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The first carbon atlas of the state of Kuwait

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ABSTRACT

This article describes the development of first carbon atlas of the state of Kuwait which is a major step forward to support the decarbonisation of an oil-rich state. The Kuwaiti power sector proved to be the predominant stationary source of carbon dioxide (CO_2) emission due to a high regional demand for electricity and water. The chemical industry ranked second in this analysis with a significant share of CO_2 emissions (26%) which was attributed to heavy and energy intensive industries followed by road transportation (16%). In terms of geographical distribution, the Shuaiba industrial area proved to have the highest carbon footprint with 15 Mt CO_2/yr followed by the Al-Zour area with 12 Mt CO_2/yr. It can be observed from the analysis that the high emission facilities are clustered mainly in the southeast which is the main industrial area in the state. This distribution could potentially be favorable to form a ‘capture cluster’ which could reduce of overall cost of carbon capture deployment as a route for a sustainable carbon mitigation practice.

1. Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) emphasized that climate change has become an observable fact without any doubt [1]. Developing countries are considered among the most vulnerable regions to be effected by climate change impacts [2]. The state of Kuwait is a member of the Gulf Cooperation Council (GCC) countries, which lies in the northwestern corner of the Arabian Gulf, i.e. Persian Gulf (29°30′N lat. and 47°45′ E long.). Kuwait has witnessed an exceptional economic and social transformation since crude oil discovery and exportation back in 1946 and it holds 8% of the world's proven crude oil reserves [3]. Average rainfall in Kuwait is recorded as 100 mm with a desert (arid land) climate with no natural lakes or perennial rivers. Due to this harsh environment, Kuwait will face a multitude of environmental challenges in the near future as a result of climate change impacts, such as rising sea levels and rapid desertification. This is expected to have a great impact on the industrial and socio-economic developments of the country [4].

In light of a shortage of research quantifying the carbon footprint of any state, Lu et al. [5] investigated the main stationary sources of carbon dioxide emission in the Illinois Basin (U.S.A.). There work proved that almost 10% of carbon dioxide (CO_2) was yielded from non-utility industrial sources mainly from petroleum refineries, cement and ethanol plants. On the other hand, Darwish et al. [6] studied the intensity of CO_2 emitted from Qatar, a neighboring country to Kuwait, power stations. Although several scientific research studies have been conducted in analyzing the configuration of Kuwait's power plants (and stationary sources in general), few of them have analyzed or quantified the carbon footprint of these sources [7–13]. Alyuz and Alp [14] investigated the primary pollutants, including CO_2, released from industrial processes in Turkey. The analysis only considered industrial emissions and excluded the combustion sources. Seven main categories and 53 sub-sectors had been studied where mineral and iron industries were ranked as the largest contributors of these emissions, followed by organic chemicals, petroleum refining, pulp and paper industries.

In recent years, there have been some valuable reviews published on the carbon footprint of refineries. Van Straelen et al. [15] showed that furnaces and boilers are the largest contributors of these emissions due to the high numbers found in typical refineries, followed by utilities then Fluid Catalytic Cracker (FCC) units. Al-Sabbagh et al. [16] presented one of the first studies in the GCC region that investigated the carbon footprint of privately owned vehicles. The analysis was carried out despite the lack of data associated with fuel economy and average journey distance of these

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Nomenclature

BF	Blast Furnace
BOF	Basic Oxygen Furnace
bpd	Barrel of Crude Oil Per Day
CCS	Carbon Capture and Storage
CKD	Calcinated Cement Kiln Dust
CO_2	Carbon Dioxide
DRI	Direct Reduce Iron
DW	Desalinated Water
EAF	Electric Arc Furnace
EF	Emission Factor
EP	Electrical Power
FAO	Food and Agriculture Organization
FCC	Fluid Catalytic Cracker
GCC	Gulf Cooperation Council
GHGs	Greenhouse Gases
KNPC	Kuwait National Petroleum Company
KPA	Kuwait Ports Authority
MAA	Mina Al-Ahamdi Refinery
MAB	Mina Abdullah Refinery
Mbpd	Million Barrels Per Day
MEW	Ministry of Electricity and Water
MO	Ministry of Oil database
MOI	Ministry of Interior
Mt/y	Million Metric Ton/year
$MtCO_2/y$	Million Metric Ton of Carbon Dioxide Per Year
NRP	New Refinery Project
PFCs	Per-Fluoro-Carbon gases
ppm	Part Per Million
SHU	Mina Al-Shuiba Refinery
TEU	Twenty-Foot Equivalent Units
WBR	World Bank Report

vehicles. This can't be valid for a country like the State of Kuwait where this type of emission is noted to be associated with high number of average vehicles owned and operated by a resident. This is considered to be one of the highest in the world for Kuwait, as detailed in the inventory analysis of this study. According to the World Bank Data report [17], the carbon footprint of the state of Kuwait is 91.03 million metric ton. The World Bank estimates their data from the local consumption of fossil fuel in each country as an indicator of energy emissions. Emissions associated with cement manufacturing are taken as an indicator of non-energy carbon emissions. Similarly, the International Energy Agency [18], declared that the carbon footprint of Kuwait from fuel consumption was 69 million metric ton in 2010. This approach is a pragmatic way of estimating the emission from multiple states using a “top-down” methodology. However, in order for each state (or country) to plan the necessary process of decarburization, a more comprehensive or “bottom-up” approach is required [19]. Therefore, it is essential to have a comprehensive study that details all carbon emission sources in a country to be able to address such a gap in energy planning for the future. This is the main topic of research that this article deals with, where a carbon Atlas is presented for the state of Kuwait that identifies the main carbon sources and their strength along the way to be able to determine their optimal routes of use and reduction. In addition, the article presents a guide to assess various carbon emission industries which is applicable to many countries and cities in the world.

