Jing-Ming Chen[a,b,c], Biying Yu[a,b,c,d,*], Yi-Ming Wei[a,b,c,d]

[a] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China
[b] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China
[c] Beijing Key Lab of Energy Economics and Environmental Management, Beijing 100081, China
[d] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China

HIGHLIGHTS

- A three-level technology selection is constructed for ethylene industry.
- A National Energy Technology model is established for China's ethylene industry.
- The impacts of production structure change and advanced technologies are evaluated.
- Technology roadmap for achieving the target of current policies are obtained.
- A more sustainable development pathway is proposed for China's ethylene industry.

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ABSTRACT

Ethylene production increases rapidly in recent years in China, which promotes the growth of energy consumption and CO_2 emissions. Ethylene industry is a technology-intensive industry, for which steam cracking, coal to olefins and methanol to olefins are three main production ways. In view of energy-efficient and low-carbon technology selection, this study aims to find a suitable roadmap to achieve the targets under current policies for China's ethylene industry by utilizing National Energy Technology model. With this roadmap, we find that the policy goal for steam cracking could be achieved and the energy consumption and CO_2 emissions of producing one-ton ethylene could decrease effectively. Specifically, for producing per ton ethylene, energy consumption could be reduced by 16.8% and 17.1% in 2030 compared to 2015 for steam cracking and coal to olefins respectively, and the values of CO_2 emissions are 18.1% and 14.8%. In addition, this study makes a discussion about how to achieve a more sustainable development for ethylene industry in China and it is found that both of energy consumption and CO_2 emissions could be reduced by about 20% in 2030 compared to the reference scenario. It is proposed that structure of feedstock in steam cracking could be optimized with more light materials and ethylene producing ways need to be planned well. Especially, environmental effect of coal to olefins should be taken into consideration in its process of development. Steam cracking with ethane and methanol to olefins with imported methanol could be encouraged as they can reduce energy consumption and CO_2 emission directly.

1. Introduction

Ethylene is a versatile chemical material and is generally considered as the building block of the chemical industry together with propylene and aromatics [1,2]. With demand growing steadily, China's capacity of ethylene has ranked second in the world. From 2005 to 2016, the yield of ethylene increases at a rate of 8.1% annually to 17.81 million tons in China (Fig. 1a) [3]. Ethylene equivalent, which also consider the demand for ethylene's downstream products like polyethylene, ethylene glycol and so on, is always considered as the real demand of ethylene, while its self-sufficiency[1] is under 50% in long term. It is predicted that quantity of ethylene equivalent would keep increasing at a rate of 3.6% annually during year 2016–2020 [4]. This would promote the yield of ethylene to increase at a rate of 11.5% annually during the 13th Five-Year Plan to 30 million tons in year 2020 [5]. China plans to construct seven petrochemical industrial bases during

* Corresponding author at: Center for Energy and Environmental Policy Research, Beijing Institute of Technology, 5 South Zhongguancun Street, Haidian District, Beijing 100081, China.
E-mail addresses: chenjm0807@163.com (J.-M. Chen), yubiying_bj@bit.edu.cn (B. Yu), wei@bit.edu.cn (Y.-M. Wei).

[1] Self-sufficiency refers to the ratio of yield to total demand.

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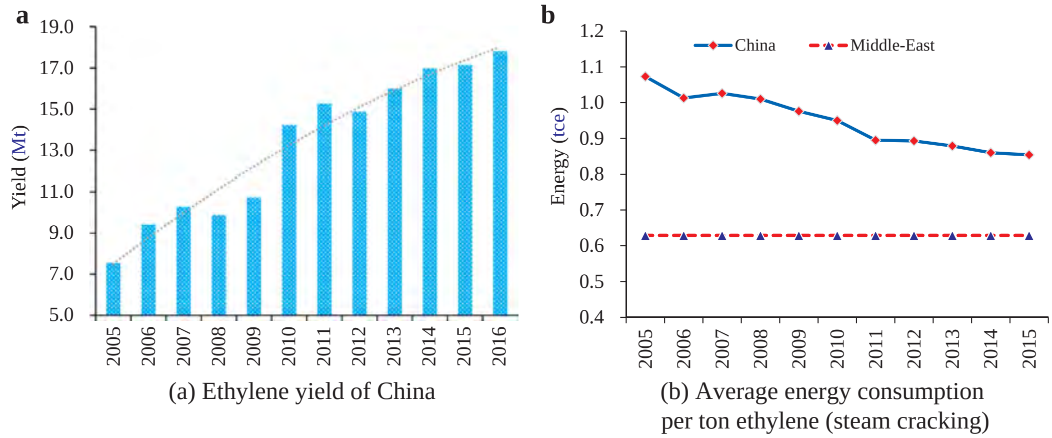


Fig. 1. Ethylene yield of China and average energy consumption per ton ethylene (steam cracking) in China and in Middle-East.

13th Five-Year Plan, which would increase 7.2 million tons of ethylene capacity[2]. Steam cracking, coal to olefins[3] via methanol (CTO), methanol to olefins directly (MTO) and catalytic pyrolysis process (CPP) are four ways to produce ethylene in China. Among which, steam cracking is the most important way which always accounts for more than 80% of the total yield, followed by CTO and MTO, which are two alternative ways but with part of production process similar. While the capacity of CPP only accounts for nearly 2% in 2015.

Energy consumption of ethylene production accounts for more than 15%[4] (including as fuel and material) in thousands of chemical products currently, which indicates that it is one of the biggest energy consumers in chemical industry. There is no doubt that the rapid growth of production would increase the total amount of energy consumption and carbon emission in China's ethylene industry. As a response to energy saving and carbon emissions reduction, great efforts have been made by developing more efficient technologies and improving the structure of feedstock. For steam cracking, energy consumption per ton ethylene has decreased from 1.07 tons of coal equivalent (tce) to 0.85 tce from year 2005 to 2015, while the value in Middle-East is 0.629 tce (Fig. 1b) [6]. The substantial difference between China and Middle-East lies in cracking material structure, which is naphtha-oriented in China while ethane-oriented in Middle-East. Meanwhile, upgrading and demonstration of several CTO projects are carried out to help reduce dependence on foreign oil. While in terms of energy saving and carbon emission, CTO might not be an appropriate way to produce ethylene, whose energy consumption and emissions are far more than steam cracking [7]. According to the national plan, ethylene production by CTO and MTO would account for more than 20% until 2020 while it is 12% in 2015 [4,5]. It can be foreseen that energy consumption and carbon emission would increase sharply and it would face great pressure for energy saving and emission reduction in the ethylene industry.

Currently, the government has introduced a series of policies to stimulate the energy saving and emission reduction in chemical industry (e.g. Petrochemical and Chemical Industry Development Plan (2016–2020) and Modern Coal Chemical Industry "13th Five-Year" Development Guide), mainly related to the chemical production structure adjustment, industrial transition and upgradation, green development and breakthrough & innovation in key technologies. Several goals have been proposed in these policies, especially, energy consumption for producing per ton ethylene with steam cracking should decrease by 3.19%[5] in 2020 compared to 2015. But in terms of the influence of existing policies on energy consumption and emissions in ethylene industry and how to achieve the proposed policy targets, it is unknown.

Consequently, this study attempts to answer two questions: (1) What's the technology roadmap to reach the goal in ethylene industry under the current national energy-saving and emission-reduction policies in China and what's the policy impacts? (2) How to achieve more sustainable development for ethylene industry in China? Considering the energy consumption and emissions for ethylene production strongly depend on the production technology, and meanwhile, the cost is the main factor influencing companies' decisions on technology deployment, this study develops a National Energy Technology (NET) model which targets each industrial process and incorporates the potential energy-saving technologies with a goal of total cost minimization under the constraint of national policy and industry development plan. Based on the sub-model NET-Chemical model, a roadmap of energy technology development in the ethylene industry are obtained to support the decision making of policy makers or enterprises for the technology deployment plan in future. Furthermore, we define a sustainable developing scenario (SDS) in this study, which can answer the potential emission reduction in the ethylene industry in China and how to achieve more sustainable development.

The following is organized as this: Section 2 is literature review. The process of ethylene production with different ways are introduced in Section 3. The NET model and NET-Chemical model, framework of technology selection, data and scenario setting are explained in Section 4. Section 5 presents the results of this study. Conclusions and policy implications are drawn in Sections 6 and 7.

2. Literature review

As an important consumer of energy consumption and emitter of greenhouse gas (GHG), industrial sectors have been a focus in terms of energy saving and emission reduction, which appeals a large number of studies. They are mostly on the sectors of iron and steel, cement and power [8,9]. While for chemical sector, as a consequence of its complex production process and data availability, less studies have been found. Especially, some studies point that data availability in chemical industry is poor and it needs to be improved [10,11].

As chemical industry is huge and complex, many studies have been carried out targeting some key chemical products which consume energy and emit CO_2 mostly and they are combined to represent the

[2] Data source: http://www.mlr.gov.cn/xwdt/jrxw/201409/t20140916_1329862.htmb

[3] Olefins include ethylene, propylene and so on. Especially, ethylene and propylene are the two most important products in olefins.

[4] It is calculated by the authors according to literatures [4,6,24,26,31–33,36], some reports and Anychem.com which has a database of coal chemical industry (http://coalchem.anychem.com/project).

[5] As a difference in statistical calibre, here the target refers to the decline ratio of energy consumption.

chemical industry in some way. For example, in addition to calculating the CO_2 emissions of the whole industry for a specific year, Zhu et al. [12] assessed the reduction potential for six key chemical products (coal based ammonia and methanol, calcium carbide and so on) till 2015 by making a policy analysis with different technological improvement rates. Similarly, Gu et al. [13] assessed the emission reduction potential for several key chemical products, including ethylene, ammonia, methanol and so on. IEA [14] made an analysis of energy and GHG reductions for catalytic process in chemical industry, which includes ethylene, propylene, ammonia and methanol and so on. To forecast the global capacity placement and CO_2 emissions for basic chemical industry, four basic chemicals (high value chemicals in which ethylene and propylene are main products, ammonia, methanol and chlorine) are chosen in reference [10]. CE-Delft [15] selected ammonia, olefins and aromatics to make analysis of breakthrough technologies in European chemical industry. To explore options towards a carbon-neutral European chemical industry, Bazzanella et al. [16] focused on the main building blocks of chemical industry including ammonia, ethylene, propylene, urea and so on.

