# ASSESSMENT OF $CO_2$ EMISSION SOURCES FROM THE PETROLEUM SECTOR IN KUWAIT

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# ABSTRACT

Kuwait is an oil dependant country that produces 3 MMbpd and processes about 900 Mbpd of crude oil via a complex network of oil fields, gathering centers, booster stations and three refineries. All of which are associated with carbon dioxide ($CO_2$) emissions from a number of sources. The aim of this work is to assess the $CO_2$ emissions resulting from various petroleum activities in Kuwait with emphasis on the downstream sector. Different processes in the downstream and upstream oil activities will be detailed. The former contributes mainly from hydrogen production units (steam reformers) and utilities (fired heater and boilers), whilst the latter from flaring of excess hydrocarbon gas. Petrochemical activities that contribute to the $CO_2$ load will also be reviewed.


# INTRODUCTION

Worldwide stringent regulations on carbon dioxide ($CO_2$) emissions from industrial sources are being enforced. Low sulfur clean fuel enhance the demand for hydrogen gas, which on the other hand increase the demand on carbon emission intense processes. This will ultimately force the petroleum sector of Kuwait to start implementing $CO_2$ mitigation measures. In 2008, it was estimated that $CO_2$ emissions from the European union (EU) was about 3,780 million tons (≈ 75% of total GHGs emissions). Refineries in the EU account for about 8% of total $CO_2$ emissions in Europe. Emissions from EU refineries have increased by 17% compared to 1990 levels. This is due to increase demand on transport fuel (e.g. diesel) and cleaner grade fuels [1]. The European Commission (EC) has implemented an emission trading system (ETS) to reduce industrial carbon emission incrementally with a roadmap until the year 2050 [2]. Since the year 2005, EU refineries are a part of the EU ETS which aims at reducing GHGs by 21% in 2020 relative to the 2005 levels [1]. In the UK, an 80% reduction target (based on 1990 levels) for greenhouse gases (GHG) was set by the government [3].

Carbon capture and storage (CCS) promises to be a solution for further $CO_2$ reduction. Reports show that up to date, 74 CCS projects are active or in final developmental stages [4-5]. Considering the aforementioned, and the start of carbon awareness in the petroleum industry on a world scale, this work was initiated. The objective of this work is twofold: Firstly, to review major sectors of the petroleum industry in Kuwait that contribute to the $CO_2$ emission load. Secondly, to focus on the analysis obtained in this research on the downstream sector of the country.

# $CO_2$ EMISSIONS IN KUWAIT FROM THE UPSTREAM AND PETROCHEMICALS SECTORS

Major criteria pollutants have been researched in Kuwait in the past decade, especially from industrial sources (including refineries). Al-Salem et al.[6] concluded using a chemical mass model (CMB) developed for determining the percent contribution of major industrial sources around an urban area in the southern part of Kuwait, that MAA refinery was the most influential source in the primary airborne pollutants load. In a series of follow up studies on different residential areas, it was concluded that Kuwait urban areas was being influenced by petroleum refineries and line sources (e.g. traffic) when considering its outdoor air quality [7-9]. An emission inventory was conducted in a past research project endorsed by KISR [10-11]. It was concluded that process heaters in refineries were the major contributor to major criteria pollutants affecting the emission rates and factors developed. All of the aforementioned studies focused on major VOCs, $NO_x$, $SO_x$, methane and non-methane hydrocarbons. However, lack of assessments in open literature for $CO_2$ warrants further estimation of its sources in the country. JNOC [12] conducted a survey for major $CO_2$ sources in Kuwait. The study concluded the following when considering the oil sector in Kuwait:

- In the upstream sector of Kuwait (where KOC is the sole responsible for its activities), it is difficult to recover a $CO_2$ volume sufficient for EOR in the country. This is due to the scattered locations of the oil fields in Kuwait.
- As for the petrochemicals sector in the country, the Petrochemicals Industry Company (PIC) operates a chlorine plant (chlorine: 15 mtpa, caustic soda: 17 mtpa and salt: 32 mtpa) and a fertilizer complex (urea: 839 mtpa and ammonia: 576 mtpa). All the $CO_2$ produced was utilized in the production of urea after emission by the ammonia plant. Hence, no available $CO_2$ was estimated by study in the PIC.
- Refineries had available $CO_2$ streams especially from the HP units (MAA: 43 MMSCFD; MAB: 43 MMSCFD and SHU: 28 MMSCFD) and the acid-gas removal unit in MAA (5 MMSCFD).