2. Methodology

The carbon atlas presented in this work is a means to understand, study and thoroughly document the sources of emissions using a geographical and sector based analysis. The carbon atlas of the state of Kuwait is a scientific database developed in order to explore and visualize the major carbon dioxide (CO_2) emission sources yield from human activities. Assessment and quantification methods in this atlas included the following:

- Identifying the major sectors that are responsible for national carbon dioxide emissions.
- Gathering data and process information from local and international institutes.
- Identifying the carbon dioxide Emission Factor (EF) for each process.
- Calculating carbon dioxide emitted from these processes and estimates these emissions in the near future.

Henceforth and based on the above stated, any process using Kuwaiti products, for example gasoline, which ultimately releases CO_2 outside Kuwait are not considered to be a *Kuwaiti* emissions. This was as assumption made to have a more clear defined boundary for the state to distinguish and validate the results obtained when comparison with past results and approaches were made. To best of our knowledge, no such attempt has been made in the past. This work can lead to the development of environmental strategic plans for the country based on energy analysis and updated data.

3. Carbon inventory and results of assessment

Due to the fact that the Kuwaiti economy is heavily reliant on the petroleum industry, this atlas separates the upstream and downstream petroleum activities which takes place in the state, in addition to the petrochemical activities. Each of the previously named petroleum activities was considered separately. Other sectors that are well known globally with regards to high carbon footprint, will also be considered, i.e. cement, iron, steel, power plants, buildings and transportation. In order to aggregate data from these sectors, both “top-down” and “bottom-up” approaches were used. In the top-down inventories, the data were obtained from national, and international institutes using their databases. Bottom-up approach, on the other hand, relies on data from local end-users (e.g. local companies, industrial inventories, etc).

After obtaining the required data, EFs for these processes were acquired from open literature and analyzed. Several agencies estimate EFs for various industries with the most well known provided Intergovernmental Panel on Climate Change (IPCC) and United States Environmental Protection Agency (EPA). The final concept of this atlas is aggregating the CO_2 emission from these sectors and comparing the final carbon footprint of Kuwait with those published values from international agencies.

3.1. Petroleum industry and related processes

3.1.1. Crude oil upstream processes and activities

In the oil and gas sector, upstream processes are usually classed as the Exploration and Production (E&P) processes of crude oil. It covers the exploring, drilling, production, enhanced oil recovery activities, until the final transportation of these natural fossil based fuels to concerned terminals. Several factors will play major roles in CO_2 emissions associated with the upstream processes such as the age of the oil field, gas to oil ratio, reservoir depth, pressure, level of contaminants and viscosity.

According to Kuwait's Ministry of Oil Database [20], the local consumption of crude oil in the oil and gas production sector is 15.1 million barrel. The EF for upstream processes in Kuwait is equal to 120.45 kg CO_2 eq./ton of oil equivalent [21], which makes the anticipated carbon dioxide emission equal to 0.255 $MtCO_2$/y (Million metric ton per year). This takes into account all associated burdens of the drilling and exploration activities in the country. It also accounts for oil production industries, which relies on heavy oil production that makes Kuwait associated with intense carbon emissions.

3.1.2. Petroleum downstream processes

After the production process of crude oil from wellhead manifolds, it is sent to refineries to start the downstream process. Gale et al. [22] indicated that refineries are responsible for 4% of worldwide CO_2 emission. The Kuwait National Petroleum Company (KNPC) owns and operates all three refineries that exist in the state. Kuwait processes almost 1 million barrel of crude oil per day (bpd) through Mina Abdullah (MAB) refinery with a capacity of 270 (Mbpd), Mina Al-Shuiba (SHU) refinery with a capacity of 200 (Mbpd) and finally Mina Al-Ahmadi (MAA) refinery with the largest capacity of 466 (Mbpd). All three refineries have been retrofitted multiple times to meet the world's increasingly tight environmental regulations for refinery products (e.g. percent of sulfur in diesel should not exceed 50 ppm). Al-Salem [23] identified and quantified the main sources of carbon emissions from Kuwait refineries (Table 1). The analysis was consistent with past reports for downstream activities, in terms of carbon load distribution, where it was reported that fired heaters are the largest contributor of these emissions (62–75%) followed by the Hydrogen Production unit (HP) (12–15%) [15]. The findings of this recent study were used to represent the downstream industry carbon emission in this work.

3.1.3. Petrochemical based industry

The petrochemical industry is a significant and leading sector in the chemical industry where it shares almost 40% of the global market [24]. The important role of this industry comes from a strong correlation with other economies: refinery products and industries dealing with downstream products. Table 2 illustrates the major petrochemical products produced in Kuwait. Due to relatively cheap feedstock of petrochemicals in Kuwait and interchanging products and utilities between the downstream sector with it (hydrogen, ethylene, etc), the country is known to host various polymerization product lines. It also hosts polyaromatic ventures with western partners. Ethylene is one of the main secondary products obtained from steam cracking process where it facilities in the production of various petrochemical derivatives. Ethylene production is an energy intensive process and its global production has increased at annual rate of 4–5% [26]. The European Chemical Industry Council for European steam crackers supports the linear relationship between ethylene production and CO_2 emission [27]. By applying the above correlation to the Kuwait petrochemicals sector, the expected CO_2 emission from producing 1.65 million metric ton of ethylene per year was 2.642 $MtCO_2$/y in the year 2016.

Table 1
Carbon dioxide emission ($MtCO_2$/yr) from the downstream industry of the state of Kuwait according to Al-Salem [23].

Source	MAA	SHU	MAB
Fluid catalytic cracking (FCC)	0.299371	N/A	N/A
Fired heater	3.220[a]	2.222	1.923
Acid gas removal (AGR)[b]	0.0272–1.0523	0.00907	N/A
Flaring	0.0635	0.0272	0.0362
Hydrogen production (HP) units	0.644	0.662	0.653
Electricity load	699	344	520
Total (million metric tons per year)[c]	3.429	2.921	2.612
% of total in Kuwait (w/o electrical import)	43.544	25.401	21.772

Notes to readers:
[a] Including gas plant side with refining activities (acid gas sweetening processes and condensate processing).
[b] Total of acid gas removal and condensate sweeting processes combined. A range is calculated based on the type of treated feed. Calculations were based on maximum CO_2 content in acid gas without the electricity load.
[c] Based on maximum CO2 content in acid gas without the electricity load.

