Adaptive CO_2 emissions mitigation strategies of global oil refineries in all age groups

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SUMMARY

Continuous expansion of fossil fuel-based energy infrastructure can be one of the key obstacles in delivering the Paris Agreement goals. The oil refinery is the world's third-largest stationary emitter of GHGs, but the historical mapping of the regional-specific refining industry, their CO_2 emission patterns, and mitigation potentials remain understudied. This study develops a plant-level, technical-specific, and time-series global refinery CO_2 emission inventory, covering 1,056 refineries from 2000 to 2018. The CO_2 emissions of the refinery industry are about 1.3 Gigatonnes (Gt) in 2018, taking up 4% in total. If continue with current technical specifications, the global refineries will cumulatively emit 16.5Gt CO_2 during 2020-2030. The refineries vary in operation age, refining configuration structure, and geographical

location, leading to the demand for specific mitigation strategies, such as improving refinery efficiency and upgrading heavy oil processing technologies, which could potentially reduce global cumulative emissions by 10% during 2020-2030.

INTRODUCTION

Climate change is one of the most fundamental challenges facing humanity today. Although global energy-related CO_2 emissions dropped by 5.8% in 2020[1], because of the impact of the Covid-19 crisis, driven by population and GDP growth, global will likely to rebound to 2019 levels or above[2,3], more efforts are still required to accelerated the energy transition envisaged by the Paris climate goals[3].

The petroleum oil refining industry is the third-largest stationary emitter of GHGs in the world[4], contributing 6% of all industrial GHG emissions[5,6], as both the consumer and the provider of energy[7-9]. The oil refining industry, thus, plays a crucial role in both the energy supply chain and climate change. CO_2 is the main GHGs emitted by petroleum refineries, accounting for about 98% of their GHGs emissions[10]. Potential CO_2 emissions reductions from the refining process at country level[5,11-13] , the impact of CO_2 emission regulations[14,15] and the carbon pricing[13,16,17]on the oil refining industry have been assessed previously. Yet a consistent and publicly published global refineries CO_2 emission dataset with detailed information can provide a firm basis for such discussion. Previous studies have combined global[5] and regional[7,11,13,18,19] oil refineries data, and noted the GHGs[5,7,18,19] [5]or CO_2[11,13] emissions mitigation potential for the global or national oil refining sector of a specific year. However, these studies only covered a limited number of refineries and have not contained the analysis of the multi-year trend of CO_2 emissions, which is the basis for exploring the potential emission hot spots and the adaptive reductions ways of the refining industry at unit, regional, global levels.

Here, we develop a new time-series global inventory of CO_2 from oil refineries from 2000 to 2018 by compiling and harmonizing the available data related to oil-refining units (Table S1) and calculated the annual emissions with corresponding emission factors, which we name the CEADs (Carbon Emission Accounts and Datasets)-Global Refinery Emission Inventory (CEADs-GREI). CEADs-GREI is a publicly available global inventory of annual emissions of CO_2 from individual refinery units, which can be accessed freely from Carbon Emission Accounts and

Datasets (CEADs, www.ceads.net). Details of the methods and data used to construct the Global Refinery Emission Inventory (CEADs-GREI) are shown in **Figure S1**. We then use the CEADs-GREI to identify the largest annual CO_2 emissions refineries by region, refinery configuration type and age, and track the temporal and spatial changes of CO_2 emission hotspots, illustrating the historical changes and characteristics of CO_2 emissions in the refining industry at the unit, regional and global levels. Furthermore, we quantify the 'committed CO_2 emissions' or 'lock-in' effect based on the actual existing or planning refineries and the facility-level historical production and emissions in CEADs-GREI, and analyze the distribution of the remaining committed CO_2 emissions from refineries and their proportion to the carbon budget if mean warming is limited to 1.5ºC and identify the key area of CO_2 reduction in oil refining industry in the future. Finally, we predicted the long-term prospects of the global oil refining industry's CO_2 emission and explored its potential mitigation measures for reducing CO_2 emissions by age groups and by regions. This study provides a detailed picture of oil refining capacity and CO_2 emissions worldwide; which is helpful to conduct a thorough and comprehensive understanding of past emission characteristics of refineries; identify the key impact factors of refineries CO_2 emissions; predict the development trends in the future. Our results provide a scientific basis for policymaking in oil refining industry carbon emission reduction.

RESULTS

Emission patterns of the global oil refining industry

Figure 1 shows the trends in oil refining industry CO_2 emissions from 2000 to 2018. As depicted in the CEADs-GREI, 755 refineries were operating in 2000 worldwide, with a total capacity of about 87 million barrels per day (Mbpd) and annual CO_2 emissions of 1000 Mt; the number of refineries in operation increased to 946 in 2018, with a combined capacity of about 98 million barrels per day (Mbpd) and annual CO_2 emissions of 1242 (±7%) Mt (see **Figure 1**).

Overall, two turning points have occurred in the development of the global oil refining industry since 2000 due to the fluctuation of refinery utilization rate (annual throughput divided by crude distillation capacity). The first was around 2003 with the growth in the global utilization rate of the oil refining industry, which was mainly driven by the growth in the utilization rate of the oil refining industry (**Figure 1.b**) in China and India, which directly resulted in a sharp rise in its CO_2 emissions. Take China as an example, driven by the surged oil demand since 2002, China's refinery output increased by 11% in 2003 and 12% in 2004, pushing the refinery utilization rate up significantly[20]. CO_2 emitted by Chinese oil refineries grew from 27.6 Mt in 2002 to 45.3 Mt in 2004. The second turning point was around 2008 with the plummet in the global refineries utilization rate caused by the onset of the global financial crisis and the drop in global petroleum product demand, resulting in the diminishing of oil refining capacity, CO_2 emissions, and the numbers of operating refineries in each region during 2008/2009[21,22]. Moreover, the distribution pattern of the global oil refining industry has changed significantly since 2009, with the rapid growth in oil refining capacity in the Asia-Pacific region, especially China and India, which may be caused by the unfolding of construction of the modern major refinery and the rapid growth of its domestic demand for refined petroleum products in the post-financial crisis era[22]. In contrast, Europe has been trapped in the “the crisis in European refining” after 2009 due to the impact of both the EU environmental and energy policies and the declining domestic demand for refined petroleum products[23]. It is clear that the development focus of the global oil refining industry has accelerated shifting eastward since 2009.

