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*Article*

# Atmospheric Emissions from Oil and Gas Extraction and Production in Greece

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**Abstract:** This paper addresses the atmospheric emissions from oil and gas extraction and production in Greece. The study was carried out in 2014 in the Kavala gulf, which currently is the only location of oil and gas production in Greece and where the exploration activities for hydrocarbons started in the late '60's. This study presents the qualitative and quantitative characteristics of atmospheric emissions, in relation also to the emissions' control management system. Particular reference is made to sulphur compounds since the existence of volcanic rocks results to increased amounts of $H_2S$. The results shows that, currently, atmospheric emissions of pollutants during extraction and production of hydrocarbons in Greece are very low and do not have any significant effect on air quality and climate change. Since it is expected that exploitation of hydrocarbons and oil and gas extraction and production will increase in the future, appropriate measures should be taken to ensure environmental protection, such as the development of integrated monitoring systems and the use of up to date emission control technologies.

**Keywords:** oil and gas production; atmospheric emissions; greenhouse gases; gas flaring; $H_2S$

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## 1. Introduction

### *1.1 Oil and gas extraction and production in Greece*

Oil and gas exploration in Greece begun in 1969, when the State granted hydrocarbon exploration concession rights, in the Gulf of Kavala, to a Consortium of foreign companies. The first well drilling in the region was the «EAST THASSOS-1» in 1971, while in 1972 the "SOUTH KAVALA" natural gas reservoir was discovered. Nowadays, there are three sour crude oil reservoirs in the Prinos area and one sweet gas reservoir in south Kavala [1].

The present work focuses on atmospheric emission from the Prinos facilities in 2014. In order to fully understand the potential impacts of oil and gas extraction on the environment, it is important to understand the activities involved [2]. The facilities in reservoirs such as that of Prinos, are developed both offshore and onshore and the produced fluid is transported through pipelines from offshore to onshore (Figure 1).

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**Figure 1** Region of Prinos in Kavala gulf, East Macedonia/Thrace, Greece.

Onshore facilities account for the final processing of the oil and gas streams into stabilized crude oil, natural gas, natural gas in liquid form and elemental sulfur. The total atmospheric emissions from the oil and gas production industry in 2014 in Greece originated from the facilities of the gulf of Kavala. The average oil and gas production of 2014 was 1,486 bopd [3]. For the following years a new investment programme will be implemented, in order to increase the current production up to 20,000 bopd [4]. Nowadays the onshore and offshore leases in Western Greece and in the Ionian Sea are increasing the exploration agenda in the western part of the country to nine leases (Figure 2) [5].

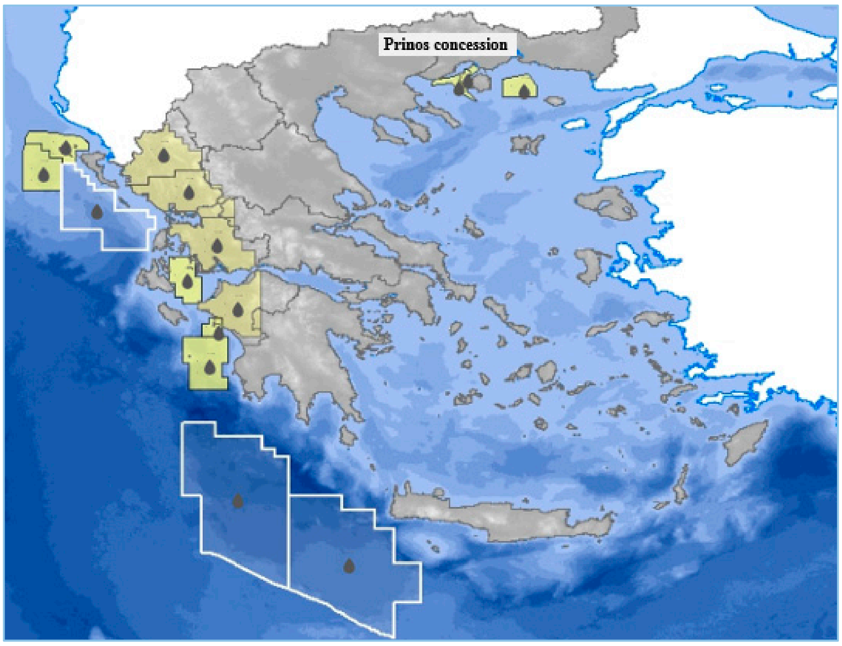


**Figure 2** The onshore and offshore leases in Western Greece, Ionian Sea and south of Crete.

Hence, it is essential examine the current situation and to provide insight so that in the future the oil and gas industry's activities in Greece will meet the atmospheric emission and air quality standards, through applying an integrated programme for the monitoring and control of atmospheric emissions.