3.2. The cement industry

The cement industry is the main participant of global CO_2 emission from non-energy sources [28] and it is responsible for 7% of global CO_2 emission [29]. Direct carbon being emitted from cement production is obtained from two main sources, the calcination process and combustion of fossil fuel. The indirect emissions are obtained from electricity consumed in the cement plant.

In this analysis, the *Tier 2* method of IPCC [30] was applied. The EF value was suggested by the IPCC as 0.459 metric ton CO_2 per metric ton clinker produced. IPCC added 2% of the CO_2 calculated because of the loss of some clinker raw materials as a calcinated cement kiln dust (CKD). The final equation to estimate carbon dioxide from calcination processes was applied thus:

$$H = 1.02EF \times C \tag{1}$$

where H is the process related emission (MCO_2/y); EF is the emission factor of 0.459 in metric ton CO_2/metric ton Clinker produced and C is the clinker production in metric ton/year.

By applying equation (1) in the Kuwait cement industry where the annual clinker production is 1,800,000 metric tons [31], the process related $CO_2$is estimated to be 0.165 $MtCO_2$/y. The intensity of CO_2 emission will be varied according to the type of fuel used and manufacturing operations applied for the cement industry. Due to the shortage of data of fuel consumption in Kuwait's cement factories, the estimated value suggested previously suggested by Ref. [31] which equals to 0.306 ($MtCO_2$/y) during 2011, was used in the analysis. From the above values, the total CO_2load from the cement industry of Kuwait from both processing and fossil fuels combustion is 0.322 ($MtCO_2$/y).

3.3. Aluminum manufacturing industry

To assess the CO_2emissions from the aluminum (Al)

Table 2
Major Petrochemical products in Kuwait in Million metric ton per year (Mt/yr) [25].

Petrochemical Category	Product	Production Rate
Fertilizers	Urea	1.05
	Ammonia	0.660
Olefins	Ethylene	1.65
	Polyethylene	0.9
	Ethylene glycol	1
	Polypropylene	0.15
Aromatics	Paraxylene	0.83
	Benzene	0.400
	Styrene monomer	0.45

manufacturing processes, three main sources of emission were identified:

- Combustion of fossil fuel (direct-energy related emission).
- Electricity used in smelting process (indirect-energy related emission), which are responsible for the biggest proportion of the emissions.
- Emission during the electrolysis process (process emission) where both carbon dioxide and per-fluoro-carbon gases (PFCs) are emitted [32].

The anticipated CO_2 emission was estimated from the following equation [33]:

$$Y = EF \times C \tag{2}$$

where Y is the total carbon dioxide emission from Al production in metric ton/year; EF is the emission factor, which is 1.4 (metric ton/metric ton Al) and C is the Al production in metric ton/year. According to GCC Industry Report [34], the total aluminum produces in Kuwait is 0.108 (Million metric ton/year) Mt/y. Therefore through applying equation (2), the carbon footprint of aluminum sector in the state is 0.167 $MtCO_2$/y showing a considerable variations attributed to change in Al production and market in the past decade.

3.4. Iron and steel industry

Iron and steel are the largest contributors of carbon dioxide emission among all industrial processes. This is mainly due to the high demand of steel in certain sectors (e.g. construction, transport, energy, packaging, appliances and industry), type of the fuel used and high-energy intensity of steel production [35]. CO_2 emissions from iron and steel production are obtained from three main sources:

- Process emission from sinter plant, non-recovery coke oven battery combustion stack, coke pushing, Blast Furnace (BF) exhaust, Basic Oxygen Furnace (BOF) exhaust, and Electric Arc Furnace (EAF) exhaust [36].
- Combustion of fossil fuel in furnaces and utilities including, byproduct recovery coke oven, battery combustion stack, BF stove, boiler, process heater, reheat furnace, flame-suppression system, annealing furnace, flare; ladle re-heater and other miscellaneous [37].
- Emission from electricity consumption, mostly from EAFs and finishing operation.

The international Energy Agency (IEA) methods were used in this analysis over Intergovernmental Panel on Climate Change (IPCC) guideline due to the limited availability of data of electricity and fuel consumption in the iron and steel manufacturing processes of Kuwait. The value of the CO_2 emission factor will be varied according to the selected pathway used to produce the steel. The emission factor is estimated to be 2.267 metric tons CO_2/metric tons crude steel for coal-based direct reduced iron (DRI) process, 1.632 metric tons CO_2/metric ton for integrated blast furnace (BF) and basic oxygen furnace (BOF). For scrap/electric arc furnace (EAF), it decreased to 0.362 metric ton CO_2/metric ton crude steel (EAF) [37].

By applying the above mentioned emission factors for United Steel Company and Kuwait reinforced steel manufacturing Co., CO_2 associated with production of 544,311 metric ton of steel using EAFs [38] is 0.197 $MtCO_2$/y. In Kuwait, the emissions associated with the production of 0.317 million metric tons (namely from the reinforced steel company) per year equals to 0.114 $MtCO_2$/y.

Table 3 details the CO_2 associated with the production of 1 km of steel pipe. The volume of the pipes produced ranged from 129.7 to 1167.4 m^3. A comparison will take place between the dimensions of Table 3 with the dimensions of steel pipe produce by the Kuwait Pipe Industries. The thickness of these pipes ranges from 4.8 to 25.4 mm and 0.168–2.032 m in diameter, and the length is between 6 and 16 m. As a result, the volumes of these pipes are between 0.133 and 52 m^3 and the associated CO_2emission is from 121.3 to 883.32 metric tons/km pipe. Based on the above results, the total anticipated CO_2 emission from iron and steel industry in Kuwait is 0.32 $MtCO_2$/y.