To consider possible alternative situations of chemical industry in future under uncertainty, most studies set different scenarios in which the technology development pathways differ. Among them, many influential factors are considered. Broeren et al. [10] considered capacity retirement, energy subsidy removal and carbon pricing. Griffin et al. [11] analyzed energy use and emission reduction in different technology pathways for UK's chemical industry, whist process improvement, process substitution, fuel switching and so on are considered and differs in different pathways. While Zhu et al. [12] mainly considered the technology improvement rate in scenarios setting, using the advanced technology level to substitute the average level in future. Gu et al. [13] took the chemical industry structure, technology improvement and so on into the scenarios setting, which assumed that the technology level would reach up to international advanced in future in a specific scenario. CE-Delft [15], IEA [14] and DECEHMA [16] took the technology improvement and even some breakthrough technologies into consideration. Winyuchakrit et al. [17] made a low carbon society scenario by sectors for Thailand, and fuel switching is considered for chemical industry, in which the chemical boilers would be energized by more biomass but less coal and oil in future. Selvakkumaran et al. [18,19] analyzed the emission reduction potential of Thailand's industrial sector with different scenarios, in which the low carbon technologies, carbon tax and emission targets are analyzed respectively. Targeting the context of UK, by combining these factors to the scenarios setting, it is found that technology improvement could indeed promote emissions reduction but the potential may be limited (at most 25% in UK) even by adopting best practice technology (BPT) [10]. Accordingly, it can be seen that improving technologies and structuring feedstocks are the keys to reduce CO_2 emissions in chemical industry. Thus, we will analyze the energy saving and emission reduction of chemical industry in view of optimizing the technology selection in this study. As most studies did, we will choose the key chemical product ethylene as the research target, which is one of the most important building blocks as mentioned in part 1.

Until now, ethylene industry has attracted relatively more attention than the other chemical products. However, existing researches on ethylene are mainly related to the techno-economic analysis, which always makes an analysis on the energy performance and economic performance of certain specific technology instead of exploring the roadmap comprised of technology portfolios for the whole process of ethylene production. For instance, Xiang et al. [7] assessed the impacts of feedstock price, production scale and carbon tax on the product cost. It is found that CTO has cost advantage over oil to olefins and CTO is economic competitive although its energy efficiency is lower. Haro et al. [20] quantified the technical and economic feasibility of ethylene produced by biomass, finding that feedstock price is important to its cost-competitiveness. Besides, several studies evaluated the environmental effect of ethylene production with a perspective of life cycle analysis. Ghanta et al. [2] predict the overall environmental effects of ethylene production from naphtha, ethane and ethanol by simulation, finding that fuel burning to produce energy contributes mostly on the environment in view of cradle-to-gate life-cycle analysis. Xiang et al. [21] evaluated the energy consumption and GHG emissions for olefins from oil, coal and natural gas with life–cycle method, finding that CTO consumes more energy and emits more than others for producing per ton olefins. Chen et al. [22] investigated the eco-efficiency of ethylene produced by oil to olefins (OTO), natural gas to olefins (NTO) and CTO, it is found that NTO has the highest eco-efficiency followed by OTO, while CTO is lowest.

Although International Energy Agency (IEA) [14] conducted a research to find the roadmap for catalytic process in terms of energy saving and GHG reduction for global chemical industry, it is a product level and not enough to provide a detailed pathway for technology deployment in the process of ethylene production. In addition, the cost of technology was not considered in the report of IEA. It can be found that, few studies have assessed the energy consumption and CO_2 emissions potential and provided a roadmap for ethylene industry development in China, especially from the technology viewpoint. Technologies for ethylene production is on researching and many advanced technologies are promoted in the market. For example, in the production process of CTO, technologies of coal gasification have made great progress [23,24], and methanol to olefins tends to be mature [25]. Consequently, it is important and meaningful to provide guides for ethylene industry transition in the perspective of technology.

Accordingly, this study aims to find a technology roadmap for China's ethylene industry in order to provide instruction for its development. A bottom-up model named National Energy Technology Model (NET) is built here to make a detailed technology selection with a goal of total cost minimization. In addition to the roadmap, the energy consumption and emissions would be assessed as well and a more sustainable pathway for ethylene industry is further explored.

There are three main contributions in this study:

(1) This study enriched the evidence in the context of ethylene industry, because limited study has focused on the energy consumption, GHG emission and development pathway of ethylene industry due to the complex production process and data unavailability.
(2) This study tries to solve two realistic problems in ethylene industry and proposed some instructive policy implications, which can provide guides for development of ethylene industry in view of energy saving and emission reduction.
(3) An effective and comprehensive method called NET-Chemical is established in this research, which can output the technological pathway and corresponding environmental impacts within the constraint of technology, resource and policy. The framework of this model can also be applied to other chemical products.

3. Process of ethylene production

This section will introduce the production process of the main ethylene production ways (including steam cracking, CTO and MTO), with a focus on the energy flow and material flow.

3.1. Steam cracking

For steam cracking, with the energy input of fuel oil, LPG, steam and electricity, after the process of steam cracking, quenching, compression and olefins separation, the cracking materials can be transformed to the ethylene (Fig. 2). Cracking furnace is the main consumer of energy which could account for approximately 50%–70% of total energy use differing with cracking materials. Different materials for cracking result in different energy consumption and CO_2 emissions. The lighter the material is, the less energy will be consumed. Thus, the total energy

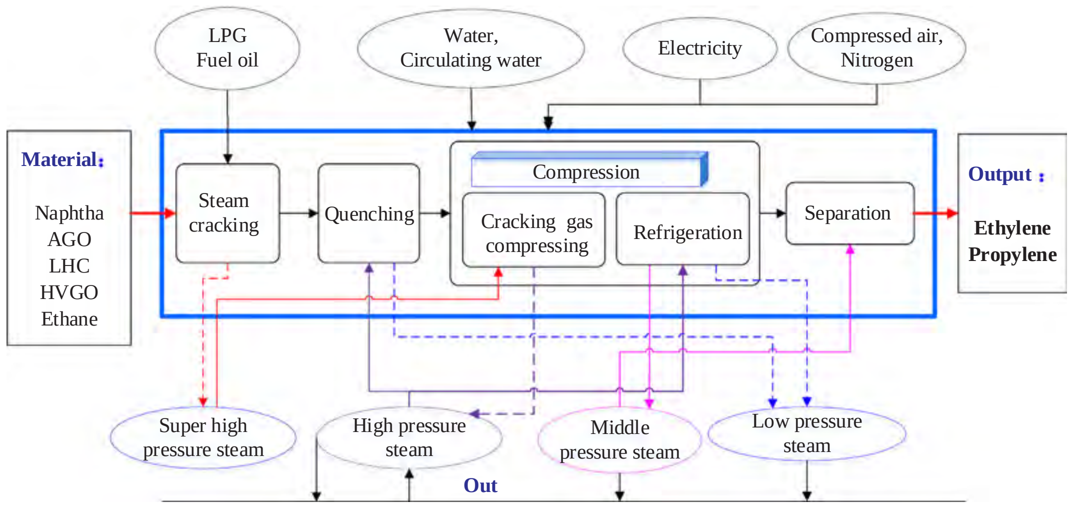


Fig. 2. The energy flow of steam cracking process.

consumption could be mainly influenced by the kinds of materials, which means that the selection of cracking material is important. In terms of cracking material, naphtha is mostly used in the world and following is ethane, which is widely used in Middle-East and North America. In China, naphtha is used mostly which accounts for over 60%, and each of atmospheric gas oil (AGO) and light hydrocarbon (LHC) accounts for about 18%, and hydrogenated tail oil (HVGO) accounts for about 3% in 2015 [26].

3.2. CTO and MTO

CTO is commercialized only in China and its process can be divided into coal to methanol and methanol to olefins. In the process of coal to methanol, with the energy input of fuel coal, steam and electricity, after going through coal gasification, transformation and purification of crude gas and methanol synthesis, material coal can be produced into methanol. Ethylene is further produced after methanol synthesis and olefins separation (Fig. 3).

The process after methanol synthesis is regarded as methanol to olefins (MTO). MTO can also be an independent process, which indicates its material methanol could be produced by other domestic projects or imported form international market. As the process occurring in China will demand energy and generate CO_2 emissions within China, the projects whose material purchased domestic are considered as CTO. Thus, in this study, CTO not only includes coal to olefin projects, but also includes methanol to olefin projects whose methanol is produced inside China. While MTO only refers to methanol to olefin projects whose material is imported from other countries.

4. Methodology

4.1. National Energy Technology (NET) model

Considering the government, industries and consumers make their decisions on industrial production or technology selection mainly following the principle of cost minimization constrained by some national and industrial regulations, a National Energy Technology (NET) model is developed to describe the technology selection behavior during the process of industrial production or consumer decision.

NET model is a bottom-up model developed by CEEP-BIT (the Center for Energy & Environmental Policy Research, Beijing Institute of Technology). NET model includes eight sub-models in terms of sectors: Iron and Steel (NET-IS), Cement (NET-Cement), Power (NET-Power), Chemical (NET-Chemical), Transport (NET-Transport), Residential (NET-Residential), Commercial Building (NET-Building) and Other (NET-Other) (Fig. 4). NET-Chemical is used in this study to make a research on ethylene, which takes various factors into account, such as ethylene demand, national policy and industry development, input materials, potential energy-saving technologies, energy consumption, carbon emissions, production cost and so on.