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*1.2 Atmospheric emissions from oil and gas extraction*

In most oil and gas reservoirs, initially the fluid flows naturally to the surface under the pressure from the bottom hole. When the produced fluid reaches the surface, it is driven to the separation units. Particularly, the crude oil is separated from the dissolved gas (associated gas) and the hydrogen sulfide ($H_2S$) and then is stored in order to be loaded in tankers. In Prinos, the recovery of hydrocarbons is mainly achieved with the use of gas lifting. The operator injects sweet natural gas into the producing wells using gas lifting facilities (enhanced oil recovery); as a result the oil & gas production is increased and the produced fluid contains less hydrogen sulfide (Figure 3).

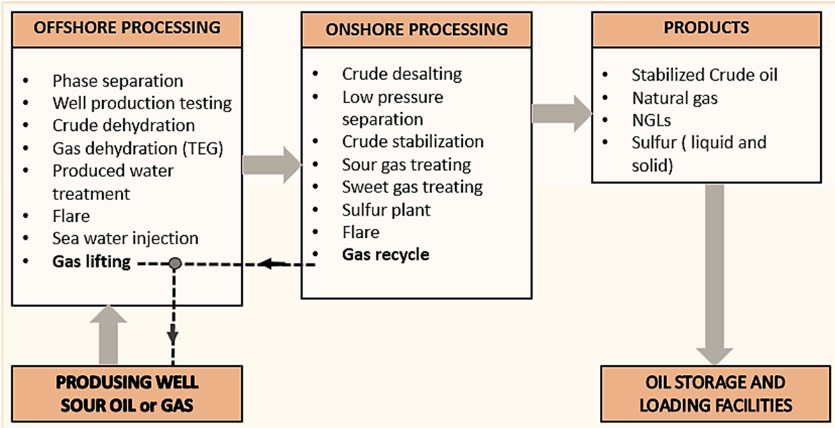


**Figure 3** Oil and gas processing in the case study area.

The extraction and storage process results to three main types of atmospheric emissions: combustion gases, fugitive emissions, as a result of the storage of fluids in tanks, and chlorofluorocarbons coming from refrigeration systems. The types of atmospheric emissions are described in Table 1. The most significant emissions from the production oil and gas in Greece are those of carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$) and nitrogen oxides (NOx).

**Table1** Air emission sources and components of Greek oil and gas extraction and production.

| **Emissions from energy production (conversion) or power generation** | **Emissions from storage and loading of oil** | **Fugitive emissions** |
|---|---|---|
| $CO_2$, NOx, $SO_2$ , Pm10, Pm 2,5 , CO and nmVOC | $CH_4$ & nmVOC | $CH_4$ & nmVOC |

## 2. Methodology

*2.1 Criteria air pollutants*

The offshore and onshore facilities are located about 8 km north-west of the island of Thasos and 10 kilometers east of the city of Kavala, respectively. According to the Greek and European Union legislation, the operator must control air pollutants into the atmosphere from all oil and gas activities within approximately 100 km from the coast in order to ensure high air quality levels and to protect the human health [6].

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**Figure 4** Locations of air quality monitoring network in Kavala gulf.

For this purpose, the operator has installed an air quality monitoring network in the gulf of Kavala (Figure 4). Furthermore, there are twelve total sulfation monitoring stations (Concentration Measurement Instruments) in different onshore locations and one central environmental monitoring station (Continuous Emission Monitoring & Recording Systems) close to the onshore facilities. The monitoring network is common for the onshore and offshore installations. The main environmental station records hydrogen sulfide ($H_2S$), sulfur dioxide ($SO_2$), total hydrocarbons (THC), methane ($CH_4$), non-methane hydrocarbons (NMHC) and meteorological parameters (wind direction and speed, ambient temperature, relative humidity). Sulphur dioxide concentrations are measured by ultraviolet fluorescence. Nitrogen oxides and nitrogen dioxide are measured by chemiluminescence.