3.5. Chemical industry

The chemical industry is one of the highest-energy intensive industries and responsible for 10% of global energy consumption and 7% of global GHGs emission [40]. The products yielded from this industry can be generally classified into: basic chemicals (e.g. polymers), specialty chemicals (e.g. adhesives) and consumer chemicals (e.g. soaps). CO_2emissions are generated throughout the entire life cycle of a chemical product starting from the extraction of raw materials to the recycling process. The Public Authority of Industry in Kuwait categorized the chemical factories in the state according to their end products. Table 4 indicates the quantities of each chemical product produced during 2010 and the anticipated carbon dioxide emissions from the production processes. Based on this result, the total CO_2emitted from the chemical industry is 31.9 Mt/y. This estimate decreased by 20% in order to avoid double counting with electricity consumed in this sector. This percentage was obtained from personal communications with personnel in both the Public Authority of Industry and the chemical factories, as electrical input to chemical industry in Kuwait is taken as part of the power sector assessment. This makes the final carbon footprint of the chemical sector in Kuwait to be 25.45 Mt/y.

3.6. Paper

Globally, pulp and paper production is responsible for 3% of direct CO_2 emission from industry [41]. The CO_2 emission from paper production had been investigated by various authors [42,43], where steam production and electricity consumption are the main causes of these emissions. Kuwait has more than seventy companies specialized in paper production; most of them located in the Sabhan and the Shuaiba industrial areas. From the data available from Food and Agriculture Organization [44], the total paper produced in Kuwait during 2013 is 432 million kg. The corresponding emission factor of paper production is 0.00242 metric ton/kg. In conclusion, the associated CO_2emission from paper manufacturing processes is estimated to be 1.045 $MtCO_2$/y.

3.7. Power stations & water desalination plants

Kuwait is one of the world's smallest countries, however it is ranked as one of the highest per captia in energy consumption [35]. The Ministry of Electricity and Water (MEW) owns and operates all power stations in Kuwait and their associated facilities. MEW sells subsidized electricity and water for both commercial and domestic consumers. There are two main reasons behind large consumption in Kuwait. First of all, ultra low cost of electricity in the country where the government handles 95% of electricity cost and citizen and factories pay only 5% of the cost [45]. Secondly, the summer in Kuwait is one of the longest and hottest seasons in any country of the world starting from April until mid November with an outdoor temperature often exceeding more than 50 °C. Additionally a rapid

Table 3
Carbon dioxide emission for steel pipe production [39].

Diameter (inch)	Thickness (mm)	Weight (ton/km pipe)	Carbon dioxide emissions (metric tons/km pipe)			
			Blast furnace	Continuous casting	Rolling and pipe production	Total
16	7.95	70.669	109.497	0.997	10.795	121.29
20	9.82	109.134	169.099	1.542	16.692	187.242
24	10.25	136.622	211.827	1.905	20.865	234.597
36	14.35	286.942	444.792	3.991	43.817	492.601
48	19.30	514.555	797.596	7.166	78.652	883.325

Table 4
The anticipated carbon dioxide emissions from Kuwait chemical industry. Adapted from Public Authority for Industry [11].

Product	Production (million Kg) in the year 2010	Emission factor (metric ton CO_2/Kg)	Carbon dioxide emission ($MtCO_2$/y)
Asphalt	5654	0.00186	10.517
Detergents	292	0.00175	0.511
Plastic products			
Plastic in primer form	2.747	0.0027	0.00741
GRP pipes	13	0.0081	0.107
Plastic produced for building boats	0.19	0.0027	0.000514
Total plastic produced for floor, ceiling, walls, coverings in the form of tiles or rolls	9.802	0.0027	0.0264
Total plastic produced for shoes and sandals	2.041164	0.0027	0.00551
Total plastic produced in curtly	36.66	0.0027	0.0989
Fertilizers	1502.908	0.00462	6.943
Paints	32.591	0.0054	0.175
Lubricating oil and greases	62.63	0.00107	0.067
Industrial gases			
Oxygen	1463.43	0.00041	0.6000081
Nitrogen	4729.954	0.00043	2.033
Hydrogen	4525.222	0.00163	7.376
Carbon dioxide	0.8001	0.00082	0.000656
Sulfuric acid	44.515	0.00014	0.00623
Other chemicals	1131.752	0.003	3.395
Total	19,505.11		31.873
Total (-20%)			25.45

growth in population (an average growth rate of 3.3%) has also contributed to the increased electricity consumption [8].

Kuwait has seven power stations, namely: Shuwaikh (252 MW), Shuaiba North (876 MW), Shuaiba South (720 MW), Doha East (1158 MW), Doha West (2360 MW), Al-Zour (5306 MW) and Sabiya (4867 MW). The unique feature of these power stations is their ability to produce both Electrical Power (EP) and Desalinated Water (DW) simultaneously. Alotaibi et al. [8] illustrated that several forms of fossil fuels exist in Kuwait and can be used in these power stations including: natural gas, crude oil, heavy fuel oil, and gas oil. The source of power generation in these stations is shared between thermal steam turbines (85%) and gas turbines (15%) [7]. Tables 5 and 6 indicate the fuel consumed in all Kuwait power stations during 2005–2013 and the associated carbon dioxide emission during this period. Based on Table 6, the estimated carbon dioxide emitted from power stations is 41.6 Mt/y.