The framework of NET-Chemical model is shown in Fig. 5, including Data module, Service demand projection module, Technology-Energy-Environmental model, Green policy module and Output module. Data module is the basis, which is consisted of the parameters of chemical devices, materials and energy consumption in the base year, energy price, emission factors and so on. With the socio-economic development, national plan and chemical industry policy, the demand for

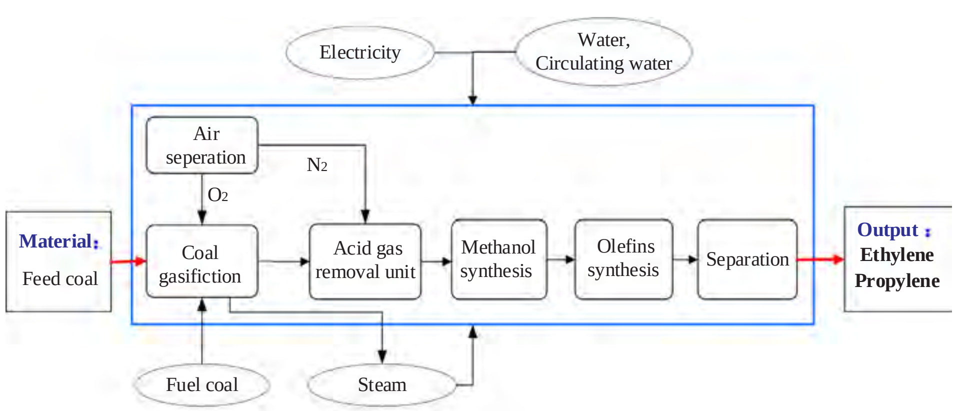


Fig. 3. The schematic diagram of CTO&MTO.

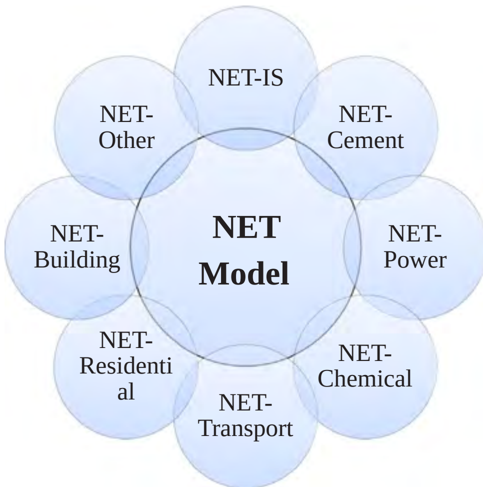


Fig. 4. Sub-models of NET model.

various chemical products can be projected by Service demand projection module. Meanwhile, by designing policy scenarios, the Green policy module can transfer policies into parameters which suit for NET-Chemical model. Under the constraint of future product demand and policy trends, Technology-Energy-Environmental model which is the core of NET-Chemical model, simulates the material and energy flows during the process of chemical industrial production and selects a combination of technologies for each process with a goal of total cost minimization. The technology roadmap can be finally obtained as well as the required investment cost. The energy consumption by fuel by products and emissions can be calculated accordingly.

The main energy-consuming devices in the industrial process for producing chemical products are included in NET-Chemical model. In terms of ethylene, it includes the process of steam cracking, CTO and MTO. In NET-Chemical model, the objective is to minimize the total annual cost during the whole production process, including annualized initial investment cost, operation and maintenance cost, energy cost, energy tax and emission tax, as shown in Eq. (1). When seeking solutions with the goal of total cost minimization, parameters in the objective function are constrained by Eqs. (2)-(15) and definition of the involved parameters are list in Table 1.

Objective function:

$$TC_t = \sum_l (AC_{l,t}\cdot R_{l,t} + OM_{l,t}\cdot H_{l,t} + \sum_k p_{k,t}\cdot Eg_{k,t}) + Eg_t\cdot Tax_t^{Ene} + Q_t\cdot Tax_t^{CO_2} \quad (1)$$

Subject to:

$$AC_{l,t} = C_l^0\cdot\frac{\alpha(1+\alpha)^{T_l}}{(1+\alpha)^{T_l}-1} \quad (2)$$

$$H_{l,t} = H_{l,t}^{group}\cdot Pr_{l,t} \quad (3)$$

$$S_{l,t} = S_{l,t-1}\cdot\left(1-\frac{1}{T_l}\right) + R_{l,t}-G_{l,t} \quad (4)$$

$$Eg_{k,t} = \sum_l \{(1-\lambda_{k,l,t})\cdot E_{k,l,t}\cdot H_{l,t}\} \quad (5)$$

$$Eg_t = \sum_k (Eg_{k,t}\cdot\mu_k) \quad (6)$$

$$Q_t = \sum_l \{H_{l,t}\cdot(q_{l,t}^{prcs} + q_{l,t}^{cmbt})\cdot ER_l\} + Q_t^{indr} \quad (7)$$

$$q_{l,t}^{cmbt} = \sum_k \{q_{k,l,t}^{cmbt0}\cdot E_{k,l,t}\cdot(1-\lambda_{k,l,t})\cdot\eta_{k,l}\} \quad (8)$$

$$Y_t = D_{t-1}\cdot(1+r)\cdot SS_t \quad (9)$$

$$0 \leqslant H_{l,t}^0 \leqslant H_{l,t} \leqslant S_{l,t} \quad (10)$$

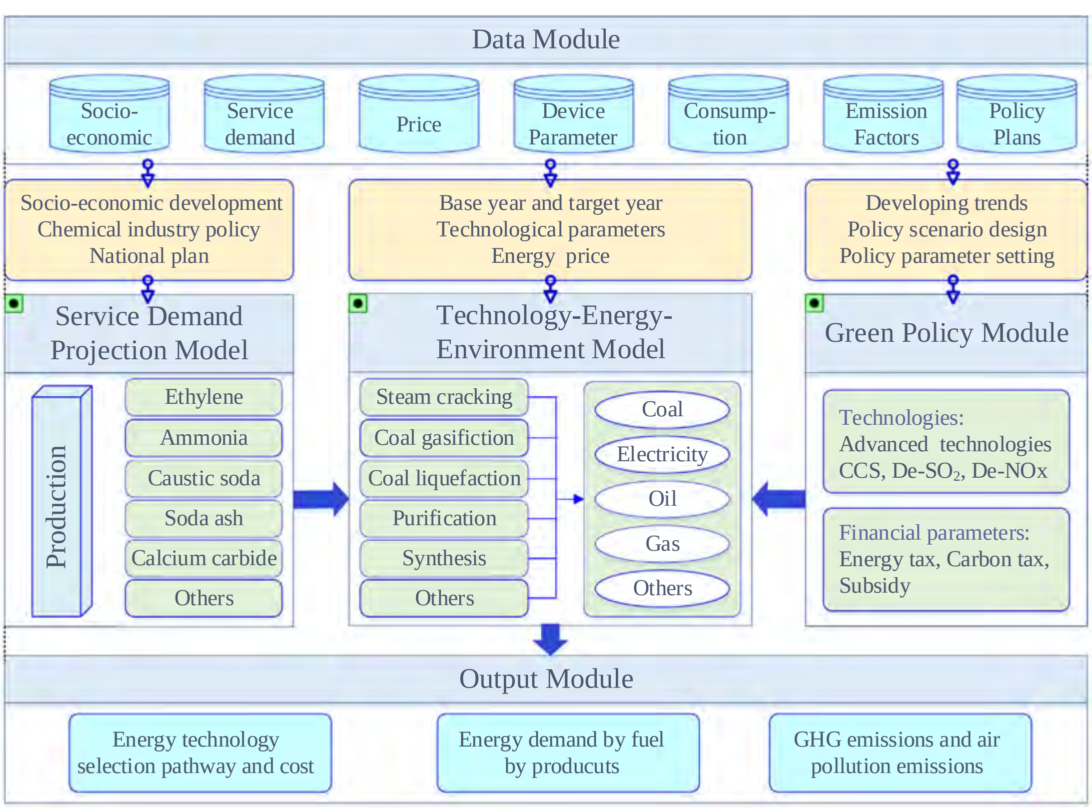


Fig. 5. Framework of NET-Chemical model.

Table 1
Parameters in NET-Chemical model.

Parameters	Definitions
k	The type of fuel, for example fuel oil, coal, LPG and so on
l	The type of device, which also represents a kind of technology
t	Year in the planning horizon, here $t \in$ [2015, 2030]
TC_t	Total cost in year t
$AC_{l,t}$	Annualized initial cost of device l in year t
$R_{l,t}$	Recruited quantity of device l in year t
$OM_{l,t}$	Operation and maintenance cost for per unit device use in year t
$H_{l,t}$	Operating quantity of device l to satisfy its service in year t
$p_{k,t}$	The price of per unit fuel type k in year t
$Eg_{k,t}$	Energy consumption of energy k in year t
Eg_t	The total energy consumption for ethylene production in year t
Tax_t^{Ene}	Tax levied on unit energy consumption in year t
Q_t	Total quantity of CO_2 emissions generated during ethylene production in year t
$Tax_t^{CO_2}$	Tax levied on unit CO_2 emissions in year t
C_l^0	Total initial cost of all devices
α	Discount rate of investments for chemical industry
T_l	Lifetime of device l
$H_{l,t}^{group}$	Total operating quantity of all devices to satisfy a specific service in year t
$Pr_{l,t}$	Penetration rate of device l in all devices competing with it in year t
$S_{l,t}$	Stock of device l in year t
$S_{l,t-1}$	Stock of device l in year *t-1*
$G_{l,t}$	Retired quantity of device l in year t
$\lambda_{k,l,t}$	Energy saving ratio due to efficiency improvement in use of energy k by device l in year t
$E_{k,l,t}$	Energy use of fuel k per operating unit of device l in year t
μ_k	The coefficient for converting energy k to coal equivalent value
$q_{l,t}^{prcs}$	Non-energy related emissions generated during the production process in year t (e.g. emission from the physical and chemical reactions of production material)
$q_{l,t}^{cmbt}$	Emissions from combustion of energy k per unit use of device l in year t
ER_l	The emission rate of CO_2 from device l, which depends on whether removal devices for absorbing emissions existing in the production process of chemical industry
$q_{k,l,t}^{cmbt0}$	Emissions from complete combustion of energy k per unit use of device l in year t
Q_t^{indr}	Indirect emissions generated by purchased electricity and steam in year t
$\eta_{k,l}$	The burning rate of energy k for device l
Y_t	Ethylene yield in year t
D_{t-1}	Ethylene equivalent demand in year *t-1*
r	The growth rate of ethylene equivalent
SS_t	The self-sufficiency in year t
$H_{l,t}^0$	The theoretical amount of device l to satisfy the basic demand of its production (e.g. the amount of ethylene, methanol and so on) in year t
$Pr_{l,t}^L$	Lower limits of penetration rate for device l in year t
$Pr_{l,t}^U$	Upper limits of penetration rate for device l in year t
$Pr_{l,t}^{U0}$	Upper limits of penetration rate for device l which will be eliminated by policies in year t
$Pr_{l,base}$	Penetration rate for device l in base year
$Pr_{l,t}^{L0}$	Lower limits of penetration rate for device l which will be promoted by policies in year t

$$0 \leqslant Pr_{l,t}^L \leqslant Pr_{l,t} \leqslant Pr_{l,t}^U \leqslant 100\% \tag{11}$$

$$0 \leqslant \lambda_{k,l,t}, ER_l, \eta_{k,l} \leqslant 100\% \tag{12}$$

$$Pr_{l,t}^{U0} \leqslant Pr_{l,base} \tag{13}$$

$$Pr_{l,t}^{L0} \geqslant Pr_{l,base} \tag{14}$$

$$AC_{l,t}, R_{l,t}, G_{l,t}, p_{k,t}, E_{k,l,t}, Eg_{k,t}, Eg_t, Tax_t^{Ene}, Q_t, Tax_t^{CO_2} \geqslant 0 \tag{15}$$