Specifically, the spatial hotspot of CO_2 emissions in oil refining sector has changed significantly since 2000, but especially around 2009. CO_2 emissions of oil refineries in China and India experienced steady growth between 2000 and 2018,with an average annual growth rate of 7% and 5%, respectively. Their contribution to global oil refineries' CO_2 emissions climbed from 6% and 3% in 2000 to 16% and 7% in 2018, respectively. In contrast, the share of Europe and the United States fell from 22% and 24% in 2000, to 17% and 21% in 2018, respectively. This change in CO_2 emissions' distribution pattern first occurred in 2003 and became more obvious after 2008. CO_2 emissions in Europe and Latin America showed a volatile downward trend since 2009. Their CO_2 emissions from the oil refining industry have been lower than in 2000, with CO_2 emissions from both regions in 2018 were only 90% of their 2000 emissions. Moreover, 2009 is also a key turning point in the age structure of carbon dioxide contributors to oil refineries (**Figure 1.c**). Before 2009, CO_2 emissions were mainly from middle-aged refineries around 50 years old. However, since 2009, refiners aged 0-19 have become the main contributor of CO_2 with the advantages of large annual increments.

Figure 2 presents the geographical location, age, and 2018 CO_2 emissions of 1056 oil refineries that have been, or are, in operation worldwide between 2000 and 2018. The age of the operating refineries is the length of time from the year of its commissioning to 2018.

In 2018, it is clear that **the global oil refining industry is dominated by two types of refineries: new refineries (less than 40 years) in China, India and the Middle East; and older refineries (40 years or older) in developed regions, Europe, the United States and Japan.** The refining capacity of the above two types of refineries accounted for 22% and 35% of the total refining capacity in 2018, respectively, and their CO_2 emissions accounted for 22% and 37% of the total CO_2 emissions of the oil refining industry, respectively.

From a regional perspective, for developing regions, the young age of refineries is striking, in 2018, new refineries aged 0 to 39 in China (**Figure 2.c**) emitted 121 (±5%) Mt CO_2, accounting for 64% of Chinese refineries' annual CO_2 emissions. As for India and Saudi Arabia (**Figure 2.f**), such new refineries emitted 73.1 (±7%) Mt CO_2 and 35.6 (±7%) Mt CO_2, respectively, accounting for 82% and 89% of total annual CO_2 emissions by local refineries. The young age of oil refineries in developing regions is the result of their rapid urbanization and industrialization in recent decades. As for developed regions, the average age of existing units in Japan (**Figure 2.d**), Europe (**Figure**

2.e) and North America (**Figure 2.b**): 56.6, 54.2 and 66.6 years in 2018, respectively. Additionally, the average operating life of refineries in the above areas is 46.0, 62.9 and 73.5 years respectively, therefore, it can be inferred that although old refineries in Japan, Europe, and the United States are still emitting large amounts of CO_2 in 2018, they are likely to be shut down in the next few years. Moreover, refineries that were closed in 2018 (grey points in **Figure 2**) are densely distributed in the above three regions and account for 10%, 38% and 13% of the total number of closed refineries in the world, respectively. Other refineries located in Africa and Latin America are distributed along the coastline, especially in the port areas, and they have a complex age distribution, the CO_2 emissions are small.

Figure 3 presents the age distribution of global oil refineries' CO_2 emissions and refining capacity in 2018 by crude oil processing depth (deep complex refineries **Figure 3a** and shallow simple refineries **Figure 3b**). The development trend of the world oil refining industry is clear through the age structure of oil refineries in each region: the oil refining industry first developed in the United States in the 1930s and 1940s (refineries older than 75), then in Europe in the 1950s (middle-aged refineries), and have sprung up in Asia and the Middle East since the 1990s.

Figure 3 also shows that the proportion of CO_2 emitted from these two types of refineries (deep processing ones and shallow processing ones) varies across regions due to the different development timing of the oil refining industry as mentioned before. A shallow processing refinery is a processing plant with a simple configuration that usually comprises facilities such as tanks, distillation units, recovery facilities, hydrotreating units, and other necessary utility systems without any conversion units. A deep processing refinery is a processing plant with a complex configuration that is usually equipped with conversion units such as catalytic cracking units and hydrocracking units, enabling treating and converting heavy crude oil fractions into lighter products. Globally, the deep processing refineries usually have a much larger refining capacity (see **Figure S3**), higher CO_2 emissions, longer service life than the shallow, simple, ones. The total CO_2 emissions and refining capacity of complex deep processing refineries are approximately six times and three times higher than those of shallow processing ones, respectively. Moreover, CO_2 emission per unit of deep processing refinery is about 4 times than the shallow processing ones (see **Figure 4**). The number of old complex refineries, older than 80 years old, is about four times that of shallow processing refineries (see **Figure 5**). Furthermore, the proportion of CO_2 emissions from deep processing refineries increases with the aging of refineries, accounting for 80%, 88% and 93% of the total CO_2 emissions from refineries in the youngest group (0-9 years old), the middle-aged group (40-64 years old) and the elderly group (> 75 years old), respectively. Thus, deep processing refineries not only dominate the CO_2 emissions at present, but will maintain this dominant position in the future due to the length of service time.