3.8. Building and construction

As a result of oil discovery in Kuwait, major economic growth resulted in the expansion of the urban sector of the state. Buildings are responsible for 30% of greenhouse gases (GHGs) emissions in both developed and developing countries [47]. Operation energy is the main source of CO_2emitted from buildings, it involves heating, cooling and lighting systems, in addition to all machines used in kitchens, offices etc. In Kuwait, this energy is translated into electrical energy obtained from Ministry of Electricity and Water (MEW) and energy from LPG and kerosene used for the household sector. In order to avoid double counting between CO_2emitted from the power plants and electricity consumption in buildings, this sector will cover only the carbon emitted from household consumption of LPG and kerosene.

According to the Ministry of Oil database [20], the household consumption of LPG during 2009 is 1.508 million barrel. The LPG per capita consumption has been estimated to 16.492 gallon.

$$W = D \times EF \tag{3}$$

where W is the total carbon dioxide emitted from LPG consumption during 2013 (Mt CO_2/y); D is the household consumption of LPG

Table 5
Fuel consumed in Kuwait power stations during the years 2005–2013 according to [46].

Fuel (million ton)	2005	2006	2007	2008	2009	2010	2011	2012	2013
Gas oil	0.088	0.488	0.444	0.784	1.221	1.0241	1.154	1.342	1.0410
Heavy fuel oil	5.223	5.972	5.461	6.283	4.992	4.947	4.387	4.345	5.293
Natural gas	2.284	3.112	3.237	3.631	3.783	5.285	6.080	6.654	6.387
Crude oil	2.177	1.169	1.867	1.0666	2.264	2.0244	2.191	1.867	1.276

Table 6
Carbon dioxide emitted from fuel consumed in Kuwait power stations during the years 2009–2016. Estimates were taken from Ref. [50].

Anticipated carbon dioxide emission ($MtCO_2/y$) from	2009	2010	2011	2012	2013	2014 (Est.)	2015 (Est.)	2016 (Est.)
Gas oil	3.555	2.9809	3.361	3.907	3.03	2.88	2.738	2.6
Heavy fuel oil	14.115	13.989	12.406	12.286	14.965	16.508	18.211	20.08
Natural gas	9.437	13.186	15.169	16.601	15.934	16.335	16.747	17.17
Crude oil	6.401	5.723	6.196	5.278	3.608	2.854	2.258	1.786
Total	33.511	35.881	37.133	38.075	37.538	38.577	39.954	41.636

and EF is the emission factor of 0.0058 Metric ton/gallon. This makes the anticipated carbon dioxide emission from LPG consumption 0.405 Mt/y and similarly kerosene is responsible for 0.14 $MtCO_2/y$ with emission factor of 0.00976 metric ton/gallon kerosene. Based on the above results, the total CO_2 emitted from Kuwait's buildings during 2016 is 0.54 $MtCO_2/y$.

3.9. Transportation sector

The transportation sector is responsible for 20% of global carbon dioxide emission [48]. In Kuwait, two transportation modes are available to the general public, road and air transport. Shipping is only used for commercial exporting.

3.9.1. Road transportation

Vehicles on Kuwaiti roads can be generally categorized as private and commercial ones. The Ministry of Interior (MOI) indicated that the total number of vehicles on Kuwaiti roads increased by 162% from 2005 to 2014 with a 61% increase in private cars (average of one car for each two residents of state). According to a World Bank Report [17], this average is higher than any developed country where on average each three residents own a car. The CO_2 emitted from vehicles varies according to the fuel economy of the vehicle and carbon content of the fuel used. Due to the limited data about fuel economy and average distance travelled by Kuwait vehicles, a general estimation of CO_2 emitted from these vehicles was derived according to the total amount of gasoline and diesel sales each year in Kuwait fuel stations. This method is adapted from the US EPA [49]. All gasoline and diesel consumed in Kuwait is derived from local refineries except for Euro4 Gasoline (95 Octane number) which is imported for ultra deluxe cars (Table 7). Due to the fact that factories also consume diesel from fuel stations, the total amount of diesel sales was decreased by 20% to estimate carbon dioxide emitted from heavy vehicles. This percentage was obtained from personal communication with engineers in KNPC. The US EPA [51] estimates emission factor of CO_2 emitted from gasoline is 0.00979 ton CO_2/gallon while diesel emits 0.0112 ton CO_2/gallon. Tables 7 and 8 illustrate both gasoline and diesel consumption in Kuwait gas stations during 2007–2016 and the anticipated CO_2 emission in this period.

3.9.2. Air transportation

Kuwait has one airport serving regional and international travelers alike. It is able to handle more than 9 million passengers per year. The number of scheduled flights in Kuwait's airport increased by 224.5% from 2004 to 2014 [52]. CO_2 emitted from any airport can be obtained from various sources including aircraft movement, transporting of both passengers and cargos and electricity consumption in the airport facilities. Due to lack of robust data associated with direct and indirect CO_2 emissions from Kuwait airport, a comparison was made between Kuwait airport and Glasgow airport (UK), which received a similar number of passengers (7.7 million). A study of Glasgow airport [53] identified its emissions on the basis of three sources which were considered in this study. The first was taken as the emissions obtained from the fuel consumed in company owned vehicles (e.g. refrigerators). The second was based on the emissions resulting from electricity consumption in the airport. This was excluded from this investigation to avoid double counting with power stations emission. The third source considered was the uncontrolled emission by the airport management (e.g. aircraft movement). In 2013, Glasgow airport emitted 0.105 $MtCO_2$/yr. Following the same analysis, the anticipated carbon dioxide emission from Kuwait international airport is 0.12 $MtCO_2/y$.