The twelve total sulfation measuring stations record concentrations of sulfur compounds using a passive concentration measurement device based on the assumption that lead dioxide can oxidize sulphur gases such as sulfur dioxide, hydrogen sulfide and mercaptans to lead sulphate (total sulfation). To this end, a special paste of lead dioxide and mastic alcoholic solution is placed on special surfaces which are exposed to the atmosphere for a period of one month. Then, they are treated in the laboratory with a sodium carbonate solution. The unreacted lead dioxide is filtered and its pH is adjusted at 2.5; as a result, the sulfates precipitate as boron sulphate (BaSO4). The turbidity due to the boron sulphate precipitation is measured using spectrophotometer at 420 nm. Finally, the total sulfur is calculated using the following equation:

$$mg\ SO_2\ per\ day/\ 100\ cm2 = \frac{mgBaSO_4\ *\ \left({MW_{SO_3}}/{MW_{BaSO_4}}\right)}{d\ *a} \tag{1}$$

Where d is the number of days, $\alpha$ is the area in $cm_2$, $MW_{SO_3}$is the molecular weight of $SO_3$ and $MW_{BaSO_4}$is the molecular weight of $BaSO_4$

Furthermore, a continuous monitoring system is used for undertaking direct emission measurements of $SO_2$ and NOx (as $NO_2$) in the furnace of the Sulfur Unit Incinerator. In the other furnaces of the combustion units discontinuous measurements are contacted every semester to evaluate the quantities of $SO_2$ and NOx present in the emissions [7]. The results from the twelve sulfation monitoring stations and from the central environmental station are presented in monthly and annual environmental reports. The calculation of $SO_2$ emissions in all combustion plants (excluding the incinerator) is based on the content of sulfur (S) in the fuel. The S content is obtained as an average of 52 measurements/year (1 measurement/week) and corresponding composition analysis. These data are used to derive an emission factor of sulfur dioxide which is related to the sulfur content (%) of the fuel and it is calculated based on the $H_2S$ content of the gas. The $SO_2$ emission factor of the flare process at the offshore installations is equivalent to 2.79*10-3tn $SO_2/m^3$ of produced water. The average value of the $SO_2$ emission factor for stationary combustion units is 30 ppmv S (81.24*10-9tn $SO_2$/S $m^3$). Exceptionally, continuous monitoring is conducted in the furnace of the Sulfur Unit Incinerator, where the amount of pollutant emitted each day adds up separately to the total annual emissions of $SO_2$ on the basis of the volumetric flow rates of waste gases. The NOx emission factor is equivalent to 0.003 kg NOx/$Nm^3$ of natural gas, for all combustion engines, while the NOx coefficient for turbines is equivalent to 0.006 kg NOx/$Nm^3$ of natural gas. NOx values for all combustion units are calculated as the average of twelve measurements per year (1 measurement per month) in each furnace using a portable analyzer [8].

*2.2 Greenhouse gases*

The operator of the oil and gas extraction and production facility monitors, controls and reports greenhouse gas emissions on the basis of the internationally agreed obligations. To this end, a greenhouse gas inventory is prepared each year, using field-specific emission factors in accordance with the requirements of the «Greenhouse Gas Emission Regulations» and the approved monitoring program of Hellenic Ministry of Environment and Energy for the relevant facility [9 &10].

