Investigating the Global and Specific Carbon Dioxide (CO₂) Emissions from the Petroleum Downstream Industry of Kuwait

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Abstract

Greenhouse gases (GHGs) have been determined to be the reason behind the global warming phenomenon. Of all GHGs, carbon dioxide (CO₂) has been considered one of the major GHGs; referenced as a ‘chemical-print’ in industrial facilities; and utilized in many ways to reduce its impact. Yet still, in Kuwait and many countries in the region, a proper analysis of its sources and emission rates are still lacking. This can only hinder future efforts for carbon application and sequestration in many areas, including industrial use, enhance oil and gas recovery and underground storage. In this paper, the petroleum downstream industry of Kuwait which consists of three refineries processing around 900 Mbd; are detailed and their layouts was studied thoroughly. Petroleum refining in Kuwait occur in the following complexes: Mina Al-Ahmadi (MAA), Mina Shuiba (SHU) and Mina Abdullah (MAB). These refineries possess the following capacities (Mbpd): 466, 200 and 270, respectively. Typical sources in petroleum refineries were investigated for carbon emissions. These include unit utilities (e.g. heaters, boilers and furnaces), flaring (typically of hydrocarbons), acid gas removal (AGR) or commonly referred to as ‘gas sweetening’ process, hydrogen production (HP) units via steam-methane reforming (SMR) and fluid catalytic cracking (FCC). It was concluded that unit utilities constitute the highest percentage of all contributing sources in all refineries, ranging from 62-74% of all sources. This estimate is higher than past reported ones found in open literature, indicating high intense operations in Kuwait. In addition, the specific emission rate of unit operations has been investigated. Emission factors based on units’ contribution and utilities have been developed and discussed in this work. It is essential to optimize direct energy supply of units in order to reduce their carbon footprint and implement effective carbon reduction strategies.

Keywords: Carbon Dioxide (CO₂), Petroleum, Refining, Carbon Capture and Storage (CCS).

1. Introduction

Globally, especially in the European union (EU), much attention has been given to carbon dioxide (CO₂) reduction strategies in industry. This is clearly evident when it comes to European countries commitment to protocols set in Kyoto and Rio de Janeiro back in 1997 and 1992, respectively. Carbon capture and storage (CCS) promises to be a solution for further CO₂ reduction. CCS’s focus has been power plants so far. However, refineries present themselves as an advantageous option for CCS. This is due to the abundance of carbon intense processes, especially various units’ utilities and hydrogen production units. Reports show that up to date, 74 CCS projects are active or in final developmental stages (IEA, 2004; Johansson et al., 2013). CCS is considered to offer the largest reductions in CO₂ emissions in the refining industry.

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Locally, Kuwait produces 3 MMbpd of crude oil and refines about 1000 Mbpd in three refinery complexes. These are: Mina Al-Ahmadi (MAA) with a capacity of 466 Mbpd, Mina Al-Shuiba (SHU) with a capacity of 200 Mbpd and Mina Abdullah (MAB) with a capacity of 270 Mbpd. 

Table 1 shows Kuwaiti refineries key characteristics. However, no CO₂ assessment is available for these refineries in literature and the routes of CO₂ capture and storage cannot be investigated without the proper flow sheets and current data about CO₂ emission sources. There is no strategy or governmental carbon mitigation plan in Kuwait. The Kuwait Environment Public Authority (KEPA) has implemented the rules and regulations set in their 2001 guidelines for major criteria air pollutants (KEPA, 2001). However, neither the new regulations set in 2012 by KEPA (KEPA, 2012) nor a carbon savings/mitigation plan for industry is activated on a state level, especially in the case of refineries carbon emissions.

Table 1: Current refineries in Kuwait key characteristics as described by Al-Ajmi (2010).