3.9.3. Sea transportation

Kuwait has six ports; three designed for dry cargos named Shuwaikh, Shuaiba and Doha while the remaining three are crude oil terminals: Mina Al Ahmadi, Mina Al Shuaiba and Mina Al Abdullah. Shuwaikh port is the main commercial port in the country where it handles most non-petroleum cargo while most of the crude oil and petrochemical products are exporting through Mina Al-Ahmadi. The Kuwait Ports Authority (KPA) is responsible for operating all the commercial ports in addition to the new port that will be located in Boubyan Island known as Boubyan port. A comparison was made between Gothenburg Port and Kuwait ports based on twenty-foot equivalent units (TEU) which is the international unit used to estimate the cargo carrying capacity of any port. TEU for Gothenburg Port in 2013 is 858,000 and the associated carbon dioxide emission is 0.16 $MtCO_2/y$. The CO_2 obtained from electricity consumption had been excluded from this analysis in order to avoid double counting. Based on a linear scaling out, the carbon dioxide emitted from all Kuwaiti ports with a total of 1,215,675 TEU is 0.2 $MtCO_2/y$ distributed on the three ports [54]. A summary of the methodology and emission factors is presented in Table 9 for the development of the Carbon Atlas of Kuwait.

4. Discussion

The carbon atlas of the state of Kuwait is summarized and presented in Table 10 (by category) and Fig. 1 (by subsectors and carbon load). Power plants were responsible for 42% of carbon dioxide emission due to high demand of electricity and water. Interrelated reasons are behind this demand and they are summarized as the high level of electricity and water subsidization by

Table 7
Fuel seals in the local market between the years 2007–2013 [50].

Fuel (million Gallon)	2007	2008	2009	2010	2011	2012	2013
Total Gasoline	802.316	831.983	850.792	881.409	904.498	944.837	990.222
Total Diesel	236.444	240.227	271.885	295.957	293.695	337.104	336.407

Table 8
Carbon dioxide emitted from gasoline and diesel consumption during the years 2008–2016 (Estimated consumption of fuel for years 2014–2016 were taken from Ref. [50]).

Carbon dioxide ($MtCO_2/y$) from	2008	2009	2010	2011	2012	2013	2014 (Est.)	2015 (Est.)	2016 (Est.)
Gasoline	8.145	8.329	8.629	8.855	9.249	9.694	10.153	10.634	11.665
Diesel	2.69	3.045	3.314	3.289	3.775	3.767	4.04	4.334	4.649
Total	10.835	11.374	11.943	12.144	13.025	13.462	14.193	14.968	16.314

Table 9
Summary of the carbon atlas assessment methodology and emission factors.

Sector	Inputs (amount)	Emission factor/formula used	Notes	Reference
Upstream industry	15.1 mbpd (2.1 Mt/d) consumed crude oil	120.45 kg CO_2-eq/ton of oil equivalent	–	[20], [21]
Downstream industry	Total CO_2 emitted (8.962 mtpa). See Al-Salem [23] for breakdown by refinery process and emission factors			
Petrochemicals	1.6 Mt/y	1.6 kg CO_2/kg ethylene	Based on ethylene production	[27]
Aluminum	108,862 tons/y	1.4 kg CO_2/kg Al.	–	[34]
Paper	432 ton	0.00242 metric ton CO_2/kg	–	[43]
Paint (chemical industry)	32.59 million kg	0.0054 metric ton CO_2/kg	–	[11]
Detergents (chemical industry)	292 million kg	0.00175 metric ton CO_2/kg		
Fertilizers (chemical industry)	1502.9 million kg	0.00462 metric ton CO_2/kg		
Plastic (Primer production)	2.74 million kg	0.0027 metric ton CO_2/kg		
Plastic (Boat building)	0.19 million kg	0.0027 metric ton CO_2/kg		
Plastic (floor)	9.80 million kg	0.0027 metric ton CO_2/kg		
Plastic (shoes)	0.20 million kg	0.0027 metric ton CO_2/kg		
Plastic (curtly)	36.68 million kg	0.0027 metric ton CO_2/kg		
Asphalt	5654.45 million kg	0.00186 metric ton CO_2/kg		
Other chemicals	1131.75 kg	0.003 metric ton CO_2/kg		
Oxygen gas industry	1463.43 million kg	0.00041 kg CO_2/kg		
Nitrogen gas industry	4729.954 million kg	0.00043 kg CO_2/kg		
Hydrogen gas industry	4525.222 million kg	0.00163 kg CO_2/kg		
CO_2 gas industry	0.8001 million kg	0.00082 kg CO_2/kg		
Cement industry	1,800,000 metric tons	0.459 metric ton CO_2/Kg	Clinker production	[30]
Road transportation	990.222 million gallons (gasoline) 336.407 million gallons (diesel)	0.00979 ton CO_2/gallon (gasoline) 0.0112 ton CO_2/gallon (diesel)	Based on fuel consumption in 2013	[49]
Sulfuric acid industry	44.515 tons	0.00014 kg CO_2/kg	–	[11]
Lube oil and grease	62.63 tons	0.00107 kg CO_2/kg		
Air transportation	Assumed to be similar to Glasgow airport receiving same number of flights and air traffic [53]			
Power plants	1.0410 million tons (gas oil) 6.387 million ton (natural gas) 5.293 million ton (heavy fuel oil) 1.276 million ton (crude oil)	Emission factor for gas oil (0.875 kg CO_2/kg) Emission factor for natural gas (0.75 kg CO_2/kg) Emission factor for Heavy fuel oil (0.85 kg CO_2/kg) Emission factor for crude oil (0.85 kg CO_2/kg)	Based on 2013 inventory	[6]
Building & construction	1.508 million barrel (LPG) 1.43 million barrel (kerosene)	0.0058 Metric ton/gallon LPG 0.00976 metric ton/gallon kerosene	Based on Government database [20]	[20], [47]
Steel industry	544,310.844 metric ton	0.36 kg CO_2/kg	For breakdown see section 3.4	[38]
Sea transportation	Taken from Ref. [54] as 0.2 $MtCO_2$/y distributed on three ports			

Kuwait government, the subtropical desert climate of the state and the significant growth rate of Kuwait population. The power sector is typically considered as the main source of carbon emissions worldwide [1,6,9,10,15,23,54], which is consistent with this study's findings. Chemical industries were ranked second in this analysis followed by road transportation. It should also be noted that the carbon emissions from the petroleum industry in this work was related to all oil and gas activities stretching from upstream to basic

Table 10
Carbon footprint of the state of Kuwait in 2016.