The total initial investment cost for each device are annualized across the life span [27] following Eq. (2). The operating quantity or capacity of device l ($H_{l,t}$) is determined by the total amount of all devices competing with it ($H_{l,t}^{group}$) and its penetration rate ($Pr_{l,t}$) in all, shown in Eq. (3). To make sure the operating quantity satisfying its production demand, $H_{l,t}$ should be grater or equal to the theoretical amount of device l ($H_{l,t}^0$) to satisfy the basic demand of its production in the study year (Eq. (10)). Meanwhile, as a limited resource, it cannot excess its stock ($S_{l,t}$) in that year (Eq. (10)). For each device or technology, its penetration rate ($Pr_{l,t}$) is constrained by lower ($Pr_{l,t}^L$) and upper limits ($Pr_{l,t}^U$) based on national policies and its development trial so as to make the technology selection more practical (Eq. (11)).

The parameter stock ($S_{l,t}$) in this study means the max production ability of that device in terms of its capacity and resource. It is dynamically determined by the stock of this device in the previous year ($S_{l,t-1}$), recruited quantity in the study year ($R_{l,t}$) and retired quantity ($G_{l,t}$), shown in Eq. (4). Its quantity will obviously influence the production capacity and total initial cost.

Total quantity of energy consumption (Eg_t) is estimated by Eq. (5) and Eq. (6), which sum up the consumption of all kinds of energy from all devices. To make it easier to compare the energy consumption of different years and different processes, we convert all of energy into coal equivalent. Energy refers to fuel oil, LPG, electricity, coal and different kinds of steam in this study.

Similar to the calculation of energy consumption, the total quantity of CO_2 emissions (Q_t) is estimated by Eq. (7), which is consisted of process emissions ($q_{l,t}^{prcs}$) and combustion emissions ($q_{l,t}^{cmbt}$) and indirect emissions (Q_t^{indr}). Especially, indirect emissions (Q_t^{indr}) in this study refers to emissions generated by electricity and steam production, which is calculated by their emission factors and quantity. Combustion emissions ($q_{l,t}^{cmbt}$) is calculated by Eq. (8), in which energy type k excludes electricity and steam.

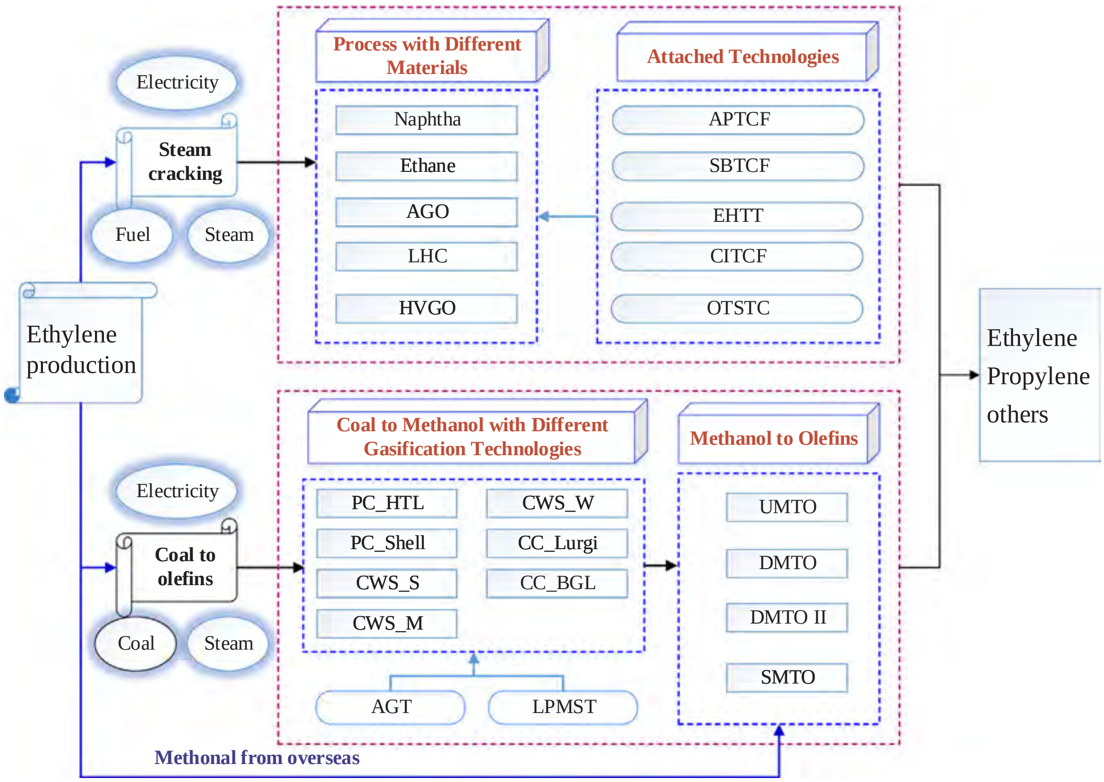
The energy consumption, emissions and cost strongly depend on the future demand for chemical products. Hence, meeting the future demand is set as a main constraint in NET-Chemical model. Ethylene yield normally comes from domestic production and import from overseas. Consequently, we specifically incorporate the self-sufficiency of ethylene yield as an instrument here. Considering the equivalent demand in previous year (D_{t-1}) and its growth rate (r) and self-sufficiency (SS_t), ethylene yield (Y_t) is calculated dynamically by Eq. (9).

For technologies or devices eliminated by policies in future, its upper limit penetration rate ($Pr_{l,t}^{U0}$) should not be larger than that in base year ($Pr_{l,base}$) (Eq. (13)). While for those promoted by policies in future, its lower limit penetration rate ($Pr_{l,t}^{L0}$) should not be less than that in base year ($Pr_{l,base}$) (Eq. (14)). Besides, some parameters like energy saving ratio ($\lambda_{k,l,t}$), emission rate from device l (ER_l) and burning rate of energy k ($\eta_{k,l}$) are between 0 and 100% (Eq. (12)) and some others need to be positive so as to make sense (Eq. (15)).

4.2. Framework of technology selection in ethylene industry

A three-level technology selection criterial is designed in this study, shown in Fig. 6. As the capacity of CPP only accounts for 2%, it would not be considered here. In this framework, several key processes which consume substantial energy and attached technologies which could save energy potentially are considered, while others are not but their cost and energy consumption are all considered in this model. In this study, the industrial process of steam cracking with different cracking materials, coal to methanol with different gasification technologies, methanol to olefins and several attached technologies are simulated.

The first level can be regarded as the mode structure selection of ethylene production, in which different producing ways are selected from steam cracking, CTO and MTO. In the second level, under the selected producing way, various basic technologies which are essential for the production will be selected according to their costs and future plan on the technology promotion (e.g. different technologies of cracking materials, gasification and methanol to olefins). All of technologies could have influence on energy consumption and carbon emission directly or indirectly. In the construction of framework, all of



APTCF: Air preheating technology of cracking furnace
SBTCF: Soot blowing technology of cracking furnace
EHTT: Enhanced heat transfer technology
CITCF: Coke inhibition technology of cracking furnace
OTSTC: Optimization technology of steam turbine compression
PC_HTL: Pulverized coal gasification with Hangtian technology,
PC_Shell: Pulverized coal gasification developed by Shell,
CC_Lurgi: Crushed coal gasification developed by Lurgi
CC_BGL: Crushed coal gasification which is joint developed by British Gas and Lurgi (BGL)
CWS_W: Coal-water slurry water wall gasification
CWS_S: Coal-water slurry gasification technology with opposed single-burner
CWS_M: Coal-water slurry gasification technology with opposed multi-burner
LPMST: Low pressure methanol synthesis technology (New generation).
AGT: Advanced gasification technology
UMTO: Methanol to olefins process developed by Universal Oil Product Company (UOP).
SMTO: Methanol to olefins process developed by Sinopec
DMTO: Dimethyl ether/methanol to olefins developed by Dalian Institute of Chemical Physics
DMTO II: Second generation of DMTO

Fig. 6. The framework of energy technology selection in NET model.

processes are simplified and combined to several main processes. For these processes, a series of technologies make a difference in energy consumption and can compete with each other or be replaced by others. On basis of the second level, the third level considers the attached technologies which are emerging or promoted recently, as its commercialization could bring more reductions of energy consumption and CO_2 emissions [28]. Different with technologies in the second level, attached technologies are auxiliary production technologies, which mean that the users could choose whether to install them or not.

Different cracking materials could make a difference in production costs significantly [29] and it differs in energy consumption and CO_2 emissions. Thus, technologies in steam cracking are classified by cracking materials in this study, including naphtha, ethane, LHC, AGO and HVGO. Actually, LHC is a kind of mixture which may contain a small proportion of ethane. While in this framework, the difference between LHC and ethane lies in whether ethane is the main component and the only cracking material in steam cracking process. Here, the technology of ethane refers to the equipment taking ethane as the only cracking material. Besides, ethane is a type of clean cracking material and is added into the selection as a potential material although it has not been promoted in China. In detailed production process, five attached technologies (air preheating technology of cracking furnace, soot blowing technology of cracking furnace, enhanced heat transfer technology, coke inhibition technology of cracking furnace and optimization technology of steam turbine compression) which have not been widely used in steam cracking are included as alternatives in the technology choice set. Four of them could be used to improve energy efficiency of cracking furnace and one is used to improve energy efficiency of compressor.