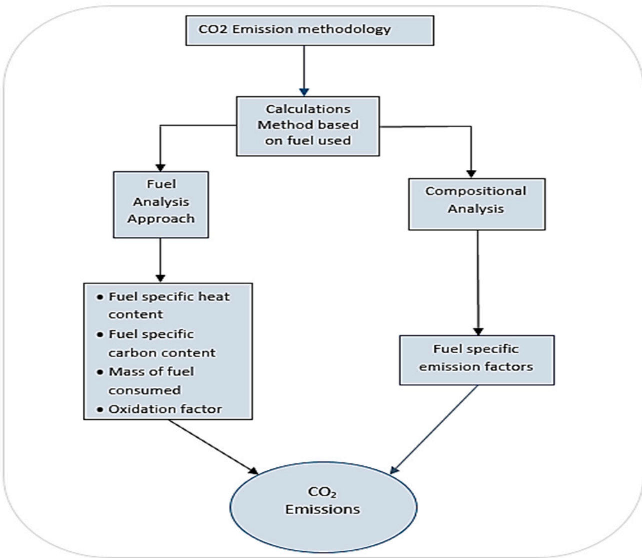


**Figure 5** Analytical framework for $CO_2$ emission estimations.

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The annual $CO_2$ emissions are calculated from the mass of fuel consumed times an emission factor (Figure 5). The $CO_2$ emissions of combustion engines are calculated using the standard tier uncertainty estimation methodology, using appropriate emission factors. Tier 2a of IPCC has been used in particular to estimate emissions from fuel combustion by source subcategories. To derive the field-specific emission factor of $CO_2$, a detailed analysis of the hydrocarbon composition is performed, taking into account the carbon contents of the fuels composition, the carbon oxidation factors and the fuel quality. (Table 2). Following this approach, the $CO_2$ emissions which have been used to estimate the annual inventory of the fuel gas domestic mixture is equivalent to 56.95 tn $CO_2$/TJ [11]. It should be noted that emission factors may vary over time, since they are associated with the composition of the fuel. Therefore, a reliable analysis of the hydrocarbon composition is the cornerstone of emission factor estimations.

**Table 2** Carbon dioxide emission factors (in t CO2 / TJ) and net calorific value (in TJ / kt) by fuel type.

| Fuel type | Net calorific value (in TJ / kt) | Carbon content CC tc/TJ | Oxidation factor % | EF (TCO2/TJ) |
|---|---|---|---|---|
| Diesel oil | 42.8 | 20.12 | 100 | 73.78 |
| Heavy fuel oil | 40.14 | 21.38 | 100 | 78.4 |
| Natural gas-Domestic | | 15.95-16.22 | 100 | 56.95 |
| Natural gas-Imports | | 15.15-15.18 | 100 | 55.55-55.67 |

## 3. Results and discussion

### *3.1 $CO_2$ emissions*

$CO_2$ is emitted during all combustion processes as a function of the carbon number of the fuel used. The major sources contributing to $CO_2$ emissions are boilers, in which fuels are oxidized in order to generate heat for internal use, and turbines (gas turbines), used for power generation [12]. Annual greenhouse gas emissions in Greece were 34933.8 tn $CO_2$ in 2014 (Figure 6). These inventories are verified by authorized external auditors, according to Regulations 600/2012/EC and 601/2012/EU. Emissions of greenhouse gases from the offshore facilities (Delta complex & Kappa) during 2014 were 1684.3 tn $CO_2$, which equals to 4.82 % of the total emissions (Figure 6). It should be noted that in offshore facilities the major $CO_2$ emissions are due to gas flaring, glycol dehydrators, electricity generator and diesel gas compressor. Although a $CO_2$ emission factor derived from compositional analysis is used, the maximum uncertainty of the flare inventory according to Tier II requirements could be ±12.5% [13].

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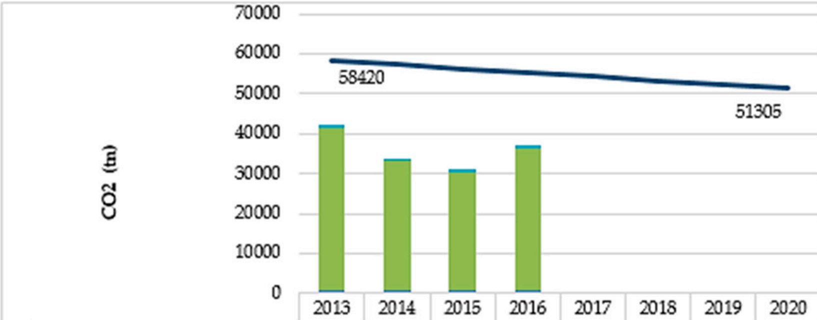


| | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|
| Delta Verified Emissions | 808 | 833.8 | | | | | | |
| Sigma Verified Emissions | 40759 | 32249.5 | | | | | | |
| Kappa Verified Emissions | 811.1 | 850.5 | | | | | | |
| Allowances in Allocation | 58420 | 57404 | 56387 | 55370 | 54354 | 53338 | 52321 | 51305 |

Figure 6 Comparison of the $CO_2$ emissions inventory (tn) with allocated allowances in the EU emissions trading system.

*For the years 2015 and 2016 the annual verified emissions are 31044tn and 36980tn respectively.