The carbon dioxide information analysis center [13] has published the total $CO_2$ value in the country from gaseous fuel consumption. This was estimated to be 22.4 mtpa. This estimation is for the carbon emitted due to energy sources combustion. The US EIA[14] has published in its country report that Kuwait ranked 42$^{nd}$ in the world in $CO_2$ emissions. It has indicated that Kuwait emits 82.4 mtpa of $CO_2$ from consumption of fossil fuels.

# ESTIMATING THE $CO_2$ EMISSIONS IN THE DOWNSTREAM INDUSTRY

Typically sources in a petroleum refinery could be divided to [1,15-18]: Units' utilities (heaters, furnaces and boilers) which can contribute up to 65% of the total $CO_2$ load of the facility, Fluid catalytic cracking (FCC) unit which can be responsible to up to 40% of total carbon emissions from the regenerator's stack due to catalyst coke burn off; Hydrogen production (steam methane reforming, SMR) which produces $CO_2$ as a byproduct of the gas/water shift reaction and can emit up to 20% of the total refinery's $CO_2$ emission; and utilities production if a refinery produces steam or electricity. $CO_2$ is a direct by-product of such process which can contribute to 50% of the total refinery $CO_2$ emission load. Kuwait produces 3 MMbpd of crude oil and the Kuwait National Petroleum Company (KNPC) is responsible for refining and marketing petroleum products within Kuwait and currently operates three refineries in the country. These are: Mina Al-Ahmadi (MAA) with a processing capacity of 466 Mbpd, Shuiba (SHU) with a capacity of 200 Mbpd and Mina Abdullah (MAB) with a capacity of 270 Mbpd. However, no $CO_2$ assessment is available for these refineries in literature and the routes of $CO_2$ capture and storage cannot be investigated without up-to-date $CO_2$ assessments detailing process emissions. In the next section, the methodology for estimating carbon emissions in the refineries will be detailed.

## HP Units in Current Refineries in Kuwait

HP units are available in all three operating refineries in Kuwait. In MAA, there are four steam methane reformers (SMR) for HP in the refinery. From the stoichiometric ratio of $CO_2$ to hydrogen from the balanced chemical reactions of methane reforming, we can obtain the ratio of $CO_2$ to hydrogen, which is 1 to 4. Hence the $CO_2$ production on a daily basis can be easily obtained using Eq.(1):

$$HPC = HPR.UC.(1/4) \quad (1)$$

Where HPC is the total carbon dioxide ($CO_2$) emission rate from the HP (MMSCFD); UC is the HP unit utilization capacity (%) and HPR is the hydrogen production rate of the unit (MMSCFD). Using the conversion factor for $CO_2$ which is 17,483 scf/ton, we can convert the $CO_2$ production to a unit mass. The total $CO_2$ produced from HP units from the refinery is estimated at $7.1 \times 10^5$ tpa without considering the heating duty of the unit. Similar to the case of MAA, SHU produces hydrogen via three identical steam HP units. A similar methodology was followed for both SHU and MAB, which resulted in $CO_2$ emissions from HP as $7.3 \times 10^5$ and $7.2 \times 10^5$ tpa, respectively.

## Estimating the $CO_2$ Emission of Fluid Catalytic Cracking (FCC) Unit

The main objective of fluid catalytic cracking (FCC) is the conversion of feedstock to gasoline and other valuable products. FCC also minimizes the production of less valuable products (i.e. coke, clarified oil, etc.)[20]. However, due to current high energy cost and progressively tightening environmental regulations, refiners have recently been expanding their FCC focus to include improved energy efficiency and reduced $CO_2$ emissions. The FCC unit in MAA, which is the only one operated in Kuwait, has an operating capacity of 43 Mbpd; with a coke production of 4.62 wt% as per the unit's design with a 89.2% utilization capacity. Hence, Eq.(2) can be used to estimate the production of coke (by weight) in the FCC based on the volumetric capacity of the unit using the conversion factor of 0.158 $m^3$/bbl.

$$CFP = 0.158\, OC.cf.SG.UC \quad (2)$$

Where CFP is the coke production rate (kg/day); OC is the unit operational capacity (bpd); cf is the coke weight fraction in the final FCC product (%); UC is the utilization capacity (%); SG is the specific gravity of crude oil at $60^oF$ (900 $kg/m^3$). The $CO_2$ emission from FCC in MAA is estimated at $3.4 \times 10^5$ tpa. The $CO_2$ composition is 15.2% of the stack, which is within expected range [20].