Sector	Anticipated carbon dioxide emission ($MtCO_2/y$)
Air transportation	0.122
Aluminum	0.167
Sea transportation	0.226
Cement	0.322
Iron and Steel	0.312
Petroleum upstream processes	0.255
Petrochemical	2.642
Building and Construction	0.545
Petroleum downstream processes	8.962
Road Transportation	16.314
Chemicals Industry	25.45
Paper	1.0454
Power and water sector	41.636
Total	98

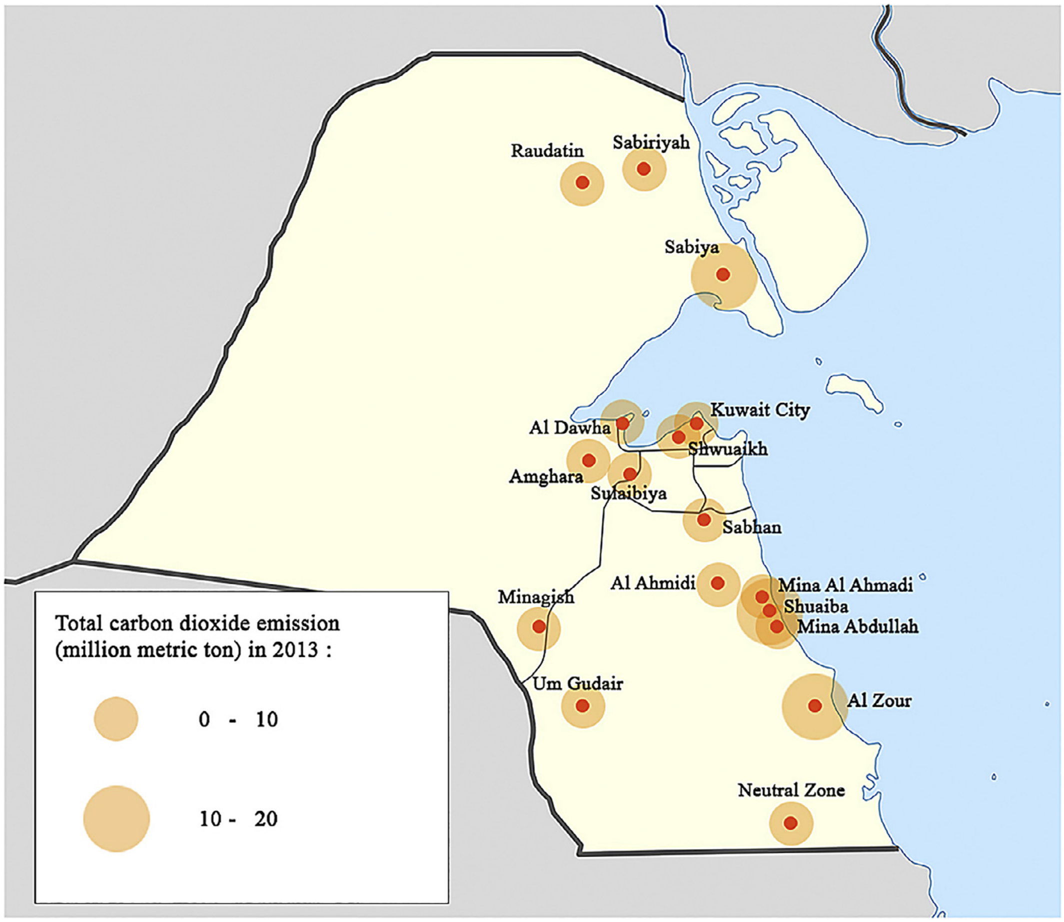

Fig. 1. Carbon footprint of the state of Kuwait in 2016 (Mt CO_2/yr).

chemicals production without double counting. This approach differentiates between the different individual carbon emission load of each industry in Kuwait which was not done in the past. The chemical processes accounted for in this study included some products that may be accounted for as petrochemicals (e.g. polymeric products, basic feedstock gases, chemical off-gases, etc.). However, since a basic chemicals industry exists in Kuwait that relays on petrochemical industries, double counting with those petrochemicals between these two sectors was avoided. In addition, the chemical industries assessed in this study also accounts for chemical products used as commodities (Table 4). Hence, this sector was suspected (and confirmed by this study) to be a major contributor to Kuwait's total carbon load (25.5%). By studying the results obtained in this work carbon inventory and comparing countries emissions by rank [55], it is noted that Kuwait has a unique carbon emission distribution due to the categorization of its industries. Since refining activities include majority of AGR and sweetening processes, downstream activities include the major share of the natural gas associated carbon emissions. The paper market in Kuwait also presents a hefty proportion of the carbon emission (about 1 Mt CO_2/y) due to its reliance on petroleum based feedstock and its GCC market share.

Fig. 2 depicts the geographical distribution of CO_2stationary sources emissions where the Shuaiba industrial area, about 50 km south of Kuwait City, has the highest carbon footprint with 15 Mt CO_2/yr in 2013 followed by the Al-Zour area with 12 Mt CO_2/yr. The high footprint of Shuaiba industrial area can be attributed to the presence of large-scale industries (e.g. chemicals and petrochemical plants), Kuwait cement plant, North and South Shuaiba power plants, Shuaiba refinery (SHU) and many small industries. The area also suited on the borders of several new ventures in chemical industries, including expansions in petrochemicals and chemical industries alike.

The Kuwaiti State total emissions has been published by both the World Bank (91.03 Mt CO_2/yr) [17] and IEA (69.82 Mt CO_2/yr) [18] with corresponding differences of 7.7% and 40%, respectively. It is considered that since the process emissions have been covered in detail for the first time in this study, the higher value of the estimated carbon dioxide emissions in comparison with the other reported values is explained. This result may well show a systematic underestimation of CO_2 emissions from those states engaged significantly in the heavy process industries. Nevertheless, the level of detail and quantity of data provided in this work is significantly greater and should therefore supersede the result of these two analysis as the figure for total Kuwaiti CO_2 emissions.