The growth of the proportion of the number of deep processing refineries is also consistent with the development trend of global oil refining industry; that is that the proportion of deep processing refineries is higher in regions where the oil refining industry started earlier (see **Figure 5**). For instance, in 2018, the proportion of the number of deep processing refineries in the United States and Europe were 74% and 72%, respectively, contributing 238 Mt CO_2 (20% from middle-aged (40-64 years old) refineries, 22% from aged refineries older than 75) and 187 Mt CO_2 (58% from 40-64-year-old refineries), respectively. The proportion of refineries with deep processing in China, India and the Middle East - where the oil refining industry started later - are smaller, and they are mainly young ones. Deep processing refineries in China represented 68% of the country's total refineries, contributing a total of 153.6 Mt CO_2, 30% of which emitted by young refineries (aged 0-9) and 30% emitted by refineries aged 10-39. India's deep processing refineries accounted for a staggering 94% of its total number of oil refineries, contributing a total of 89.5 Mt CO_2, 42% from young refineries (aged 0-9), and 32% from refineries aged 10-19). Deep processing refineries in the Middle East accounted for 57% of the region's total refineries, emitting about 78.0 Mt CO_2, of which 24% came from young refineries (aged 0-9) and 18% from refineries aged 10-19. In contrast, the oil refining industry in Africa is dominated by shallow processing refineries, accounting for 56% of the total number of local refineries, with merely 14.6 Mt CO_2 emissions in 2018. The average emissions per refinery of young deep complex processing refineries in China, India and the Middle East are also significantly higher than those in other regions. CO_2 emissions per refinery (the average CO_2 emissions of refineries in this group) of 0-9-year-old young deep complex processing refineries in China, India and the Middle East are all around 2.0Mt, about twice as much as those of 0-9-year-old young deep complex processing refineries in Europe and the United States (see **Figure 4**). Therefore, younger complex deep processing refineries - dominated by refineries in China, India, and the Middle East nowadays (see **Figure 5**)- will become the centers of the world's oil refining industry, indicating Asia, represented by China and India, will gradually become the center of both production and CO_2 emission of the oil refining industry in the future.

Committed CO_2 emissions of global oil refineries

Figure 6a shows the committed emissions accounting for the global oil refining industry in 2018 and in 2025. Committed emissions are demonstrated as the total emissions (cumulative amount of annual emissions) that occur over the lifetime (since the date of commissioning) of refineries, which is a new way to quantify the long-term consequences of current actions[24,25]. Over time, the proportion of the committed emissions that have been achieved and the proportion that is still maintained of each refinery can be tracked[25].

In 2018, global total commitment from oil refineries was 38.1 Gt CO_2, 11.5 Gt of which remained to be emitted (orange area before the white dashed line in **Figure 6a**). As of 2025, the committed CO_2 emissions of global refineries still maintains the upward trend: the 154 planned refineries (39% of which located in Asia, 17% in the Middle East, and 23% of which will be located in Africa) in the CEADs-GREI that will be put into operation between 2019 and 2025 will generate another 7.2 Gt of remaining CO_2, bringing the total committed CO_2 emissions to 45.3 Gt. The increase in remaining committed CO_2 emissions in 2025 will result in the growth of total CO_2 commitment in the next decade, which further diminished the gap between the carbon budget and the future CO_2 emissions that are locked in by existing and planning oil refineries. In 2025, up to 18.7Gt CO_2 emissions will be locked in the operating oil refineries, almost twice that of China in 2018 (10.0Gt)[26], 3.4 times that of the United States in 2018 (5.4Gt)[26], and 7.2 times that of India in 2018 (2.6Gt)[26], respectively. Moreover, such growth in commitment from 2018 to 2025 is mainly driven by planned refineries in Asia. This indicates that Asia (especially East Asia, see in **Figure S4**) will become not only the core of the world's oil refining industry, but also one of the key areas for reducing CO_2 emissions.

Figure 6.b illustrates the changes in the spatial distribution of global remaining CO_2 committed since 1960. Among the stories **Figure 6.b** tells are the growth of the oil refining industry in Europe during the period 1960 to 1980, the growth of oil refining sector in the Middle East and the United States since 1984, and the rapid expansion of the oil refineries in Asia, China and India particularly since 1996. The global remaining committed emissions experienced a sharp increase in 2000, reaching over 7000 Mt per year, before rising steadily to over 9000 Mt per year in 2010. This was mainly driven by the emission growth in Asia and the Middle East and the massive shutdown of European

and the United States refineries, which in turn led to the shift of the remaining commitment distribution pattern from Europe to China, India, the rest of Asia and the Middle East. Specifically, in 2018, China's refineries contributed 2380.0 Mt CO_2, or 21% of the total remaining commitments, while refineries in India and the Middle East represent 1721.6 Mt (15% of the total remaining) and 1545.8 Mt (13% of the total remaining) CO_2, respectively. In comparison, Europe's and the United States' remaining committed emissions of oil refining sector are a mere 1199.6 Mt and 811.4 Mt, respectively. Moreover, based on the CEADs-GREI and the estimation results of the remaining committed emissions, we predict that a new significant transition of CO_2 emissions from the oil refining sector will appear around 2020, which will be promoted by a large number of planned refineries in Southeast Asia and Africa. More specifically, the remaining committed emissions from traditional oil refining regions, such as Europe and the United States, will both be stable and around the 2018 level. In contrast, remaining commitment from developing regions, such as India and Africa, will soar from 1722 Mt and 282 Mt in 2018 to 3184 Mt and 714 Mt in 2025, respectively. Considering the rapidly growing demand for oil-related products in these emerging regions[27], we find that the development of oil refining industry in such regions may face more severe pressure of CO_2 emission reductions and rapid expansion than developed regions.

In summary, the growth of commitment accounting indicates that the CO_2 emissions of oil refineries will continue to grow in the next decade, mainly driven by Asia, with numerous young refineries and planned refineries. Moreover, the current investment in refineries, one of the representatives of carbon-intensive fossil fuel-based infrastructure will lock the CO_2 emissions in the future, lead a challenge to the achievement of the objectives of the Paris Agreement[28]. According to the longest expected lifetime of refineries (57 years) that we selected, our estimates of CO_2 emissions that are "committed" or "locked-in" of oil refineries in 2025 already account for 9%-23% of the cumulative global CO_2 budget in all pathways limiting global warming to below 1.5°C pathways from 2025 to 2030[29,30], much more than the current refinery's annual CO_2 emissions proportion to the global CO_2 emissions. Moreover, if all oil refineries will operate as historically and their annual CO_2 emissions of each refinery remain unchanged until 2050, the cumulative remaining emissions from operating refineries in 2050 will be 8.2 Gt without any carbon mitigation measures, much surpass the net-zero carbon emission[31] target of 2050 under the Paris agreement climate target of 1.5ºC.