## Heaters and Boilers Carbon Emission from Refineries in Kuwait

Utilities of operation play a major role in petroleum refineries through process heaters. They supply through fired heater and boilers the energy needed for the various units to operate at desired conditions. Fuel gas or oil is typically employed as a fuel for various utility operations. Heaters in their flue stream can contain anything between 3% to 12% of $CO_2$ depending on the type of fuel being combusted [21]. Other gases include $O_2$, $SO_2$, $SO_3$ and $NO_x$. Fuel gas is used in Kuwait's refineries for fired heaters. Based on the US EPA assessment of combustion emissions, emission factors for natural gas, fuel oil and LPG are reported in Table 1. MAA is the largest refinery in Kuwait with the most complex network of operation, and has two sides (refinery and gas plant sides) on its industrial location. Excluding the gas plant side, there are 45 fired heaters in operation in MAA refinery side. These could be classed according to its dedicated unit of service as per the following: Atmospheric distillation, vacuum distillation, hydrocracking, catalytic reforming, hydrogen generation, residual desulfurization, kerosene desulfurization and treating, distillate desulfurization and treating and others. The gas plant utilities, which hosts three trains of gas for acid-gas removal, were detailed separately for carbon emissions. Similar methodology was followed for SHU and MAB.

## Flaring in Kuwati Refineries

Flaring in refineries and other industrial facilities occur as an alternative to venting hydrocarbons to the atmosphere. Martin et al.[22] reported a correlation based on emission inventory analysis that estimates the amount of GHG ($CH_4$ and $CO_2$) emitted by refineries flares. This was used in this study to estimate the amount of $CO_2$ emitted based on the following:

$$FCE = 3.12\,(RT) \qquad (3)$$

Where FCE is the flares $CO_2$ emissions (kg) and RT is the refinery's throughput in tons. Kuwait's crude (more commonly termed Kuwait Export Crude, KEC) is of a 30.2 API in recent years with an estimated density of 875 kg/m$^3$. Hence, each refineries throughput in tons per day (tpd) is estimated and the amount of $CO_2$ from flaring is calculated based on reported data (2012). As expected, since the amount of $CO_2$ emissions is directly related to the processing capacity of a refinery, MAA has the major share of such emissions (≈50%) due to its capacity being largest. Flares in refineries are high in concentrations of hydrocarbons (typically rich in methane, $C_1$), which with complete combustion with methane can produce in a 1:1 ratio carbon dioxide ($CO_2$) and with ethane in a 1:2 ratio [23]. A flare system has multiple flares to treat the waste gases in a refinery. $CO_2$ can range between 0.02% to 2.8% depending on the type of operation, hydrocarbons in the flares and operating conditions [24]. Fisher and Brennan[25] and Peterson et al.[26] discussed the benefits of installing flare gas recovery units (FGRUs). Such systems capture gases (pre-flaring) for use in the refinery or for cleanup and polishing. Furthermore, flare gas may encompass substantial heating value and could be used as a fuel within the refinery to reduce the amount of purchased fuel.

## Acid Gas Removal Carbon Emissions

Acid gas removal (AGR) processes are common in petroleum refineries and are a crucial part of the operations in gas treatment plants. In MAA on the gas plant side of this refinery, $C_3$, $C_4$ and gasoline are cryogenically extracted through extraction/dehydration, cooling/chilling, fractionation and product treating. The gas plant contains an acid gas sweetening unit to remove $H_2S$ and $CO_2$ from the gas feed. Diethanolamine (DEA) solution is used in this unit which of 230 capacity MMSCFD. The gas feed enters an absorber where $H_2S$ and $CO_2$ are absorbed using DEA. The treated gas is fed to a separator to separate the carried DEA. The design specifications reported for this unit are summarized in Table 2, which show the three cases of treated gas in this process. Using the absorber balance equation for $CO_2$, we can estimate the amount of $CO_2$ exiting the system as follows [27]:

$$E(CO_2) = V_{in}\left[\frac{vol_{in} - vol_{out}}{1 - vol_{out}}\right] \qquad (4)$$