At the onshore facilities (Sigma), the main emission sources are the direct-fired boilers, the super heater and the sulfur tail gas incinerator of the Sulfur Plant (two Claus units in parallel and three sulfreen type batch reactors). Turbines have not been used since 2010, therefore they are not included in the greenhouse gas emissions for the year 2014. It should be noted that the operator has a holding account in the Greek Registry of GHG Emissions and participates in the emission trading system, and will meet the greenhouse gas emission reduction commitment requirements until 2020 (Figure 6).

Figure 7 presents the historical trend for direct and indirect $CO_2$ emissions, per barrel of hydrocarbons delivered per day, in the 2000-2014 period [14]. The data from the period 2000 to 2014 revealed that the trend of oil production was linearly decreasing, while $CO_2$ emissions were in general rising for the same period. Furthermore, emissions of $CO_2$ decreased by 67.73% for 2014 as compared to $CO_2$ emissions in 2008, a year where emissions had peaked [15].

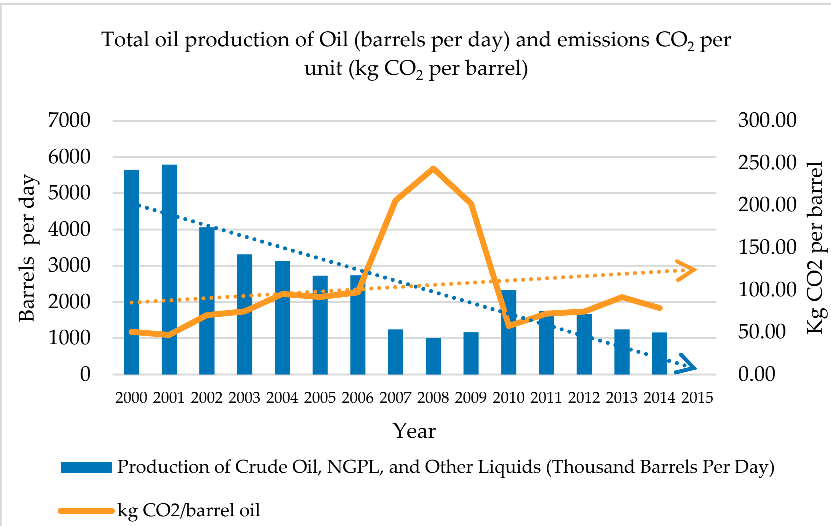


**Figure 7** $CO_2$ emissions and Oil and Gas Extraction in Greece for the period 2000 – 2014.

It is also observed that for the years 2007, 2008 and 2009, oil production was quite low [11]. On the other hand, $CO_2$ emissions presented maximum values. One possible reason could be that more

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energy is required to extract the oil and gas from the reservoir, due to more energy demanding activities [16], as well as to the fact that during these years, turbines were operated (both electricity and heat). Then, in 2010, the operator decided to close all the turbines in order to cover the energy demand with natural gas provided by the Public Gas Corporation (DEPA) for financial and technical reasons [8].

Overall, $CO_2$ emissions of oil and gas production are mainly due to the operation of boilers using sweet gas, to diesel combustion engines, to boilers for glycol regeneration using sour gas, and to flaring.

### *3.2 Sulfur emissions ($H_2S$ and $SO_2$)*

Emissions of sulfur dioxide are related to the sulfur content (%) of the fuel and are calculated based on the $H_2S$ content of the gas, indicated in ppm. The composition of hydrocarbons depends on the geological formations in each region and affects the quantity of $SO_2$ emissions. $SO_2$ emissions from oil and gas extraction and production in Greece are important, due to the existence of significant quantities of hydrogen sulphide ($H_2S$) in volcanic rocks. Two adjacent reservoirs may produce crude oil with a different composition, with the composition varying even in terms of extraction depth. The average content of $H_2S$ in the deposit reservoirs of Kavala Gulf ranges from 35% to 40% [17].

For the year 2014, data on sulfur dioxide ($SO_2$), collected by the central monitoring station and the twelve (12) linked sulphur monitoring stations, show that the measured values are below of the permitted limits (Figures 8 & 9). More specifically, $SO_2$ concentrations have a maximum value of average daily concentrations of approximately 25 ppb or 0.06547 mg/m3 and a maximum value of one hour concentration of 50 ppb or 0.13 mg/$m^3$. The limit values according to the European union legislation are 125mg/$m^3$ for an averaging period of one hour (not to be exceeded more than 3 times a calendar year) and 350 mg/$m^3$ for an averaging period of one day (not to be exceeded more than 3 times a calendar year).