Potential changes in oil refining future emissions

Heavier and lower quality of crude oil supply[32] and stricter emission regulations[12] are driving the continuing development of refinery equipment technology, which means that cleaner heavy oil processing technologies represented by hydrocracking are bound to be an upgrade trend for refineries. Against this background, we estimated the potential CO_2 emissions from refineries in different regions in the case of efficiency improvement, upgrading of deep processing units or refinery configuration structure, and both, as shown in the **Materials and Methods section** and **Table S3**.

Figure 7 summarizes the potential pathways in refineries' CO_2 emissions from 2020 to 2030 under different assumed refineries improvement. If all the existing and proposed refineries operate as usual, without the adoption of any low-carbon measures (baseline), we estimated the cumulative CO_2 emissions of global oil refineries from 2020 to 2030 will as large as 16.5Gt. The development trend of deep processing and cleanliness in the oil refining industry has bidirectional effects on the CO_2 emissions of global refineries.

Figure 7a illustrates the changes in oil refineries' CO_2 emissions varies across regions under different scenarios due to the different development characteristics of refineries in each region.

Improving the efficiency of refineries without adding new refineries and refining equipment is the surest way to reduce the CO_2 emissions of the oil refining industry. Given that, the possibility of refineries taking efficiency improvement measures may vary across different countries. We divide all countries into three groups: the top 10 countries with refining capacity, the top 30 countries with refining capacity and other countries. We also divide the improvement of global refining efficiency into three stages: 1) efficiency improvement only occurs in refineries in the Top 10 countries with refining capacity; 2) efficiency improvement only occurs in refineries in the Top 30 countries with refining capacity; 3) efficiency improvement occurs in all refineries worldwide. Globally, from 2020 to 2030, improving the efficiency of refineries could reduce CO_2 emissions by 3%-6%, with the cumulative reduction of CO_2 emissions growing from 532 Mt (efficiency improvement occur only in refineries in the top 10 countries) to 928 Mt (efficiency improvement occur in all refineries). China and India have the most significant reductions in CO_2 emissions, at 193 Mt and 105 Mt, respectively.

The technical progess of refining processes can also reduce CO_2 emissions in the oil refining industry. Upgrading the catalytic cracking units to the cleaner hydrocracking ones will cut about 3% of oil refineries CO_2 emissions, and the cumulative reduction of CO_2 emissions from the global oil refining industry during the period 2020 to 2030 is 446-555 Mt. The United States has the greatest potential for emission reduction, with cumulative CO_2 reductions of up to 196 Mt in the scenario that all deep processing refineries upgrade to hydrocracking-type refineries (HCU, see **Table 1**). However, cumulative CO_2 emission reduction in Africa, where deep processing refineries are scarce, is merely 3 Mt.

In order to meet the growing demand for light refined oil products, such as petrol, upgrading the configuration of light processing refineries to increase the depth of crude oil refining will contribute additional CO_2 emissions to the oil refining industry. In this scenario, the global oil refining industry's CO_2 emissions will increase by about 422 Mt to 807 Mt between 2020 and 2030. If all shallow processing refineries are equipped with hydrocracking and other related units, CO_2 emissions in Asia (with numerous shallow processing refineries), is the most obvious area for improvements, reaching about 417 Mt, accounting for more than 50% of the total emission reduction potential of the oil refining industry under this scenario. Growth of CO_2 emissions from the oil refining industry in other developing regions, such as Africa, Latin America and the Middle East, are also significant in this scenario, with 74 Mt, 63 Mt and 68 Mt respectively.

From the perspective of industry development, we explored the potential changes of CO_2 emissions in the oil refining industry under the scenario of keeping the source of refined oil products unchanged, or the scenario of meeting the growing demand for light oil products, respectively.

In order to minimize the CO_2 emissions of the oil refining industry, while keeping the source of refined oil products unchanged, the combination of the two measures will bring more significant CO_2 emissions reduction than improving refineries' efficiency or upgrading deep processing refining units alone. From 2020 to 2030, the world's total CO_2 emission could reduce by 4%-9%, with the cumulative reduction ranges from 731 Mt to 1452 Mt. CO_2 emissions from the oil refining industry in China and Europe decreased most significantly, with cumulative reductions reaching 271 Mt and 219 Mt respectively.

Considering the growing demand for light refined oil products, we also estimate the CO_2 emissions under the scenario that combines the configuration upgrade of shallow processing refineries with the general efficiency improvement of all refineries to explore the potential changes of CO_2 emissions in the oil refining industry and the trend of refinery complexity. In this scenario, due to the offset of positive and negative effects of the two measures on carbon dioxide in the oil refining industry, the cumulative change of CO_2 emissions in the oil refining industry is only about 177 Mt-274 Mt. Note that the optimal emission reduction combination, with 274 Mt cumulative CO_2 emission reductions, is to consider only the configuration structure upgrade and efficiency improvement of the large and medium-sized refineries with the top 30 refining capacity, as this scenario avoids the additional CO_2 emissions brought about by the transformation of more shallow refineries.

As shown in **Figure 7b**, in each scenario, the CO_2 reduction potential varies across the age group of the refineries. Young refineries (aged 0-19, mainly in Asia and the Middle East) have the greatest potential for reducing CO_2 emissions with the improvement of refining efficiency. For example, CO_2 emitted by refineries aged 0-19 will reduce by nearly 407 Mt between 2020 and 2030 in the scenario that all refineries improve efficiency. **For the middle-aged refineries (aged 40-59) eliminating the backward catalytic cracking and coking unit to cleaning the deep processing refineries, are the key measures to reduce CO_2 emissions**. In addition, refineries between the ages of 40 and 59 years (25% of them in Europe) will reduce CO_2 emissions by up to 164 Mt between 2020 and 2030 as a result of the technical progress of having deep processing units for all refineries. However, the upgrading of refining process configuration for shallow processing units will add the most obvious additional CO_2 emissions for the middle-aged refineries, with up to 265 Mt for refineries between the ages of 40 and 59 in the scenario that all shallow processing refineries will be upgraded to the deep complex HCU type (see **Table 1**).