The differences do however highlight the shortcomings of the simplified analysis published previously and a need for similar work to be carried out for all national states as the potential margin for error appears to be within the same order of magnitude (i.e. tens of percentage points) as existing and on-going planned GHG emission mitigation targets. This outcome demonstrates that any benchmark of CO_2 emissions used as a reference point could easily be incorrect and the World Bank and IEA estimates should be considered with greater care.

5. Conclusion and policy implications

The first comprehensive evaluation of the main carbon dioxide

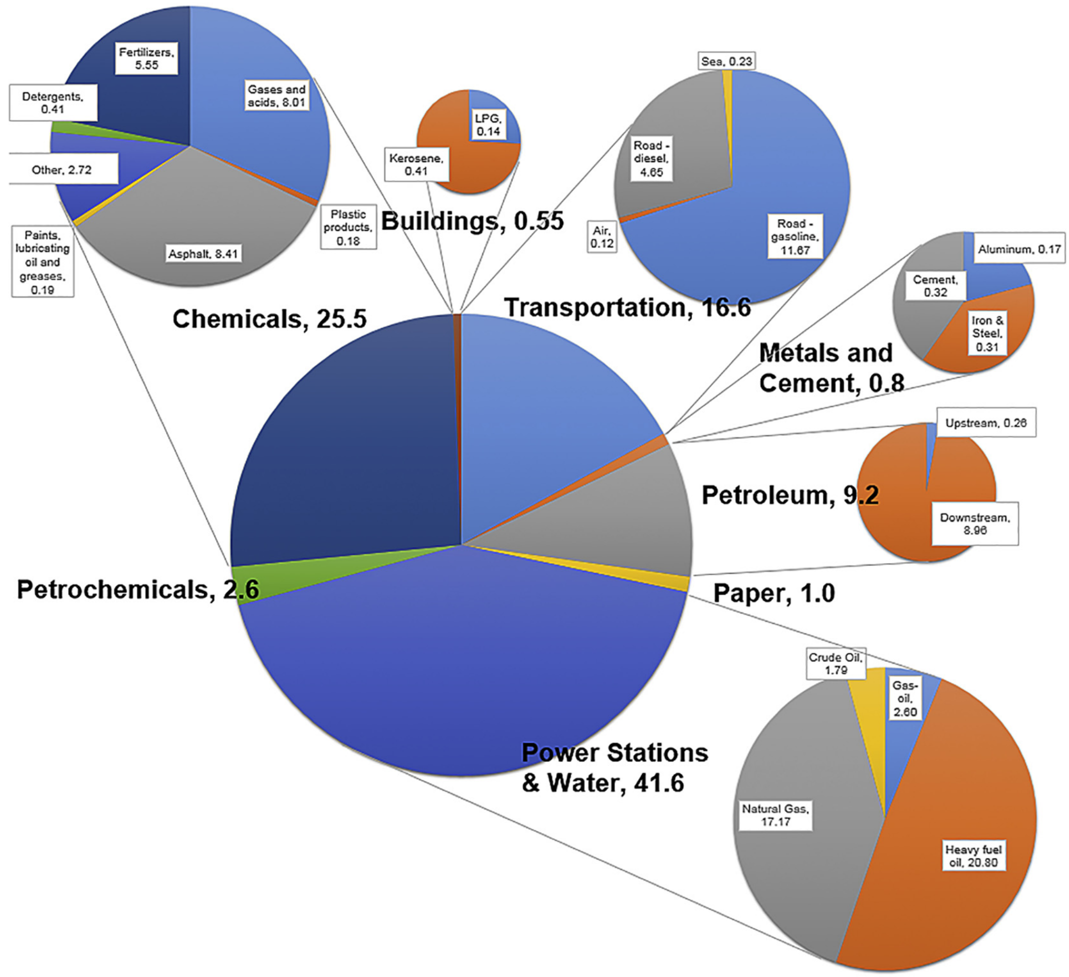

Fig. 2. Geographical distribution of carbon dioxide emission stationary sources.

(CO_2) emission sources in Kuwait was conducted and presented in this work. The total process emissions were determined in detail for the first time, which explains the variation between the real carbon footprints of Kuwait with previously published total emission values. Most of the high emission facilities are clustered in the Shuaiba (15.15 Mt) and the Al-Zour (12.21 Mt) industrial areas in southeast of Kuwait. These high emission areas can be considered as Kuwait's CO_2hotspots representing 40% of total carbon emissions in Kuwait.

The comparison with other estimates of CO_2 emissions show the limitations of the more simplistic evaluation methods. With differences of 7% and 40% respectively attributed to the level of detail considered in the quantification of CO_2 emissions from the heavy process industries it highlights the importance of the proposed work. Especially in the context that a successful GHG mitigation policy is measured relative to historical GHG emission benchmarks – which could well carry significant error and uncertainty.

By identifying and benchmarking the sources of CO_2in Kuwait and their corresponding geographical locations, decision takers and policymakers now have the opportunity to consider how to mitigate emissions across the state. This could be in the form of additional infrastructure, (for example, the Shuaiba and the Al-Zour industrial areas are regions in which there may well be sufficient quantities of carbon dioxide emissions to justify carbon capture and storage technology), or simply using the data to quantify the benefits of a policy which facilitates the transition from heavy fuel oil to natural gas power generation. It can be noted that cleaner fuel projects coming up to the downstream industries scene in the near future, can reduce such emissions. However, reliance on heavy crude must be assessed before undertaking any future mitigation plans especially that the country is embarking on upstream ventures that will increase the production of crude oil to the global market in 2020.

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