Where $E(CO_2)$ is the existing amount of $CO_2$ from the system in SCFD, $vol_{in}$ is the mol fraction of $CO_2$ in the entering stream and $vol_{out}$ is the existing mol fraction taken as (1.2% maximum). Estimated amounts of $CO_2$ are shown in Table 2. Acid condensate is treated in a similar fashion but is a different unit in this refinery. Composition of the condensate is shown in Table 3. A density of 750 $kg/m^3$ is assumed for this condensate [28]. Converting the flow rate of the entering stream to unit volume can allow the assessment of the total amount of moles by multiplication with the average molecular weight of the stream. From the unit inert balance we can estimate the $CO_2$ amount exiting the system taking $CO_2$ mol% (maximum out) as 0.5%. As for SHU refinery, a similar methodology was used to estimate the $CO_2$ vented. The amount of $CO_2$ out from gas and condensate treated in SHU was estimated to be $1.07 \times 10^5$ and $1.02 \times 10^5$ tpa, respectively.

# DISCUSSION AND ANALYSIS

The results obtained in this study regarding the $CO_2$ emission from the three refineries in Kuwait are discussed hereafter. Table 3 summarizes the results obtained for the three refineries (mtpa). The total of $CO_2$ emission was considered without the electricity import by the 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 [29]. The total amount of $CO_2$ emitted from MAA is 3.78 mtpa (Table 4). The global distribution of $CO_2$ 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. As previously indicated; utilities pose the major source of $CO_2$ in refineries. Fig.1 shows the distribution of $CO_2$ sources in MAA. There is a lack in open literature regarding utilities contribution to $CO_2$ emission and which heaters and boilers typically emit the largest amounts of $CO_2$ 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 $CO_2$ in SHU and MAB, respectively. Heaters and furnaces (unit utilities) represent 62-74% of $CO_2$ in the refineries. Past research also indicated that heaters contribute to anything between 26-65% of the $CO_2$ emissions from a petroleum refinery [1,15-17,29]. 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*' [1]. Past assessment of EU refineries given by Johansson et al.[1] 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.[5] reported $CO_2$ 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 $CO_2$ 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 $CO_2$ 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.

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 $CO_2$ emissions when natural gas is used as a fuel sources. 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.5). For a 250 Mbpd capacity refinery, HCPC[29] 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% [1,15]. In Kuwait, 12-25% of the refineries $CO_2$ 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 $CO_2$. 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 $CO_2$ emitted. 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 $CO_2$ 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 $CO_2$ emission from such units. Table 4 summarizes the $CO_2$ 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 4). Atmospheric and vacuum distillation use about 45% of refineries energy due to topping separation units. In Kuwait, refineries distillation units consume 18-28% of the refineries energy. SMR is also one of the most energy intensive operations in refineries, where hydrogen ($H_2$) gas is produced. Table 4 shows the contribution of units' utilities and the contribution of hydrogen production, in terms of specific $CO_2$ emission. Hence, it includes all contributions from the unit itself and support units to the carbon emissions load.

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 [31]. For example, FCC gasoline contributes to the sulfur content by 85-95% [32]. 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. A number of influencing factors affect the specific emission rate of a refinery, especially the quality of the crude oil processed. When considering the type and configuration of a refinery and the properties of crude oil it processes, one can observe the influence of operational conditions on the emission rate. Crude feed density, sulfur content, light liquids ratio to other products and unit utilization capacity, are all factors that influence $CO_2$ emissions. A correlation (with a high regression coefficient of 0.9) was established between these factors and the emission rates of US refineries by Karras [33], with an increasing trend. In addition, lower API which indicates heavier crude and higher sulfur content influences the carbon emission of the refinery. Both these factors indicate a more intense energy requirements (energy per barrel) and severe process intensity (HCPC, 2010). Such an effect could be attributed to two major factors. Firstly, lighter, sweeter crudes require less conversion and desulfurization. Secondly, for lighter and sweeter crudes, the refinery's energy requirements are met by more low-carbon fuel gas and less coke, fuel oil and other higher-carbon streams. Other crude oil properties also influence the carbon emission of a refinery, consequently the specific emission rate, such as the distribution of hydrocarbons (i.e. naphtha, distillates, gas oil), and the type of heteroatom compounds which can play a role in emissions, as well [29]. A useful tool for refiners is to estimate the specific emission of a certain process to carbon emission [29,34]. This was achieved in this work by determining the emission factors for most influential processes on carbon emissions (Table 4). Higher requirements for energy and utilities are going to be needed to achieve such low sulfur in products. Current refineries in Kuwait have an estimated specific emission rate ranging between 1.6-16 ton $CO_2$/bbl processed (Table 4). The specific emissions of a refinery can range from 0.02 to 0.82 tons of $CO_2$ per ton of crude oil processed [35]. Hence, if a density of 875 $kg/m^3$ was assumed for each barrel of crude and a volume of 0.16 $m^3$/bbl, the specific emission rate could be allocated to the range between 0.1 to 4.4 ton $CO_2$/bbl crude processed. Pagano et al.[34] reported a specific emission rate of US refineries operating with API of 32-38.3 with residue gasification to be 0.7 tons of $CO_2$ per ton of crude oil processed (3.82 ton $CO_2$/bbl crude processed). Lu et al.[36] reported an average emission rate of Illinois basin refineries in the US as 11.4 ton $CO_2$/bbl processed. Hence, a strong relationship between API and emission rates of refineries can be witnessed in past work and the estimates of Kuwait are on the same trend, where higher API of crude oil corresponds to a lower emission rate. This can be clearly witnessed in the case of the state of Kuwait where estimated API of processed crude could fall well above 22 and averages around 30.