DISCUSSION

Our study has built a unit-based global refineries emission inventory and explored the committed emission and potential CO_2 emission against the backdrop of growing oil demand and the pressure of greenhouse gas emissions reduction.

Our global refineries' CO_2 emissions inventory, CEADs-GREI, provides a scientific basis for the further reduction of CO_2 from oil refineries, the formation of CO_2-constrained regulations, and investment in oil refining technologies to reduce emissions in the future. Although previous studies have defined the global refining CO_2 emissions of a specific year at the country level, there is a lack of analysis of the temporal and spatial laws of the development of the global oil refining industry, which leaves a vast possibility space in the assessment of the regional-specific growth trend of CO_2 emissions and the possibility of emission reduction. Understanding the past and future development trends of the oil refining industry is crucial in guiding the regional and global emission reduction. Our time-series inventory of global oil refineries, CEADs-GREI, provide a substantial data basis for the tack of developing trends of crude oil distillation capacity and CO_2 emissions of refineries of different regions and ages, which can help decision-makers understand the development trend of the refining industry and prioritize the focus of refineries' improvement. For example, our results indicate a large-scale and complex development trend of oil refineries in the recent two decades. The average output of global oil refineries gradually increased from 65.1mbd to 80.2 mbd from 2000 to 2018. In addition, of the 110 refineries shut down or mothballed during this period, 49 are small refineries with a capacity of less than 60 mbd, of which 22 are located in Europe and the United States. In terms of age groups, the average capacity of young refineries (0-19 years old), which are mainly distributed in Asia-Pacific and the Middle East, increased significantly, from 6.8mbd in 2000 to 63.1mbd in 2018, while the average capacity of refineries in the other age groups remained stable. Given the greater committed emissions brought about by the long remaining operating time of young refineries, there is an urgent need for these refineries to adopt low-carbon technologies to reduce their CO_2 emissions. As for middle-aged and elderly refineries, improving operational efficiency, eliminating the backward capacity, and speeding up the upgrading of refining configuration are the key means to balance growing refined demand and the reducing CO_2 emissions.

In addition, our results define a baseline of committed CO_2 emissions of the oil refining sector based on the known existing and proposed refineries in the near term worldwide, which may help to elucidate the regional-specific potential CO_2 emissions and also help to identify targeted regional opportunities of unlocking future CO_2 emissions Specifically, due to the impact of resources, emissions, and climate change, five countries/regions will be key to successfully addressing the challenges, and different emission reduction strategies need to be adopted according to the age structure, refining configuration and refining efficiency of their refineries.

The oil refining industry in the United States and Western Europe experienced a period of rapid development in the 20th century, and it has gradually become stable in those two regions in the 21st century. Nowadays, the number of new operational and planned refineries in the United States and Western Europe is significantly less than that in Asia, Africa, and Latin America. Moreover, according to the operating lifetime of refineries, 59.6 years, a large number of middle-aged and elderly refineries in those two regions may shut down in the next decade. Furthermore, due to the limitation of the strict CO_2 reduction policies (European Union Emissions Trading Scheme), middle-aged refineries, which dominate the oil refining industry in those two regions, are in urgent need of upgrading for longer-term development.

The past two decades have been an excellent period for the rapid development of the oil refining industry in China and India. A large number of new refineries have come into production in these two countries, with the crude oil refining capacity of China and India also leaping to second and fourth place in the world, respectively, becoming one of the main producing areas of the oil refining industry nowadays. Moreover, the number of refineries planned for production in China and India in the next decade accounts for 10.4% and 11.7% of the global total planned refineries, respectively. However, refining processes in these two regions are relatively backward compared to the other two major oil refining centers in the world, the United States and Western Europe. China still has a large number of shallow processing, especially the young shallow processing ones, indicating the CO_2 emissions of its oil refining industry still have a great potential to rise (115 Mt growth in CO_2 emissions lead by shallow processing refineries upgrade to deep processing ones). In addition, China also has a large number of FCC refineries and urgently needs to improve its refining technology to reduce the total CO_2 emissions of its refining industry. The installation of hydroreforming units will not only help China meet its demand for cleaner petro products, and reduce refinery emissions, but also put itself in a more competitive position in a future world of carbon restrictions. As for India, improving refining efficiency is the key to reducing CO_2 emissions from its large HCU refineries.

After 20 years of rapid development, the Middle East, which has huge crude oil reserves, has become one of the emerging oil refining bases in the world. Similar to China and India, its oil refining industry will continue to expand rapidly over the next decade, with the number of planned refineries accounting for 16.9% of the total number of planned refineries in the world. Shallow processing refineries also account for a large proportion (43%) in the Middle East nowadays. Speeding up the upgrading of the configuration structure, extracting more value from oil production, and meeting the world's demand for light oil products are the three main directions in the future development of the oil refining industry in the Middle East. However, the upgrading of the configuration structure may lead to the significant growth of carbon dioxide emissions from its refining industry (68 Mt growth in CO_2 emissions lead by shallow processing refineries upgrade to deep processing ones), while improving refining efficiency to reduce emissions per refined unit is the key to alleviate that growth.

A comprehensive analysis was performed to assess uncertainties in our results. The CEADs-GREI is subject to uncertainties and limiations, with the average uncertainties of global CO_2 emissions estimated to be 5% to 20%. The uncertainties of unit-level emissions varies across regions and the refining configuration, with larger uncertainties for unknown configuration structures refineries and developing regions due to incomplete information. A detailed description of uncertainties is presented in the Materials and Method section. CEADs-GREI might be still incomplete due to the lack of more detailed data such as unit-level operating hours, the energy consumption data by each refinery configuration structure. More national industrial databases should be collected and incorporated in the future. CEADs-GREI will be updated and improved in the future as more and better data become available.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and data should be directed to and will be fulfilled by the lead contact, Dabo Guan (guandabo@tsinghua.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The numerical results plotted in **Figures 1–4** are provided with this paper. Our analysis relies on five different data sets, each used with permission and/or by license. **We listed all the data sources and their detailed information in Table S1.** Four are freely accessible from their original creators: (1) the Industryabout database: https://www.industryabout.com/world-oil-refineries-map; (2) the A barrel Full database: http://abarrelfull.wikidot.com/list-of-global-oil-refineries; (3) the British Petroleum database: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html; (4) the Google Maps website to geolocated the remaining refineries: https://www.google.com/maps/place/; The fifth data set includes plant-level data for Global refinery infrastructure, which we obtained from Enerdatabase: https://www.enerdata.net/research/world-refineries-database.html. We do not have permission to share the raw data, but we provide cross-links to the original database. Users can purchase the relevant database and merge with CEADs-GREI to get complete information at plant level.