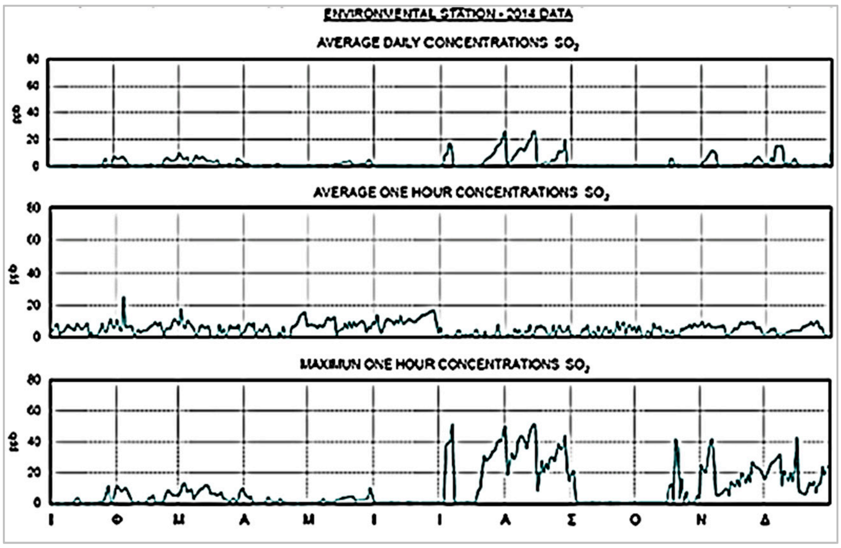


**Figure 8** $SO_2$ emissions (ppb) at the central monitoring station in the onshore installations.

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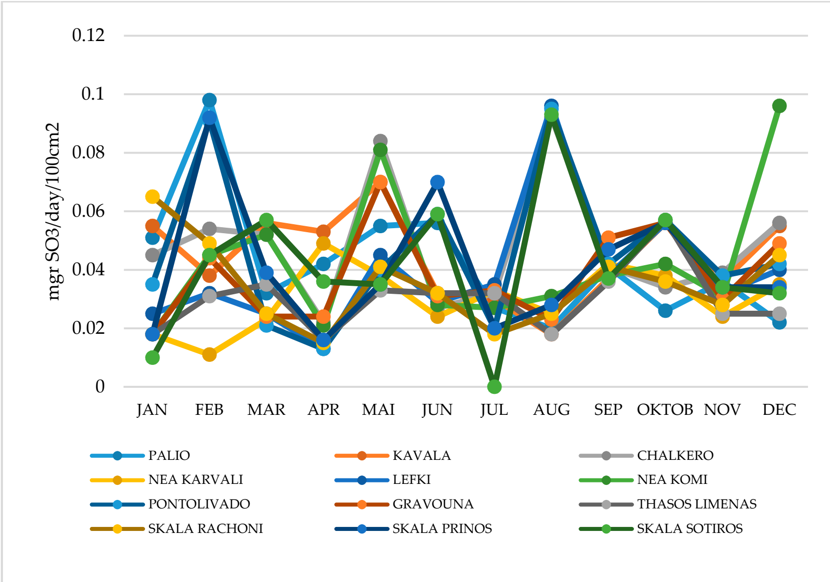


**Figure 9** $SO_2$ emissions at the twelve (12) linked Sulphur monitoring stations located at the Kavalla gulf.

Emissions of sulfur dioxide ($SO_2$) from the offshore installations (Kappa & Delta complex) in 2014 were 1517tn, which is equivalent to 79.13% of the total emissions (Figure 10). The main source of $SO_2$ was the gas flare; sweet gas and a small amount of sour gas were burnt in the process of water treatment. Combustion engines were using diesel fuel with very low sulfur content (ultralow sulfur diesel), and therefore their emissions have not been calculated for the annual inventory.