<table>
<thead>
<tr>
<th>Refinery</th>
<th>MAA</th>
<th>SHU</th>
<th>MAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total area (km²)</td>
<td>10.5</td>
<td>1.3</td>
<td>7.8</td>
</tr>
<tr>
<td>Year of commissioning</td>
<td>1949</td>
<td>1966</td>
<td>1958</td>
</tr>
<tr>
<td>Refining capacity (Mbpd)</td>
<td>466</td>
<td>200</td>
<td>270</td>
</tr>
</tbody>
</table>

CO₂ emissions from refineries account for 4% of the global CO₂ emissions (≈ 1 billion metric tons of CO₂ per year) and rank third in world stationary CO₂ producers behind the power sector and cement industry (van Straelen et al., 2010). It is estimated that for a 300 Mbpd refinery a 0.8-4.2 million tons of CO₂ is emitted annually. The objective of this work is twofold, firstly; to estimate the amount of CO₂ and analyze its source in the downstream industry of Kuwait, secondly to develop emission factors for specific CO₂ emissions that could serve unit operators in the future.

2. Materials and Methods

The first stage of this work involved the collection of all process and operation data for processing lines in Kuwait’s refineries. On the basis of the collected data, the amount of CO₂ emissions were calculated and estimated. In addition, each unit contributing to the estimated CO₂ was detailed for a more comprehensive overview. Furthermore, an emission factor based on the gathered data and calculations for each process, was developed in this work. The main contributing factors to the total CO₂ load in oil refineries were examined carefully and divided to the following categories: 1. Hydrogen Production (HP) units (via steam methane reforming, SMR); 2. Fluid Catalytic Cracking (FCC) units; 3. Utilities of the refinery (heaters, boilers and furnaces); 4. Flares; and finally, 5. Acid Gas Removal (AGR). Process contribution in addition to utilities were used to develop the emissions factors. Reaction stoichiometry and established emission factors were used in the estimation of CO₂ from each unit.

3. Results and Discussion

Table 2 summarizes the results obtained for the three refineries (mtpa). The total CO₂ emission was considered without the electricity import by the ministry of electricity and water (MEW). This load contributes to the total carbon footprint of the refinery, but cannot be considered as a source of emission by petroleum processing within the studied boundary, i.e. the refinery processing scheme. Typically is considered as an indirect burden (HCPC, 2010). The total amount of CO₂ emitted from MAA is 3.78 mtpa (Table 2).

The global distribution of CO₂ sources in a petroleum refinery is highly dependent on the type of refinery and what processes it hosts. Hence, the load of certain categories may vary depending on
the type of refinery and desired product specifications. Utilities pose the major source of CO\textsubscript{2} in refineries. Fig.1 shows the distribution of CO\textsubscript{2} sources in MAA. There is a lack in open literature regarding utilities contribution to CO\textsubscript{2} emission and which heaters and boilers typically emit the largest amounts of CO\textsubscript{2} with respect to unit type and capacity. However, we know that some unit operations in refineries are quite energy intensive. Figs.2-3 present a similar percentage based contribution of CO\textsubscript{2} in SHU and MAB, respectively. Heaters and furnaces (unit utilities) represent 62-74\% of CO\textsubscript{2} in the refineries. Past research also indicated that heaters contribute to anything between 26-65\% of the CO\textsubscript{2} emissions from a petroleum refinery (Stockle and Bullen, 2008; van Straalen et al., 2009; 2010; HCPC, 2010; Johansson et al., 2012). Refineries in Kuwait contribute to slightly larger degree when it comes to process heaters, which can be attributed to two reasons. Firstly, the capacity of Kuwaiti refineries is considered on the larger side worldwide; and secondly, both SHU and MAB are energy intensive refineries dealing with heavier crude oils with low APIs and high unit utilization capacities (> 70\%). Furthermore, the requirement of lower sulfur content in products is now increasing which requires certain unit utilities to be supplied to meet such demands. This is more commonly termed as the ‘petroleum refining paradox’ (Johansson et al., 2012).

Table 2: Carbon dioxide (CO\textsubscript{2}) emission (Million tons per annum, mtpa) from the three existing refineries in Kuwait.