Coal gasification is one of the most important processes in coal to methanol, which can be divided into coal water slurry gasification technology, pulverized coal gasification technology and crushed coal gasification technology in terms of the form of feedstock and each one contains detailed technologies. In process of methanol to olefin, the technology developed by Sinopec (SMTO), technology developed by Dalian Institute of Chemical Physics (DMTO) and its second generation (DMTO II) have realized localization. DMTO II is upgraded on basis of DMTO, which could reduce 10% of methanol usage than DMTO when producing the same quantity of ethylene[6]. There is no doubt that it is more efficient.

4.3. Data and basic parameters

This study targets the ethylene industry in China and will make a discussion about the three main ways for ethylene production, including steam cracking, CTO and MTO. Time span starts from year 2015 and ends in 2030, which covers the 13th, 14th and 15th Five-Year plan of China. Discount rate is set as 10% [1]. The economic life span of chemical producing equipment is generally considered as 10–20 years [30] and 15 years is chosen in this study. For steam cracking, the investment of equipment and energy consumption differ in producing the same quantity of ethylene with different feed stocks. Its parameters are shown in Table 2. The attached technologies and its energy saving potential are from [31,32]. Parameters of coal to methanol are shown in Table 3.

For CTO and MTO, the share of a specific technology is defined as how much its capacity accounts for in the total capacity, which is between 0 and 100%. In this study, these values are processed and calculated according to the database of anychem.com[7].

The energy and raw material prices adopted here are the average prices in 2015. CO_2 emission factor is calculated by low calorific value, carbon oxidation rate and so on, shown in Table 4. Need to mention that, the new capacity additions of electricity will be more and more contributed by non-fossil fuel power plants in future [38], indicating that the emissions emitted for generating one unit of electricity may change with the energy structure change of electricity generation. Consequently, emission factor and energy intensity of electricity used in this study are obtained from NET-Power model which considered the energy structure change of electricity generation under the existing policy plans.

It is projected that China's ethylene yield would increase to 30 million tons [5] and the ethylene equivalent would be 48 million tons in 2020 [4], which means that the self-sufficiency would be 62.5% in 2020 for China. During year 2021–2030, we assume that the self-sufficiency would be the same as 2020, and the growth in ethylene equivalent would be commensurate with the period between 2016 and 2020. Linear growth for ethylene yield is assumed in this study. Some other basic data is shown in Tables A2–A5 in Appendix.

4.4. Scenarios setting

To portray the future pictures for the ethylene industry in China, two scenarios are designed here, including business as usual scenario (BAU) and sustainable development scenario (SDS). BAU is for exploring a roadmap for China's ethylene industry, in which the industry would develop normally following the current policies and trends. While SDS is set for exploring a more sustainable pathway for the ethylene industry with less burden on the environment compared to BAU. In both of these two scenarios, attached technologies with less energy consumption and low carbon emission would be recruited and low-efficiency technologies would be replaced. But the technology penetration rate differs in these two scenarios.

In BAU, for steam cracking, four main types of materials are considered: naphtha, AGO, LHC and HVGO; and they would compete with each other in the market. Light cracking materials are promoted in future [4]. Thus, the share of AGO and HVGO would decrease in future steadily. Revolution of shale gas in north America has stimulated ethane as cracking material [2]. China has settled down to construct equipment with ethane to produce ethylene, which is planned in Caofeidian Industrial Zone in Hebei province. This study assumes that ethane would be used as cracking material after 2020 and its max share in steam cracking would not exceed 10% in 2025 and 20% in 2030 according to the estimated capacity.

CTO and MTO are considered as an alternative way to produce ethylene and its share would be more than 20% in total ethylene yield in 2020 [5]. For CTO projects, existing policies proposed that coal-water slurry gasification and pulverized coal gasification need to be researched deeply and promoted in future [4,5]. For the process of

Table 2
Parameters of producing one-ton ethylene with five different cracking materials in steam cracking.

Material	Feedstock/t[a]	Ratio factors (%)	
		Investment of equipment[b]	Energy consumption [c]
Naphtha	3.18	100	100
Ethane	1.3	81	70.4
AGO	3.79	115	116
LHC	2.38	93	79.4
HVGO	3.4	105	105

[a] The data of feedstock is from [33].
[b] The equipment investment of cracking naphtha is from [34] and ethane is from [34–36]. Naphtha is taken as a benchmark 100%, the values of AGO, LHC and HVGO are calculated by the relevant ratio factors.
[c] Energy consumption of naphtha and ethane are from [6]. Energy consumption of naphtha is taken as a benchmark 100%, the values of AGO, LHV and HVGO are calculated based on relative ratios according to [36].

Table 3
Parameters of coal to methanol with different gasification technologies.

Technology	Ratio factors (%)	
	Investment of equipment	Energy consumption
PC_HTL	110	93.8
PC_Shell	120	90.6
CWS_S	100	100
CWS_M	100	98.8
CWS_W	93.3	101.3
CC_Lurgi	100	90.6
CC_BGL	110	84.4

Data Source: The ratio factors are calculated by the authors according to [24]. Investment of coal-water slurry gasification technology with opposed single-burner (CWS_S) is from [37] and it is taken as the benchmark. Investment of other technologies are calculated with their ratio factors. Energy consumption for producing per ton methanol with different gasification technologies are set according to [24].

Table 4
Emission factors of different kinds of energy.

Energy type	Emission factor (t CO_2/tce)
Coal	2.6604
Fuel oil	2.2100
LPG	1.8091
Steam	2.4600
Electricity	2.4413 in 2015 and 2.3492 in 2030[c]

[c] Emission factor of electricity is from NET-Power model which is a sub-model of NET. This value is for the whole China, which includes all kinds of ways to produce electricity (e.g. thermal power, hydropower, wind power and so on).

[6] Data source: Deutsche Bank Markets Research-China's Coal to Olefins Industry, 2014
[7] Anychem.com has a database of coal chemical industry, and the shares of different technologies are processed and calculated based on it (http://coalchem.anychem.com/project).

Table 5
Major differences between BAU and SDS.

	BAU	SDS
1st level (Production mode)	CTO&MTO is supposed to account for more than 20% in 2020 according to the policy. After 2020, its production would account for more than 25% in 2025 and 30% in 2030, respectively	Share of CTO&MTO is supposed to increase from 12% to 20% in 2020. After 2020, the growth will slow down. It could still be developed but with its share not excessing 20%
2nd level (Production process)	Maximum share of technologies encouraged by policies will increase steadily, and minimum share of other technologies would decrease **Steam cracking**: cracking material tends to be lighter. LHC and ethane will account more **Coal to methanol**: coal-water slurry gasification and pulverized coal gasification are encouraged in future **Methanol to olefins:** DMTO-II is encouraged and DMTO will be replaced	For energy efficient technologies, the maximum share is set as 10% larger than that in BAU For energy inefficient technologies, the minimum share is set as 10% less than that in BAU
3rd level (Attached technology)	According to its historical diffusion rate	The maximum share is set as 10% larger than that in BAU

methanol to olefins, technology DMTO-II has been developed successfully and it is possible to be widely used in future. For technologies that have not been promoted, for example, enhanced heat transfer technologies, it is assumed that the ratio of its promotion increases 10%–20% every five-year based on its development and cost change.

To make a deep discussion, we also consider a sustainable developing scenario (SDS) based on BAU. The major differences between these two scenarios lie in the production structure and promotion of attached technologies, shown in Table 5. According to current policies, CTO and MTO will be promoted during the period of 13th Five-Year (2016–2020). BAU would continue this trend and keep the share of CTO and MTO rising during 2021 to 2030. While in SDS, considering the heavier burden of CTO and MTO on the environment, we limited the penetration of CTO and MTO after 2020, with the share being commensurate with that in 2020 so as to slow down the growth of CO_2 emissions in the ethylene industry. Limiting the share of CTO and MTO does not mean hindering their proper development. Its yield and capacity will increase with the total yield increasing. It should be noted that, when a technology is encouraged or limited according to the policies, its development potential becomes larger or smaller. For all technologies, their shares are derived by technology selection under the defined constraints via NET-Chemical model.

5. Result analysis and discussion

In this section, we will introduce the results related to ethylene demand projection, the technology selection, the corresponding energy consumption and CO_2 emissions obtained from NET-Chemical model under BAU and SDS scenarios.

5.1. Ethylene demand and production structure

As shown in Fig. 7, production of ethylene would keep rising in future, which would reach to 30 million tons in year 2020 and 42.7million tons in 2030. The total quantity of ethylene is the same in BAU and SDS, while their structures of producing ways make a difference. Actually, the structure of production is the first level selection in NET-Chemical model. Following the existing national and industrial plans, the model results show that to minimize the total cost, steam cracking is likely to be replaced by CTO&MTO in BAU, with the share in total production decreasing from 88% to 70.9% during 2015 to 2030. While share of CTO will increase steadily from 6.5% to 20% and maintain at about 20%, and share of MTO will increase from 5.5% to 12.0% firstly and then drop to 9.0%. In contrast, the proportion of these three production ways are more stable in SDS, which would maintain at about 80%, 14.5% and 5.5% after 2020 for steam cracking, CTO and MTO, respectively. CTO, as a national strategy to accelerate the transformation of coal consumption, it is promoted as usual in BAU. While in SDS, it is promoted with a limitation on its production capacity so as to get a more sustainable producing pathway.