# CONCLUSIONS

Kuwait is an oil dependent country that hosts mega crude production facilitates and refining networks, operating three of the world's largest refineries, namely MAA, SHU and MAB. In the upstream sector of Kuwait it is difficult to recover a $CO_2$ volume sufficient for EOR in the country. This is due to the scattered locations of the oil fields in Kuwait. As for the petrochemicals sector, all the $CO_2$ produced is utilized in the production of urea. Kuwait's refineries have been studied and a critical analysis of their $CO_2$ emission sources has been discussed 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 $CO_2$/bbl processed per day. 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.

# ACKNOWLEDGMENTS

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**Table 1.** Emission factors for $CO_2$ based on fuel type used in this work.

| Fuel | $CO_2$ (kg/GJ) |
|---|---|
| Natural Gas | 50.6 |
| Fuel Oil | 68.6 |
| LPG | 58.7 |

**Table 2.** Acid gas sweetening unit treated feed specifications showing entering main hydrocarbons and $CO_2$ (%mol) and estimated $CO_2$ existing (tpa).

| Item | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Flow rate (MMSCFD) | 149 | 230 | 89.2 |
| $C_1$ | 55.75 | 54.38 | 56.89 |
| $C_2$ | 19.13 | 18.63 | 17.98 |
| $C_3$ | 11.43 | 11.18 | 10.2 |
| $CO_2$ | 7.19 | 8.02 | 9.28 |
| $CO_2$ (Out) (tpa) | $1.83 \times 10^5$ | $3.27 \times 10^5$ | $1.50 \times 10^5$ |

**Table 3.** Acid gas condensate treated in the refinery showing feed composition (mol%) and estimated $CO_2$ existing the system (tpa).

| Item | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| Flow rate (bpd) | 34,700 | 39,000 | 11,100 |
| $C_1$ | 16.78 | 16.4 | 18.22 |
| $C_2$ | 18.42 | 17.94 | 19.54 |
| $C_3$ | 25.91 | 25.35 | 27.37 |
| $C_4$ | 18.66 | 18.43 | 17.59 |
| $C_5$ | 11.7 | 11.63 | 9.39 |
| $C_6$ | 3.3 | 3.27 | 0.69 |
| $O_2$ | 0 | 0 | 0 |
| $N_2$ | 0.06 | 0.06 | 0.1 |
| $H_2O$ | 0.02 | 0.02 | 0.02 |
| $CO_2$ | 3.81 | 4.25 | 5.44 |
| $H_2S$ | 1.36 | 2.64 | 1.64 |
| Total in (mol) | $95 \times 10^6$ | $108 \times 10^6$ | $32 \times 10^6$ |
| $CO_2$ (Out) (tpa) | $7.4 \times 10^5$ | $8.36 \times 10^5$ | $2.47 \times 10^5$ |

**Table 4.** Carbon dioxide ($CO_2$) emissions formulations developed in this work based on each major unit utilities and support units contribution.

| Process | Specific $CO_2$ emission* | Notes |
|---|---|---|
| Atmospheric Distillation | CE = 1.4 TP | - |
| Vacuum Distillation | CE = 1.5 TP | - |
| Hydrogen Production (HP) via SMR | CE = 112 TP + 0.25(HP) | Throughput and production rate are based on million tons per hour. |
| Hydrocracking | CE = 1.1 TP | Hydrocracking uses about 54 $m^3 H_2/m^3$feed [30]; which should be added to the formulation depending on the unit throughput. |
| Residual Desulfurization | CE = 0.28 TP | Desulfurization $H_2$ flow should be added depending on the unit throughput. |