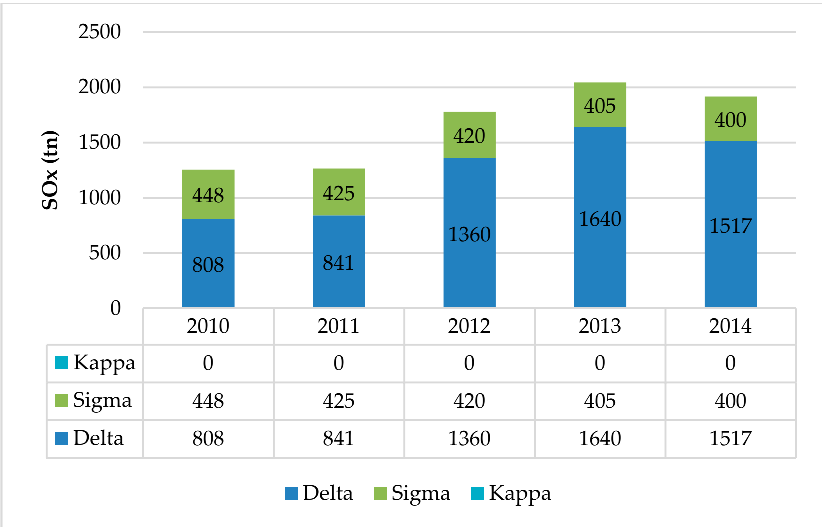


**Figure 10** SOx/$SO_2$ atmospheric emissions inventory from Oil and Gas extraction from 2010 to 2014.

On the contrary, at the onshore facilities (Sigma), the Sulfur Plant converts 99% of the $H_2S$ included in the sour gas to sulfur. As a result, the produced natural gas is low in sulfur content and is used as fuel for energy production. Hence, the emissions of $SO_2$ at the onshore facilities were very low, as shown in Figure 10. The main source of sulfur emissions at the onshore facilities is the incinerator stack, where the sulfur unit tail gas is safely burned.

$H_2S$ measured concentrations have a maximum value of about 15 ppb (0.015ppm) or 0.021 mg/m$^3$ (Figure 11). The limit of 10 ppm time-weighted average (TWA) is used, according to OSHA Standards. The ambient concentration measurements of $H_2S$ at the twelve total sulfation monitoring stations and at the central environmental monitoring station located close to the onshore facilities, suggest that $H_2S$ emissions are negligible (Figure 11). It should be noted that the lowest-adverse-effect

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level of hydrogen sulfide is 15 mg/m[3]. As result hydrogen sulfide concentrations should not be allowed to exceed 7μg/m3, with a 30-minute averaging period [18].

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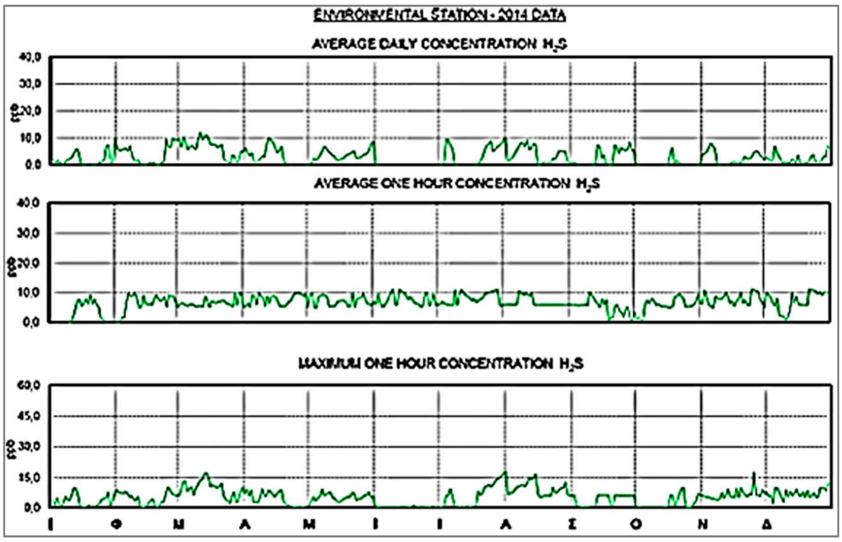


**Figure 11** $H_2S$ concentrations (ppb) measured at the central monitoring station at the onshore installations.

As noted above, $H_2S$ concentrations have a maximum value of about 15 ppb or 0.021 mg/m3 (Figure 11). There is not an established limit for the hydrogen sulfide ($H_2S$) emissions; some people can detect hydrogen sulfide odor at a concentration equivalent to 0.5 ppb, but 90% of people detect hydrogen sulfide in concentrations equivalent to 50 ppb. Hydrogen sulfide is a key parameter for the daily operation of the facilities and $H_2S$ concentrations are measured to ensure the protection of the employees and of the inhabitants of the surrounding region. The $H_2S$ concentration measurements of show that $H_2S$ emissions are negligible.