<table>
<thead>
<tr>
<th>Source</th>
<th>MAA</th>
<th>SHU</th>
<th>MAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid catalytic cracking (FCC)</td>
<td>0.33</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Fired heaters</td>
<td>3.55*</td>
<td>2.45</td>
<td>2.12</td>
</tr>
<tr>
<td>Acid gas removal (AGR)*</td>
<td>0.03-1.16</td>
<td>0.01</td>
<td>N/A</td>
</tr>
<tr>
<td>Flaring</td>
<td>0.07</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Hydrogen production (HP) units</td>
<td>0.71</td>
<td>0.73</td>
<td>0.72</td>
</tr>
<tr>
<td>Electricity load</td>
<td>770</td>
<td>379</td>
<td>573</td>
</tr>
<tr>
<td>Total (million tons per year)**</td>
<td>3.78</td>
<td>3.22</td>
<td>2.88</td>
</tr>
<tr>
<td>% of Total in Kuwait (w/o electrical import)</td>
<td>48</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>Specific CO\textsubscript{2} emission of refinery (ton CO\textsubscript{2}/bbl processed)</td>
<td>8.1</td>
<td>16</td>
<td>1.6</td>
</tr>
</tbody>
</table>

*Including gas plant side (acid gas sweetening processes and condensate processing)
+ Total of acid gas removal and condensate sweetening processes combined. A range is calculated based on the type of treated feed.
++ Based on maximum CO\textsubscript{2} content in acid gas without the electricity load.

Past assessment of EU refineries given by Johansson et al. (2012) included mostly refineries with no vacuum distillation, hydrotreating units or FCC units; which is the case of most European petroleum refineries. Only 18 refineries (out of 144 in the EU) operate complex systems that include such units. Hence, the source distribution when considering complex configuration refineries (as in the case of Kuwait) shows a larger contribution of heaters to the total emission load. This is evident in the case of MAA where a FCC unit is in operation (only one in the country), in addition to hydrocrackers and vacuum distillation units. Johansson et al. (2013) reported CO\textsubscript{2} emission for two refineries in the EU. The first is a hydro-skimming refinery (which includes in addition to crude distillation, a catalytic reforming, hydrotreating units, naphtha upgrading units and product blending capabilities are included in its scheme) with a capacity of 6 mtpa and a CO\textsubscript{2} emission rate of 0.5 Mtpa. The second is a complex refinery of a capacity equal to 11.4 mtpa and an emission rate of 1.9 mtpa. By comparison to Kuwait, where availability of feedstock is an influential factor, emission rates of CO\textsubscript{2} are minimal. This needs to be considered.
by the energy policy makers in the country to implement a more green operation in the downstream sector.

Fig.1. Percent contribution of each source in MAA with respect to CO₂ emissions.

Fig.2. Percent contribution of each source in SHU with respect to CO₂ emissions.
When considering the basis of estimating the heaters emission, fuel oil was considered as the fuel of choice. A noticeable reduction (≈25%) is noticed in CO₂ emissions when natural gas is used as a fuel sources (Fig.4). This gives way in Kuwait for more carbon savings in terms of developing new energy policies in the country. The majority of associated gas in the country is not utilized and flared in gathering centers. This could be utilized to fuel some heaters in the downstream industry to minimize the carbon load.

HP units’ contribution in the country is evenly spread between the three refineries. Considering the capacities of the three refineries in Kuwait, the intensity of the operations in both SHU and MAB, with the addition of the impurities and level of contaminants in the processes gas in the reformers could explain the high percentages these refineries show (Fig.5). However, due to the larger number of units (including the gas plant side), MAA contributes to 50% of the emissions from heaters stacks in comparison to the other two refineries (Fig.6). For a 250 Mbpd capacity refinery, HCPC (2010) has indicated that HP units will contribute by 3.3% of the total refinery carbon load or between 2.6-6% when scaled to Kuwait’s refinery capacities. Other researchers have indicated that HP units could contribute to anything between 5-20% (Stockle and Bullen, 2008; Johansson et al., 2012a). In Kuwait, 12-25% of the refineries CO₂ emission was due to HP units. The estimate is slightly higher in the case of MAB and SHU. This is primarily due to the varied number of sources in MAA of CO₂. AGR activities and flaring are highly dependent on the processing capacity of each process block in the refinery. However, the purity of the feedstock is crucial in AGR. This can influence regeneration of the solvents (in stripping columns), hence influence the CO₂ emitted.
Fig. 4. Variation in using fuel oil, natural gas (NG) and liquefied petroleum gas (LPG) as a fuel for process heaters in refineries.