Materials and Method description

CEADs-Global Refinery Emissions Inventory

The CEADs-Global Refinery Emissions Inventory (CEADs-GREI) encompasses 141 countries or regions (aggregated into seven world regions for this study; **Figure S4**) and all refining units that are operational, stopped, test, under construction or cancelled (10 specific refinery status, see in **Table S1**)

Here, we developed a new time-sequence global refinery CO_2 emission invntory. We started with Enerdata refinery database to compile unit-based information of refineries in service as of 2019 (for example, production capacity, start and stop year of operation, physical address, refinery status, ownership).

Because geographical locations (exact latitudes and longitudes) are not included in the Enerdata refinery database, we obtained the locations of 649 refineries (45% of the total 1444 refineries) from the IndustryAbout database[33]. We then geolocated and cross-checked one-by-one all operational refinery units using data from Google Maps, the website of Barrel Full [34] and the websites of some refineries (for example, Sinopec [35], Shell[36]), which represent locations for an a additional 720 units (50%). For the remaining smaller refineries or refineries that have been closed, we obtained locations by using Google Maps to map the physical address provided in the Enerdata refinery database. Further details of this analysis and a summary refinery unit are shown in **Table S1**.

Unit-based CO_2 emission estimation

Of 1444 oil refinery units included in the basic information dataset of global refineries, 1056 are operating during the period from 2000 to 2018, or 73% of the unit, while 155 are ‘planned’, ‘bid process’, ‘approved’, or ‘under construction’ that will be put into operation by the end of 2025, which amounts to 11% of the units. The remaining 16% are ‘stopped’, ‘mothballed’ units that were closed before 2000.

We estimate annual CO_2 emissions of the 1056 refineries operating from 2000 to 2018 using the following equation:

$$E_{i,t} = A_{i,t} \times EF_{j,t} \quad (1)$$

Where *i*, *t*, *j*, represent the refining unit, year, refining configuration respectively. *E* represents unit-based emissions (t), *A* represents specific annual production for each refining unit (t); *EF* represents the emission factors (t CO_2 per t for refined oil production)

Activity rates

Because detailed activity data for each refinery are not available, we estimate unit-based activity data from the total refinery throughput at country level as reported by British Petroleum (BP). Unit-level production is a function of crude atmospheric distillation capacity, annual operating hours and the detailed refined units, but of these, only crude atmospheric distillation capacity data and the regional-level operating hours are readily available. We therefore make the simplifying assumption that the annual average operating hours of a refinery are consistent at the regional/country level. Thus, we calculate unit-level refinery throughput from country-level throughput by the equation:

$$A_{i,t} = A_{k,t} \times \frac{C_i}{\sum C_{i,k}} \quad (2)$$

Where *k r*epresent the country, A represents refined oil production; C represents the installed capacity of refining units;

CO2 emissions

A large proportion of process emissions is one of the main emission characteristics of the refinery industry, which is also the main difference between oil refineries and other industries in terms of CO_2 emission.

CO_2 emissions from oil refineries vary with configuration, process integration, crude oil quality, refined petroleum products and so on [13]. Historic data of CO_2 emissions has been estimated by several sources, but we have found no comprehensive record for the world's refining industry. The most freely available information of CO_2 Emission Factor for the worldwide refining industry which are suitable for the fundemental information of refineries we collect previously is purposed by IEA based on European refinery research[37,38]. Based on this study and the study of Johanson[13], we divided these refineries into five types according to their configuration structure, and selected different emission factors to estimate their CO_2 emissions, as shown in Error! Reference source not found.. Details of refining configuration classifications are described in **Table S2**. As for refineries whose refining configuration is unknown, the default CO_2 Emission Factor, 0.219 t CO_2/t of product, proposed by the IEA Greenhouse Gas Program was used to estimate the refineries CO_2 emission. Estimates of the emissions are based on standard global average conversion factors compiled on the basis of average carbon content of the refining product and suggested that for 95% of the time refineries operate at full load (8300 hours)[38]. Therefore, we estimated the unit-level CO_2 Emission Factors as follows:

$$EF_{i,t} = EF_{IEA} \times \frac{A_{i,t}/C_i}{0.95} \quad (3)$$

where $A_{i,t}/C_i$ represents the refineries operable utilization rate, 0.95 was the operable utilization rate IEAGHG used to calculate the Global Emission Factor.

Committed CO_2 emissions accounting

In this paper, committed emissions of each device were estimated based on five pieces of information: 1) the year of commissioning, 2) operational status of the device, 3) if the device is no longer operating, the year of the decommissioning, 4) average annual emissions, 5) the expected operating lifetime. We assume that the date of commissioning and decommissioning of each refinery provided by the CEADs-GREI are an accurate estimate throughout a unit's lifetime. Therefore, the first four types of information (information 1 to 4) can be obtained directly from the CEADs-GREI we constructed, while the fifth (information of the expected operating lifetime of device) needs to be obtained from the analysis of the year of commissioning and the average lifetime of the refinery.

Of 1444 refineries listed in the CEADs-GREI, 266 units have stopped operating, about 18% of the total. Of these, we chose the 157 refineries cover all geographical regions and all refinery configurations with known commissioning year and the decommissioning year as our primary data source to estimate the expected lifetime.