### *3.3 Emissions of nitrogen oxides (NOx) and nitrous oxide ($N_2O$)*

The total emissions of nitrogen oxides (NOx=NO+$NO_2$) and nitrous oxide ($N_2O$) at the offshore and onshore facilities during 2014, expressed as $NO_2$ equivalent, were 36.535 tn (Figure 12). The emissions from onshore facilities accounted for 97.6% of the total emissions, as at the offshore facilities combustion engines for power generation (which are the main source for NOx and $N_2O$) were not used. Onshore facilities are supplying electricity to the offshore installations through a submarine cable. Moreover, natural gas is used as a fuel to cover energy needs at the onshore facilities and is the main reason for the very low, emissions of NOx from the oil and gas production in Greece.

Nitrogen oxides are emitted by diesel combustion engines, by drilling rig engines, by flares and by the dehydration process of sour gas. The biggest source of NOx emissions from the oil and gas exploration and production activities, are the combustion engines at the onshore installations.

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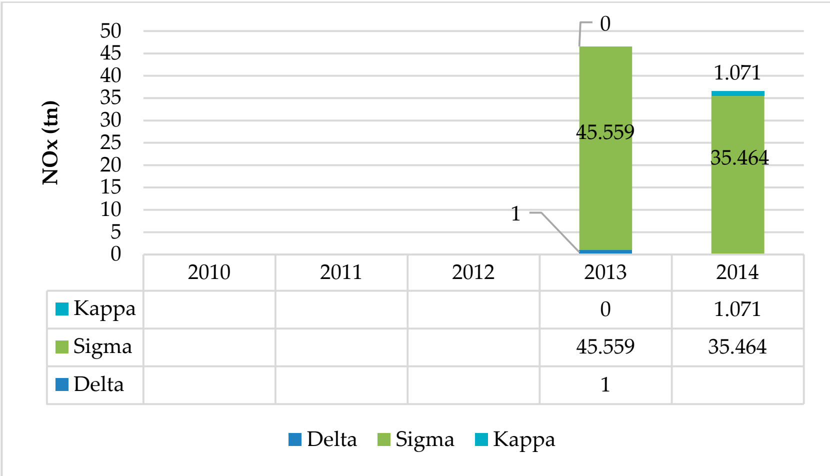


**Figure 12** $NO_2$ atmospheric emissions inventory from Oil and Gas extraction for year 2014.

## 4. Conclusions

The monitoring of atmospheric emissions represents a critical component of the assessment of the environmental performance of oil and gas exploration and production, and is necessary for ensuring a good air quality status and for protecting the health and safety of employees and the quality of life of the local population.

Concentration measurements and emission inventories for the year 2014 from oil and gas activities in Greece confirm that emissions of atmospheric pollutants and greenhouse gases are very low and within the limits set by the national air quality standards and the European Union legislation. The examination of the $CO_2$ emission inventories for the years 2007, 2008 and 2009, showed that the main source of $CO_2$ emissions were the turbines. Emissions of $CO_2$ were low, since they are controlled within the framework of efforts of the European Union to reduce greenhouse gas emissions up to 2020, contributing to the global emissions reduction goals.

The total offshore emissions (Delta complex) of sulfur dioxide ($SO_2$) are equivalent to 1517 tn for the year 2014. The majority of $SO_2$ emissions originates from combustion of sweet gas and off a small amount of sour gas (process of water treatment) in the flare of the offshore facilities. Although the produced oil and gas contains about 50% hydrogen sulfide, the operator has developed specific techniques to make the development of sour resources as safe as possible for the environment.

In conclusion, the oil and gas production industry in Greece does not result in significant atmospheric emissions, taking to account the progress made in the efforts to reduce emissions and to protect the environment, through the use of emission control technologies and the continuous monitoring and assessment of atmospheric emissions and of local air quality. However, since the establishment of the Hellenic Hydrocarbons Management Company S.A. in 2011 (Law 4001/2011), rights for exploration and exploitation of hydrocarbons are being granted in Greece, and it is expected that following this first stage, exploitation of hydrocarbons and oil and gas extraction and production will increase in the future. Therefore, it is necessary for decision-makers and operators to ensure environmental protection and the health and safety of employees and general population, *inter alia* through the development of appropriate monitoring systems and the use of up-to-date emission control technologies, thus establishing a closed optimization system.

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