5.2. Roadmap for China's ethylene industry under current policy target

5.2.1. Technology selection

To meet the ethylene demand and the existing policy targets, technology development path of ethylene production is obtained on the basis of total cost minimization. Fig. 8 displays the second level selection, which includes the proportion of different materials or technologies in the process of steam cracking and gasification. Fig. 8(a) shows that cracking material tends to be lighter. As a light cracking material, ethane would be promoted in China in future, whose share would gradually increase to 7.0% and 14.6% in 2025 and 2030 from zero, respectively. Light hydrocarbon (LHC) will slowly increase to 28.2% in 2030. While as heavier materials, naphtha, AGO and HVGO will account for less and less. Selection of gasification technologies is showed in Fig. 8(b). Coal-water slurry gasification (including technologies CWS_W, CWS_S and CWS_M) and pulverized coal gasification (including technologies PC_HTL and PC_Shell) may reach up to 90%. This is

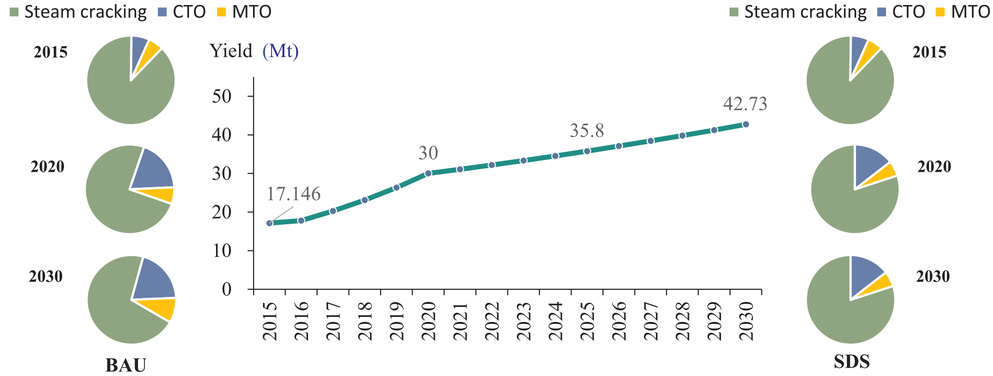
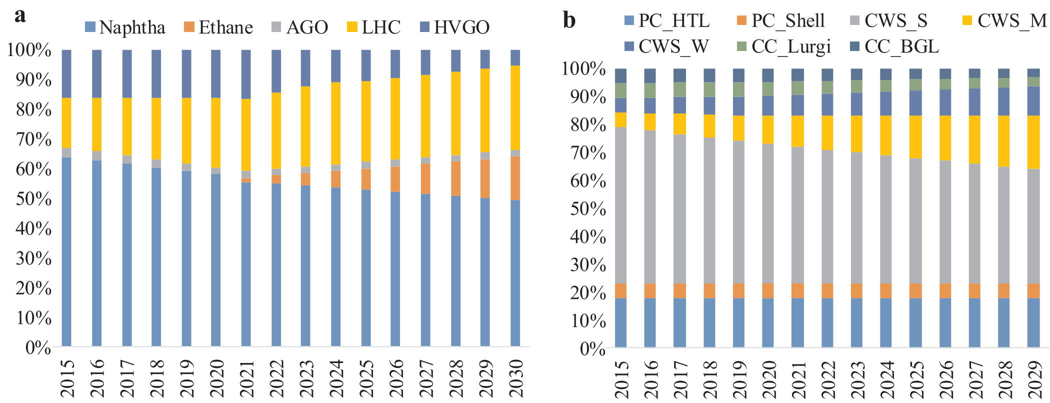


Fig. 7. Projected ethylene yield in BAU and SDS.



(a) Technology share of cracking material (b) Technology share of coal gasification

Fig. 8. Technology development pathway of key production processes in BAU.

consistent with the national plan, in which the coal-water slurry gasification and pulverized coal gasification with large scale are encouraged to be researched and developed [4,5].

The third level of attached technology selection is shown in Fig. 9. According to their development scenario and the total cost minimization, they will have different development pathways. Air preheating technology of cracking furnace is easily to be promoted in future and almost all of steam cracking equipment will install this technology by 2030. It is similar to soot blowing technology of cracking furnace, whose penetrate rate could reach 80% in 2030. Optimization technology of steam turbine compression, advanced gasification technology and low pressure methanol synthesis technology have similar trend of penetration, which are developed slowly in the first five years (2016–2020) but a little faster in the next two five years (2021–2030). Penetration rate of coke inhibition technology of cracking furnace will not keep at 40% till 2030. This is mainly because it consumes a large amount of expensive chemical reagents, which results in a too high operating and maintenance cost to have advantage over others. While, the fixed share does not mean there is no newly recruited capacity of this technology after 2015.

5.2.2. Energy consumption

With more efficient technologies and lighter cracking materials of steam cracking being selected in this roadmap, it needs less energy input for producing per ton ethylene (Fig. 10). For steam cracking, with

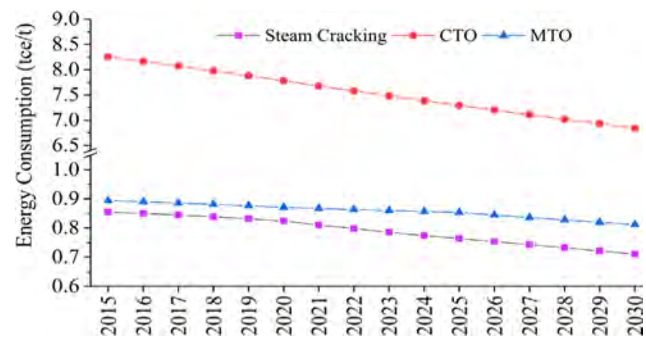


Fig. 10. Energy consumption for producing per ton ethylene with different ways in BAU.

share of ethane and light hydrocarbon increasing steadily to replace heavier materials, and technologies like enhanced heat transfer technologies being promoted, the energy consumption for producing one-ton ethylene would decrease from 0.854 tce/t in 2015 to 0.824 tce/t in 2020 and 0.711 tce/t in year 2030. Following this path, the energy consumption for producing per ton ethylene will be decreased by 3.53% in 2020 compared to the value in 2015. This improvement is able to meet the target of national plan which proposed that the energy consumption per ton ethylene should decrease by 3.19% in 2020 compared

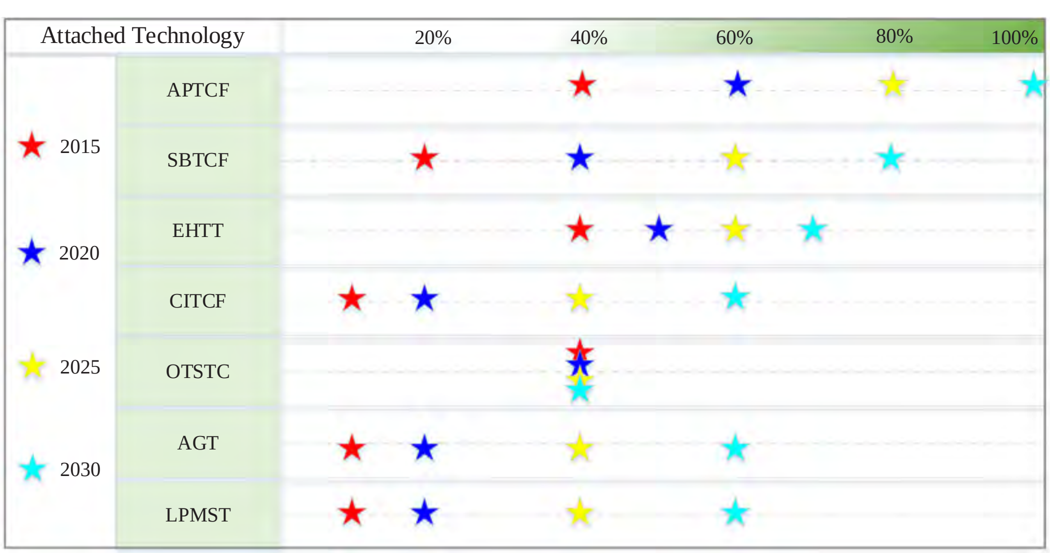


Fig. 9. Technology selection of attached technologies in different years in BAU.

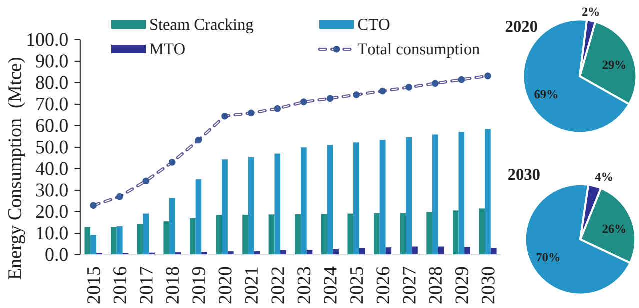


Fig. 11. Total energy consumption in BAU.

to 2015. While for CTO, although energy consumption is larger than that of the other two ways, it would be more efficient in future, for which energy consumption is likely to decrease from 8.26 tce/t in 2015 to 7.78 tce/t in year 2025 and 6.84 tce/t in year 2030 for producing one-ton ethylene. This benefits from the wider use of Coal-water slurry gasification technology and the promotion of advanced gasification technology and low-pressure methanol synthesis technology. While for MTO process, the energy consumption will decrease slower than the other two, from 0.89 tce/t in 2015 to 0.87 tce/t in year 2020 and 0.81/t tce in year 2030 for producing one-ton ethylene. This is mainly because methanol is purchased from overseas countries directly, which do not need to consume energy to produce methanol in China.

Although cracking materials and technologies tend to be energy efficient, the rapid growth of ethylene yield contributes to the growth of total energy consumption (Fig. 11). Total energy consumption will increase rapidly from 22.9 million tce (Mtce) to 64.5 Mtce during year 2016 to 2020 and then slow down from 65.9 Mtce to 83.2 Mtce during year 2021 to 2030. In terms of producing structure, energy consumption of all three ways keep rising in this period at an annual speed of 3.7%, 11.2% and 9.6% respectively for steam cracking, CTO and MTO. Although the ethylene share of CTO process is less than 20%, it contributes most of the energy consumption, which accounts for about 70% of total consumption in year 2020 and 2030. Steam cracking contributes 29% and 26% in the total consumption in 2020 and 2030. As a reason of lower yield and lower energy input, MTO process only contributes 2%–4% of the total energy consumption.

5.2.3. CO_2 emissions

Similar to energy consumption, with the improvement of technologies and less energy input for producing per ton ethylene, the carbon emissions of ethylene will accordingly decrease year by year (Fig. 12a). During year 2015–2030, CO_2 emissions for producing one-ton ethylene would decrease form 1.94 ton/t to 1.59 ton/t for steam cracking, from 17.97 ton/t to 15.30 ton/t for CTO process and from 2.09 ton/t to 1.93 ton/t for MTO.

With the growth of ethylene yield and total energy consumption, total CO_2 emissions would increase sharply from 51.3 million tons (Mt) in year 2015 to 186.5 Mt in year 2020 attributing to the increment of CTO. After year 2020, as the yield of CTO slows down, total CO_2 emissions of China's ethylene industry increases at a rate a 2% annually (Fig. 12b). CTO process contributes more than 68% of total CO_2 emissions after year 2020, while this value is about 40% in year 2015.