As for the refineries which were installed since 1960 and were operated between 2000 to 2018, we chose the expected lifetime of each refinery based on the median lifetime of its refining category. As is shown in **Error! Reference source not found.**, the median ages of small refineries (≤60 thousands barrels per day, mbd), Mid-sized refineries (>60Kbpd and ≤110mbd) and large refineries (＞110mbd) are 36, 49, and 57 years, respectively. The average annual emissions of each refinery are its average annual CO_2 emissions from 2000 to 2018

The same method was used to choose the expected lifetime for planned refineries, which will be put into operation from 2019 to 2025 based on their expected refining capacity. The annual emission of each planned refineries was calculated using its expected refining capacity and the median capacity utilization rate (actual output divided by refining capacity) of 2018 in its region.

Adjustments (defined as age + five years) are necessary if refineries operated more years than the assumed lifetime over the entire period (1960-2018, 1960-2025 respectively). However, we assume that all refining units older than its expected lifetime in 2018/2025 will be shut down immediately, which means that the units whose operating age is equal to its expected lifetime in 2018/2025 have realized all its committed emissions.

Potential changes in refinery CO_2 emissions estimation

Based on the previous studies and statistical data from global[7] and regional institutions[39,40], two key factors that have had, and most likely will continue to have, implications for refineries and CO_2 emissions have been identified in the analysis: refining configuration and efficiency of refineries. Thus, we set up five sets of scenarios of oil refining industry CO_2 emissions in the future.

Scenario efficiency improvement: Referring to the United States experience[40], we assumed that the CO_2 emissions per unit production of global refineries will decrease by 1.4% per year due to shifts in production to more efficient refineries and/or implementation of energy efficiency projects at existing refineries[40]. Considering the differences in the development of oil refining technology among regions, we simulated CO_2 emissions under three specific scenarios according to the regions where the refinery is located: 1) assuming that the CO_2 emission factors for refineries located in the top 10 countries of oil refining capacity will decline by year; 2) assuming that refineries in the top 30 countries of oil refining capacity will decline by year; 3) assumes that all refineries' CO_2 emission factors will decrease due to the improving efficiency. Detailed information on refinery capacity country rankings are shown in Supplementary Information.

Scenario technical progress of deep processing units: Assuming that the global deep processing refineries will upgrade to Hydrocracking (HCU) type deep processing refineries from 2020, that is, the catalytic cracking units will be eliminated from the refineries and replaced by hydrocracking units. We simulated CO_2 emissions under three specific scenarios according to the capcity of each refinery: 1) assuming that only large refineries (refining capacity > 110mbd) will upgrade to HCU type refineries; 2) assuming that large and medium-sized refineries (refining capacity > 60mbd) will upgrade to HCU type refineries, and 3) assuming that all refineries will upgrade to HCU type refineries. We also assumed the configuration type of the planned refinery is HCU, with CO_2 emission factor is 0.327 t CO_2/t of product.

Scenario upgrading of refining process configuration: Assuming that the global shallow simple refineries will upgrade to Hydrocracking type deep processing refineries from 2020 by equipping with hydrocracking units, which will result in the growth of global production of light oil products. CO_2 emissions in three specific scenarios are estimated according to the capcity of each refinery. The classification of refining capacity is the same as the scenario for technical progress of deep processing units.

Scenario efficiency improvement and technical progess of deep processing units: assuming that the world's refineries will carry out the improvement of efficiency and upgrading of deep processing units at the same time. We show the three most representative of the nine specific scenarios in this scenario set: 1) assumes that only large oil refineries in the top 10 countries of oil refining capacity will upgrade both in the deep processing units and the efficiency; 2) assumes that large and medium-sized refineries in the top 30 countries will upgrade; 3) assumes that all refineries will upgrade.

Scenario efficiency improvement and configuration upgrade of shallow simple refineries: assuming that the world's refineries will carry out the upgrading of shallow simple refineries' refining configuration and the improvement of efficiency at the same time. We show thethree most representative of the nine specific scenarios in this scenario set: 1) assumes that only large oil refineries in the top 10 countries of oil refining capacity will upgrade both in the refining configuration structure and the efficiency; 2) assumes that large and medium-sized refineries in the top 30 countries will upgrade; 3) assumes that all refineries will upgrade.

Baseline: the control group, indicating the CO_2 emissions without any improvements of oil refineries. We also assumed that no refineries will be shut down after 2020 and that all refineries will be operational by 2030.

Uncertainty Analysis

Emissions estimates may be uncertain due to incomplete information of activity data and emission factors[41-44]. We conducted a comprehensive analysis of national emissions and unit level estimates to assess uncertainties in our results. Following the method demonstrated by Tong et al[43] for uncertainty analysis of global power plant emissions, we used a Monte Carlo simulation method that varied key parameters (activity data, emission factors). The term "uncertainty" in this study refers to the lower and upper bounds of a 95 % confidence interval (CI) around our central estimate[41]. Input parameters, activity data and emission factors are both simulated 10,000 times based on their probability distribution in a Monte Carlo framework to analyze the uncertainty of estimated emissions by oil refining configuration types.

For the uncertainty analysis of the national CO_2 emission estimates, we assumed national activity rates are normally distributed, with coefficients of variations (CV) ranging from 0.02 to 0.03 according to the data sources, British Petroleum (BP) database and IPCC guidelines[45]. For the uncertainties of emission factors, we assume that the emission factors of refineries with known configuration types (Shallow Process, HCU Deep Process, FCC Deep Process, HCU+FCC Deep Process; see Appendix **Table 1**) are normally distributed, with the coefficient of variation (CV) of 5%, while for refineries with unknown configuration structures (Unknown type; see in Table 1), we again assume that their emission factors are normally distributed, with CV of 10%. In summary, the global average uncertainty of CO_2 emissions in the CEADs-GREI ranges from -7% to 7% (at 95% confidence level).