Heaters and boilers in refineries are crucial in operation and it is paramount to consider their contribution to the carbon load. However, to be able to make a sound judgment based on the operation of any given unit, we need to estimate the amount of CO₂ emissions based on the whole operation, i.e. utility, process emissions, impact from support processes, etc. Based on the work conducted in this project, we have developed factors for each unit operation considered in the refineries to be able to estimate the CO₂ emission from such units. Table 3 summarizes the CO₂ emission factors formulations based on the work conducted in this study. Distillation units were formulated based on the heaters and furnaces direct heat (energy) supply to the units (Table 3). Atmospheric and vacuum distillation use about 45% of refineries energy due to topping separation units (API, 2000). In Kuwait, refineries distillation units consume 18-28% of the refineries energy. Steam methane reforming (SMR) is also one of the most energy intensive operations in refineries, where hydrogen (H₂) gas is produced. Table 3 shows the contribution of units’ utilities and the contribution of hydrogen production, in terms of specific CO₂ emission. Hence, it includes all contributions from the unit itself and support units to the carbon emissions load.
Fig. 5. Distribution of HP units CO$_2$ emissions in Kuwait.

Fig. 6. Distribution of heaters CO$_2$ emissions in Kuwait.
Table 3: Carbon dioxide (CO₂) emissions formulations developed in this work based on each major unit utilities and support units contribution.

<table>
<thead>
<tr>
<th>Process</th>
<th>Specific CO₂ emission*</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Distillation</td>
<td>CE = 1.4 TP</td>
<td>-</td>
</tr>
<tr>
<td>Vacuum Distillation</td>
<td>CE = 1.5 TP</td>
<td>-</td>
</tr>
<tr>
<td>HP via SMR</td>
<td>CE = 112 TP + 0.25(HP)</td>
<td>Throughput and production rate are based on million tons per hour.</td>
</tr>
<tr>
<td>Hydrocracking</td>
<td>CE = 1.1 TP</td>
<td>Hydrocracking uses about 54 m³H₂/m³feed (Gary and Handwerk, 1994); which should be added to the formulation depending on the unit throughput.</td>
</tr>
<tr>
<td>Residual Desulfurization</td>
<td>CE = 0.28 TP</td>
<td>Desulfurization H₂ flow should be added depending on the unit throughput.</td>
</tr>
</tbody>
</table>

*Where CE is the carbon emission (tpa), TP is the unit throughput (bpsd) and HP is hydrogen production in million tons per hour.

Refineries face a lot of challenges in carbon emissions mitigation especially when considering the changes in fuel mix, energy process, increasing fuel quality demands and heavier crude feeds. Moreover, environmental quality specifications for diesel and gasoline affect other unrelated ones, such as lubricity and gasoline octane number (Szklo and Schaeffer, 2007). For example, FCC gasoline contributes to the sulfur content by 85-95% (Bruent et al., 2005). However, due to its high olefin content (20-40 wt%), gasoline has a high octane number as a standalone product. Hence, to produce a low sulfur product, refineries need to consider optimizing the high energy requirement to its operation.

4. Conclusions

Carbon dioxide (CO₂) emitted from refineries in Kuwait was estimated in this work. The emission rates of these refineries were estimated at 3.78, 3.2 and 2.88 mtpa. The specific refinery emission rate could be estimated for MAA, SHU and MAB at 8.1, 16 and 1.6 ton CO₂/bbl processed per day. These estimates show that Kuwait’s downstream sector is a major carbon emitter that needs energy and operation optimization in a more environmentally friendly manner. The analysis revealed that utilities (mainly fired heaters) in current operating refineries constitute the major share of carbon emissions (62-74%). This could be managed with an energy optimization strategy and a collection of stack gases that could reduce the carbon footprint of this structure in the near future. HP units, which can contribute up to 25% of current refineries carbon load, can be an ideal candidate for capture projects in the future. Operational utilities and space availability are two major advantages for such units to be considered for future capture projects. Optimally, carbon emissions will reduce in Kuwait after taking into account direct heat requirements of units in the near future for better utilization of recovered heat. This will pave the way for future processing of crude in the country, especially when considering the lower API feedstock refineries are starting to process.
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