5.3. Pathway for achieving a more sustainable ethylene industry on the basis of existing policies

In the sustainable development scenario, advanced technologies will be promoted more than in BAU in future, and the development of CTO&MTO would slow down. In this section, we will firstly discuss how much energy could be saved and emissions could be reduced in future if more sustainable strategy is applied for China's ethylene industry, and then show the pathway to achieve the strategy.

5.3.1. Energy consumption and CO_2 emissions in SDS

On the basis of BAU, large energy saving and carbon emissions reduction can be derived in SDS, which is shown in Fig. 13. The quantity of energy saving and emissions reduction increase year by year in SDS. Accordingly, it could reduce the energy consumption and CO_2 emissions effectively in SDS. In the sustainable development scenario, energy saving would reach 10.8 Mtce, 14.5 Mtce and 16.7 Mtce in year 2020, 2025 and 2030, respectively. Cumulative amount of energy consumption will be saved by 13.2%, 18.5% and 19.7% during 2016 to 2020, 2021 to 2025 and 2026 to 2030, respectively compared to the energy consumption in BAU. As a consequence, the total CO_2 emissions reduction would reach 23.3 Mt, 31.8 Mt and 37.1 Mt in year 2020, 2025 and 2030 in SDS, respectively.

Concerning the details, because ethylene yield produced by steam cracking is larger in SDS than in BAU, although more advanced technologies would be used in SDS, the total amount of energy consumption and carbon emissions by steam cracking are larger than that in BAU, which results in the total energy saving and emission reduction showing negative in Fig. 13. While as shares of CTO and MTO are smaller than in BAU, they would contribute for more energy saving and emissions reduction.

5.3.2. Technology development path in SDS

Figs. 14 and 15 show the second and third level of technology selection in SDS to achieve the reduction of energy and emissions as mentioned in Section 5.3.1. The main difference between these two scenarios lies in the penetration rate of technologies with lower energy consumption and emissions. In the second level, steam cracking with material ethane and LHC need to be additionally promoted by about 2%

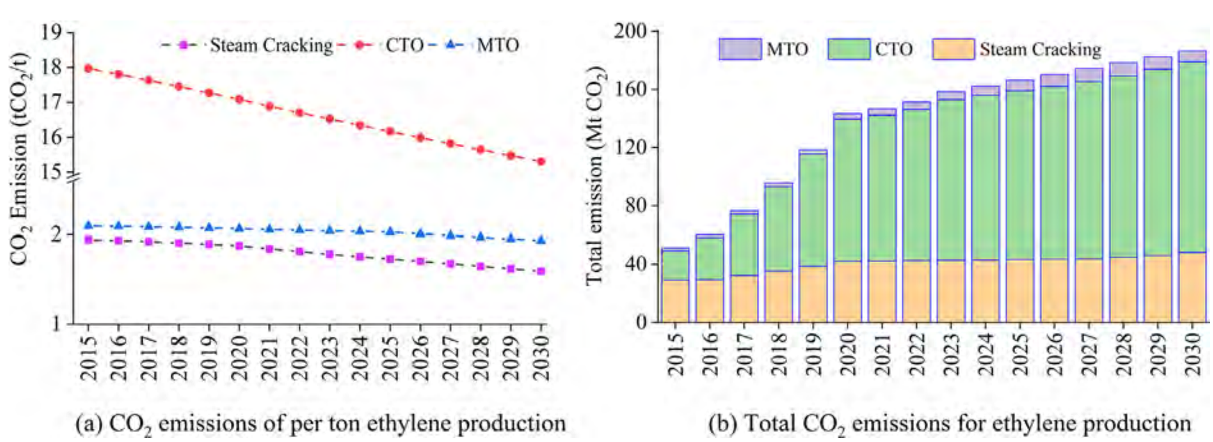


Fig. 12. CO_2 emissions for ethylene production in BAU.

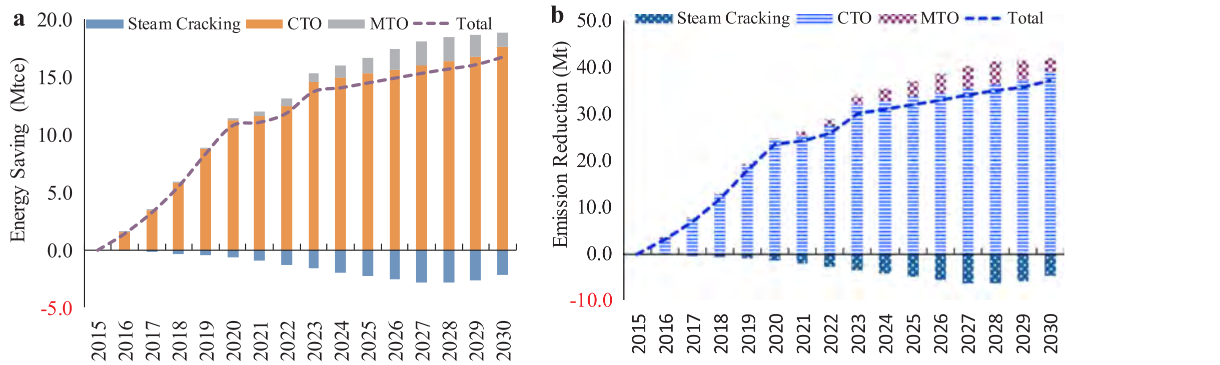


Fig. 13. Energy saving and CO_2 emissions reduction for ethylene production in SDS compared to BAU. Note: Negative value in the axis means the energy consumption and emissions in SDS are larger than that in BAU, resulting negative energy saving and emission reduction.

and 4% respectively compared to the share in BAU (Fig. 14a). For coal to methanol, there are only slight changes between BAU and SDS (Fig. 14b).

In the third level of technology selection, except for Air preheating technology of cracking furnace and coke inhibition technology, almost all of the attached technologies would be promoted by another 10% after 2020 in SDS than in BAU (Fig. 15). It can be seen that the coke inhibition technology of cracking furnace would keep at 40% in SDS caused by the high cost in operation and maintenance.

Actually, the second and the third level of technology optimization could achieve only limited savings of energy consumption and emissions as there is no evident change between these two scenarios. While, the main contribution to energy saving and emission reduction is achieved by the first level of selection, which is the change of production structure. Indeed, CTO consumes substantial energy, which could not be significantly offset by selection of current technologies. Thus, in view of energy saving, the less share of CTO is, the better it would be. While the difficulty is how to make a balance between energy saving & emissions reduction and coal transition strategy when developing CTO. This implies that more advanced technologies which could bring a revolution for CTO are needed in the near future so as to release the dilemma situation of CTO in China.

6. Conclusions

This study aims to find a roadmap to reach the existing policy targets and explore a more sustainable development path for China's ethylene industry. To this end, a bottom-up method named NET-Chemical model is developed to describe the three-level decision making process for technology selection in ethylene industry, along with the goal of total cost minimization. Several conclusions can be drawn.

(1) Following the existing national and industrial policies for ethylene industry, we find a roadmap for ethylene production till 2030 whose key parameters are shown in Table 6. In terms of production structure, share of CTO&MTO will increase in future while steam cracking will still be the main way to produce ethylene in China, whose share will be more than 70% till 2030. For steam cracking, the cracking material tends to be lighter and ethane and LHC will account for more in future. For CTO, coal water slurry gasification technology and pulverized coal gasification will be further promoted. For methanol to olefins process in CTO and MTO, the share of DMTO II technology will be increased to about 46% in 2030 according to technology selection.

(2) Total amount of energy consumption and CO_2 emission in China's ethylene industry would keep increasing attributing to the rising demand. Following the current polices in BAU, energy consumption would be 64.5 Mtce in 2020 and 83.7 Mtce in 2030, while the amount of CO_2 emissions would reach to 143.3 Mt and 186.5 Mt in 2020 and 2030, respectively. CTO is the biggest contributor for total energy consumption and carbon emissions, which accounts for about 70%. In terms of energy consumption of producing per ton ethylene, it would decrease from 0.854 tce/t to 0.711 tce/t for steam cracking, from 8.26 tce/t to 6.84 tce/t for CTO and from 0.89 tce/t to 0.81 tce/t for MTO during 2015–2030. Especially, the energy consumption per unit ethylene target for steam cracking in 2020 mentioned in the national plan could be reached with this roadmap.

(3) Further promoting attached technologies (e.g. Air Preheating Technology and Enhanced Heat Transfer Technology) on the basis of existing trends and limiting the share of CTO no more than 20% after 2020 could additionally reduce the energy consumption by

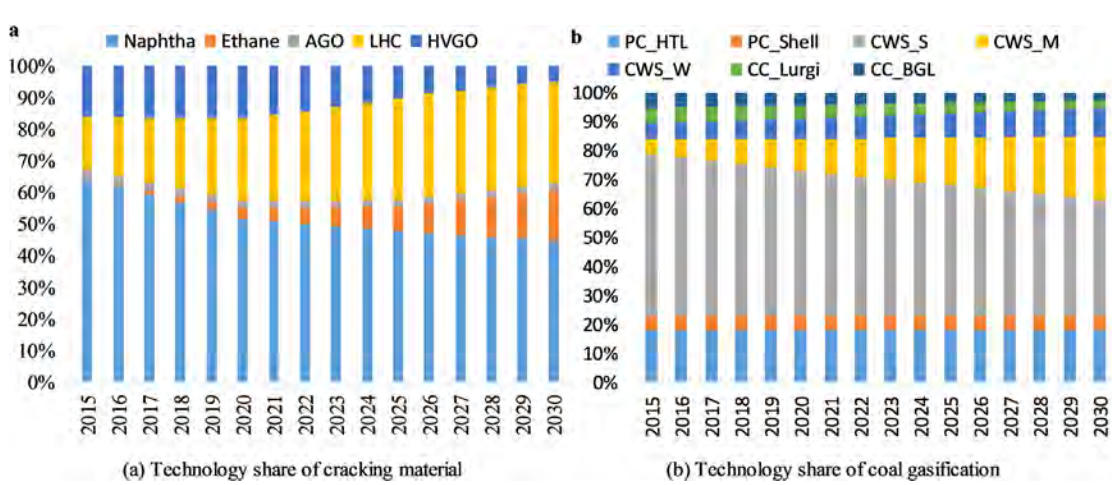


Fig. 14. Technology development pathway of key production processes in SDS.