For the uncertainty analysis of unit-level CO_2 emission estimates, uncertainties associated with emission estimates varied with regions and refining configuration types. Following the method proposed by Tong et al.[43], we select a specific refinery from each region (see **Figure S2**) and each refining configuration type (**Table 1**) to assess the uncertainties of different types. We again assume the activity rates are normally distributed, for the uncertainties of unit-level refining production in developed regions, Europe, the United States and Canada, we assume the coefficients of variation (CV) of activity rates are normally distributed with CV of 5%, while for the uncertainties of unit-level refining production in developing regions, such as China, India and the Middle East, we assume the coefficients of variation (CV) of activity rates are normally distributed with CV of 10%. The uncertainty analysis of emission factors is the same as national emission estimates. In summary, the global average uncertainties for CO_2 emissions from refineries with HCU Deep Process, FCC Deep Process, HCU+FCC Deep Process, Shallow Process, and unknown configurations are -20%-20%, -19%-19%, -18%-18%, -26%-26%, respectively, with larger uncertainties for unknown configuration structures refineries and developing regions due to incomplete information.

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AUTHOR CONTRIBUTIONS

DABO GUAN, QIANG ZHANG, SHU TAO, and BO ZHENG conceived the idea and supervised the entire project. TIANYANG LEI and YULI SHAN collected the basic requisite global plant-level refineries information and region/country-level oil refining industry information. TIANYANG LEI, BO ZHENG, and YULI SHAN estimated the historical plant-level specific CO_2 emission and committed CO_2 emissions of global refineries. DABO GUAN and LIANG XI led the construction of a plant-level inventory model for global oil refineries CO_2 emissions reductions. TIANYANG LEI and JING MENG evaluated the specific reductions of CO_2 from the five low-carbon upgrading measures. DABO GUAN, QIANG ZHANG, and SHU TAO contributed to the planning and coordination of the project. TIANYANG LEI, DABO GUAN, BO ZHENG, and JING MENG co-wrote the manuscript. TIANYANG LEI led the drafting of the manuscript. All authors discussed the results and commented on the manuscript.

DECLARATION OF INTERESTS

The authors declare that they have no competing interests

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FIGURE TITLES AN LEGENDS

Figure 1 Trends from 2000 to 2018 by region and age group. (a), The trends of CO_2 emissions and refining capacity from each region. (b), Changes in annual CO_2 emissions relative to 2000 by regions. (c), Changes in annual CO_2 emissions relative to 2000 by age groups. The change of CO_2 emissions in global refineries distribution pattern worldwide since 2009 is apparent.

Figure 2 Maps of oil refinery CO_2 emissions in 2018. (a), Location, age and CO_2 emission of 1056 refining units worldwide. (b)-(f), Oil refineries located in the United States (b), China (c), Japan (d), Europe (e), India and Saudi Arabia (f). Refining units are classified by age in 2018 (0-19 years old, 20-39 years old, 40-59 years old, 60-79 years old, 80-99 years old, >100 years old) and CO_2 emissions in 2018 ($\leq 2*10^2$ t, $\leq 2.0*10^6$ t, $\leq 4.0*10^6$ t, $\leq 6.0*10^6$ t)

Figure 3 Global 2018 CO_2 emissions by region and by age. (a), (b), Bars indicate the estimated CO_2 emissions distribution from different regions by each age group of deep complex units (a) and shallow simple units (b). Note that the 0 years means that the refineries began operating from 2018 in this study. The CO_2 emissions are mainly controlled by three age groups: young (0-9 years old), middle (40-64 years old), old (>75 years old) which are dominated by refineries located in East Asia, Europe, the United States, respectively. The definition of seven regions in this study is shown in Figure S2. A detailed description of the refining configuration type in this study is shown in Table S2.

Figure 4 Global average CO_2 emission per refinery by region and by age. (a), (b), Bars indicate the estimated average CO_2 emission per refinery from different regions by each age group of deep complex units (a) and shallow simple units (b). Note that the 0 years means that the refineries began operating from 2018 in this study. The definition of seven regions in this study is shown in Figure S2. A detailed description of the refining configuration type in this study is shown in Table S2.

Figure 5 Number of oil refineries by region and by age in 2018. Bars indicate the number of oil refineires by regions and by age group. Colors of bars represent the age groups of the oil refineries and the changes of hue represent the processing depth of oil refineries in the corresponding age group from light (shallow processing refineries) to dark (deep processing refineries).

Figure 6 Committed emissions and future emissions in 2018 and 2025 from oil refineries operated since 1960, under different assumed generator lifetimes. a, Committed CO_2 emissions from existing refineries in 2018 (before the white dashed line) and Committed CO_2 emissions from existing and planned refineries in 2025 (after the white dashed line). b, Remaining commitments by region from existing refineries in 2018 and Remaining commitments by region from existing and planned refineriess in 2025. X axis represents the commissioning year of the refinery, and the area represents the cumulative committed emission (a) and cumulative future emission (b) since 1960.

Figure 7 Potential changes in CO_2 emissions from oil refineries under different assumed refineries improvement. Emission changes for five different upgrades of the refineries: improvement of refineries' efficiency, technical progress of deep processing units, upgrading of shallow refineries' refining configuration structure, efficiency improvement and technical progress of deep processing units run at the same time, and efficiency improvement and structure upgrade of shallow simple refineries run at the same time). For all scenarios sets, we project annual CO_2 emissions for all refineries (operational and planned) from 2020 to

2030. We also assumed the configuration type of the planned refinery is Hydrocracking type units (HCU, see Appendix Table 1), with CO_2 emission factor is 0.327 t CO_2/t of product. Throughout this period, the impact of the improvement of the world oil refineries on CO_2 emissions varies between both regions (a) and age groups (b). In each panel, bars show the changes in CO_2 emissions under improving scenarios compare to baseline (Δ). Panels are organized by region and age group. Top 10 countries and Top 30 countries refer to the top 10 and top 30 countries in total refining capacity, respectively.

TABLES AND TABLE TITLES AND LEGENDS

Table 1 Emission factor by refining configuration and Expected lifetime by refining capacity

Refining Configuration	Emission factor (t CO_2/t crude oil distillation)[37,38]
Shallow Process	0.205
Deep Process-1 (HCU)	0.327
Deep Process-2 (FCC)	0.337
Deep Process-3 (HCU+FCC)	0.362
Unknown	0.219
Refining Capacity	Expected lifetime
Small (≤60mbd)	36 years
Mid (≤ 110mbd)	49 years
Large (>110mbd)	57 years