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

# LIST OF FIGURES

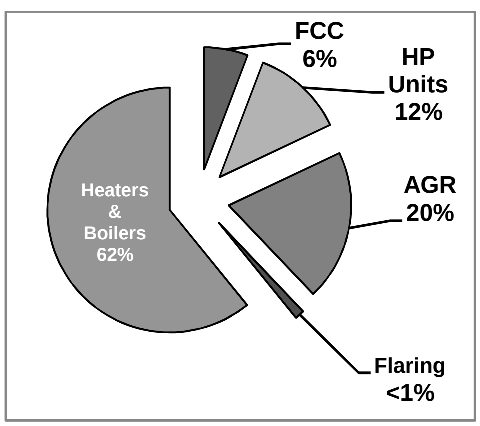


**Figure 1.** Percent contribution of each source in MAA with respect to $CO_2$ emissions.

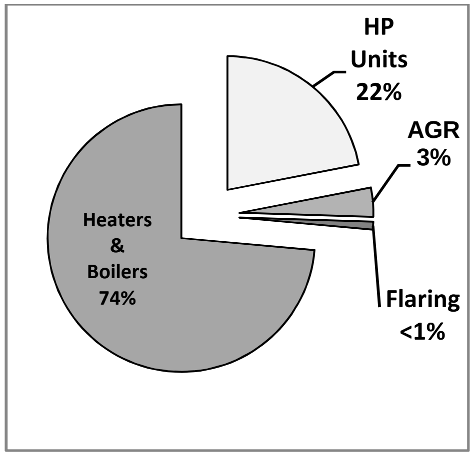


**Figure 2.** Percent contribution of each source in SHU with respect to $CO_2$ emissions.

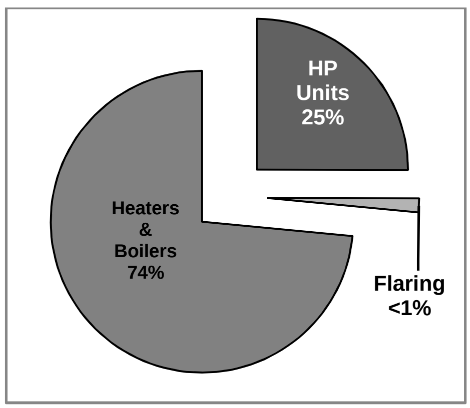


**Figure 3.** Percent contribution of each source in MAB with respect to $CO_2$ emissions.

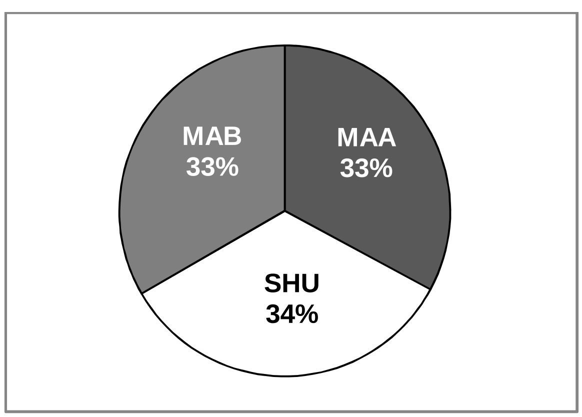


**Figure 4.** Distribution of HP units $CO_2$ emissions in Kuwait.

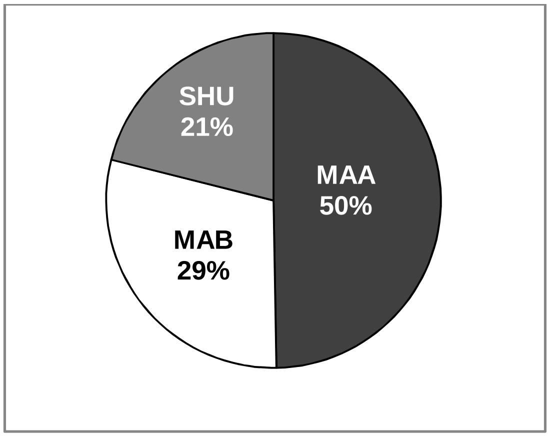


**Figure 5.** Distribution of heaters $CO_2$ emissions in Kuwait.

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