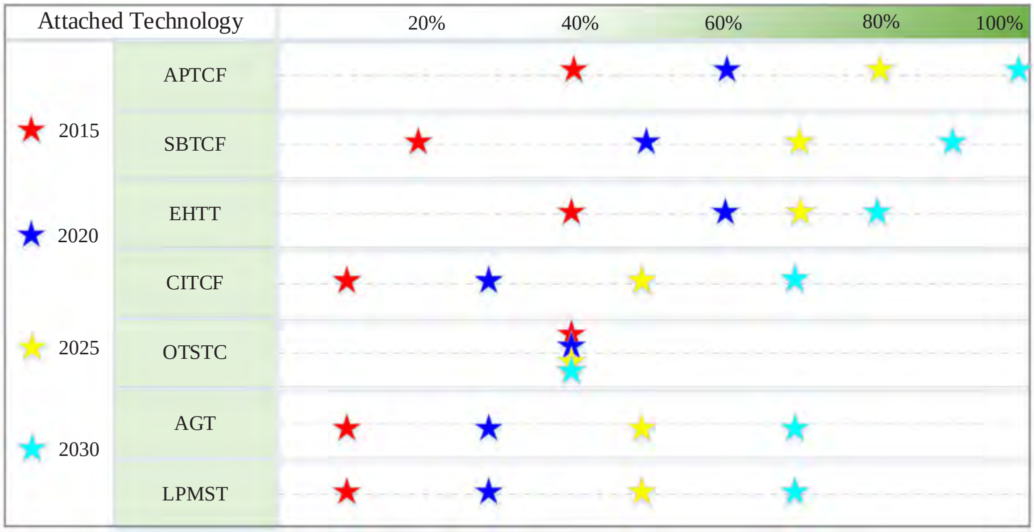


Fig. 15. Technology selection of attached technologies in different years in SDS.

Table 6
Optimized development path for ethylene production in China under current policy (BAU).

Producing ways	Process	Item	2015	2020	2030
Steam Cracking	Cracking Material	Naphtha	63.8%	58.1%	49.4%
		Ethane	0.0%	0.0%	14.6%
		AGO	3.2%	2.2%	2.3%
		LHC	16.7%	23.4%	28.2%
		HVGO	16.3%	16.4%	5.5%
CTO	Coal to methanol with different Gasification technologies	PC_HTL	17.9%	17.9%	17.9%
		PC_Shell	5.3%	5.0%	5.0%
		CWS_S	55.7%	50.0%	40.0%
		CWS_M	5.3%	10.0%	20.0%
		CWS_W	5.3%	7.1%	11.1%
		CC_Lurgi	5.3%	5.0%	3.0%
		CC_BGL	5.3%	5.0%	3.0%
CTO&MTO	Methanol to olefins (including the process in CTO and MTO)	SMTO	6.9%	18.8%	9.8%
		MTO	13.8%	16.0%	24.3%
		DMTO I	72.5%	38.9%	19.7%
		DMTO II	6.8%	26.4%	46.2%

16.7% in 2020 and 20.1% in 2030, and CO_2 emissions could be reduced by 16.3% and 19.9% in 2020 and 2030, respectively when compared to BAU. To achieve more sustainable development compared with BAU, the shift of production structure should be utilized, especially promotion of CTO should be restrained after 2020.

7. Policy implications

In terms of technology roadmap and how to achieve more sustainable development for China's ethylene industry, some policy implications are proposed.

For steam cracking, the lighter the cracking material is, the less energy would be consumed and the better it would be for the environment. Thus, the lighter cracking materials ethane and light hydrocarbon should be developed preferentially in future. The American shale gas is undergoing a revolution currently which is promoting the ethane production booming. In future, it would be a good choice for China to import ethane form the USA to promote its cracking material lighter in ethylene industry. While the heavier material should be limited but not forbidden although they consume more energy and emit more emissions, because it is a good way to handle the overcapacity of for example AGO and HVGO by ethylene production.

For CTO, although its development can slow down the dependence of oil for China and promote the adjustment of coal structure in view of national strategy, the limitation of its promotion should be set in consideration of its burden to the environment. Even attached technologies are used for CTO, it will consume 6.84 tce and emit 15.30 t CO_2 to produce per ton ethylene, which is about 9 times of steam cracking. Current energy saving technologies in CTO are not enough and need to be further researched in future. Especially, coal water slurry gasification and DMTO-II technology should be further promoted in future. Besides, the government should also pay more attention to the shift of production structure in ethylene industry when promoting advanced technologies.

For MTO with methanol form overseas, it is a good way for energy saving and emission reduction. Methanol production is the most important energy consumer and CO_2 emitter in the process of CTO. By importing methanol from foreign countries, it can slow down the rapid growth of energy consumption and CO_2 emissions for China's ethylene industry. Actually, the global energy saving and emissions reduction could also benefit from this way as overseas methanol is mostly produced by natural gas which is with lower energy use and lower CO_2 emissions than coal. Thus, to satisfy the same ethylene demand, both of China and the global world could benefit by adopting MTO in China in terms of energy saving and emissions reduction, which indicates that MTO should be encouraged appropriately in future in China's ethylene industry.

The developed NET-Chemical model in this study can be further applied to some other situations, for example, (1) to measure the change of energy consumption and emissions in ethylene industry when the structure of cracking material is adjusted; (2) to assess the environmental impact of coal to olefins (CTO) on the total ethylene industry as there are still different opinions on its development; and (3) to calculate the CO_2 abatement cost of low-carbon and energy saving technologies so as to identify whether they are economical feasible and provide references for carbon tax design. In addition, NET-Chemical model can also be applied to other chemical products, especially for the technological intensive chemicals, for example ammonia, to make analysis of their special conditions.

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Appendix A.

See Tables A1–A5.

Table A1
Share of different producing ways in 2015.

Producing way	Steam cracking	CTO	MTO
Share	88.0%	6.5%	5.5%

Note: The share of steam cracking is calculated by authors according to Ministry of Industry and Information Technology of China (MIIT, 2016). According to MIIT, total share of CTO and MTO is 12%. As the specific share for each one cannot be obtained, it is substituted by their capacity shares in 2015.

Table A2
Basic parameters of different cracking materials and attached technologies in steam cracking process in 2015.

Technology	Input material	Output product	Feedstock (t/t product)	Energy consumption (tce/t ethylene)	Initial cost CNY/t ethylene capacity	Share in 2015
SC_Naphtha	Naphtha	Ethylene	3.18	0.886	4050	63.0%
SC_Ethane	Ethane	Ethylene	1.3	0.629	3280.5	0.0%
SC_AGO	AGO	Ethylene	3.79	1.028	3772.6	3.0%
SC_LHC	LHC	Ethylene	2.38	0.703	3847.5	18.0%
SC_HVGO	HVGO	Ethylene	3.4	0.93	4252.5	16.0%
APTCF	NA	NA	NA	−0.011	13	40.0%
SBTCF	NA	NA	NA	−0.021	6	20.0%
EHTT	NA	NA	NA	−0.067	5	40.0%
CITCF	NA	NA	NA	−0.045	10	10.0%
OTSTC	NA	NA	NA	−0.003	5	40.0%

Notes: 'SC' represents steam cracking in this table, followed by its cracking material. For example, 'SC_Naphtha' represents steam cracking with material of naphtha, and it is same to others.

Table A3
Basic parameters of different coal to methanol technologies and attached technologies in CTO.

Technology	Input material	Output product	Feedstock (t/t product)	Energy consumption (tce/t methanol)	Initial cost CNY/t ethylene capacity	Share in 2015
PC_HTL	Feed coal	Methanol	1.20	1.555	3017.1	17.9%
PC_Shell	Feed coal	Methanol	1.18	1.515	3291.3	5.3%
CWS_S	Feed coal	Methanol	1.30	1.659	2742.8	55.7%
CWS_M	Feed coal	Methanol	1.28	1.599	2742.8	5.3%
CWS_W	Feed coal	Methanol	1.32	1.679	2559.9	5.3%
CC_Lurgi	Feed coal	Methanol	1.20	1.462	2742.8	5.3%
CC_BGL	Feed coal	Methanol	1.10	1.350	3017.1	5.3%
AGT	NA	Methanol	NA	-0.1	60	10.0%
LPMST	NA	Methanol	NA	-0.2	120	10.0%

Notes: Energy consumption of these technologies includes feed coal.
Shares of the first seven technologies account for 100% and they are calculated by the authors based on their capacity in 2015. For technologies CWS_M, CWS_W, CC_Lurgi and CC_BGL, as a result of data availability, their shares are averaged.
The share of different technologies are calculated by authors based on Anychem.com who has a database of coal chemical industry.

Table A4
Basic parameters of different methanol to olefins technologies in CTO.

Technology	Input material	Output product	Feedstock (t/t product)	Energy consumption (tce/t ethylene)	Initial cost CNY/t ethylene capacity	Share in 2015
C_SMTO	Methanol	Ethylene	5.66	0.907	4600	10.9%
C_MTO	Methanol	Ethylene	5.36	0.991	5421.4	6.3%
C_DMTO	Methanol	Ethylene	5.94	0.865	4300	70.2%
C_DMTO II	Methanol	Ethylene	5.34	0.648	4800	12.6%

Notes: The share of different technologies are calculated by authors based on Anychem.com who has a database of coal chemical industry.

Table A5
Basic parameters of different methanol to olefins technologies in MTO.

Technology	Input material	Output product	Feedstock (t/t product)	Energy consumption (tce/t ethylene)	Initial cost CNY/t ethylene capacity	Share in 2015
M_SMTO	Methanol	Ethylene	5.66	0.907	4600	0.0%
M_MTO	Methanol	Ethylene	5.36	0.991	5421.4	23.1%
M_DMTO	Methanol	Ethylene	5.94	0.865	4300	76.9%
M_DMTO II	Methanol	Ethylene	5.34	0.648	4800	0.0%

Note: In terms of production process, MTO is a part of CTO. This makes that many basic parameters of MTO are same to methanol to olefins process in CTO. While shares of different technologies differ between these two.
The share of different technologies are calculated by authors based on Anychem.com who has a database of coal chemical industry.

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