



**A satellite-based
analysis of the Val
d’Agri (South of Italy)
Oil Center gas flaring
emissions**

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**A satellite-based analysis of the Val d’Agri
(South of Italy) Oil Center gas flaring
emissions**

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Abstract

In this paper the Robust Satellite Techniques (RST), a multi-temporal scheme of satellite data analysis, was implemented to analyze the flaring activity of the largest Italian gas and oil pre-treatment plant (i.e. the Ente Nazionale Idrocarburi – ENI – Val d’Agri Oil Center – COVA). For this site, located in an anthropized area characterized by a large environmental complexity, flaring emissions are mainly related to emergency conditions (i.e. waste flaring), being the industrial process regulated by strict regional laws. With reference to the peculiar characteristics of COVA flaring, the main aim of this work was to assess the performances of RST in terms of sensitivity and reliability in providing independent estimations of gas flaring volumes in such conditions. In detail, RST was implemented on thirteen years of Moderate Resolution Imaging Spectroradiometer (MODIS) medium and thermal infrared data in order to identify the highly radiant records associated to the COVA flare emergency discharges. Then, exploiting data provided by ENI about gas flaring volumes in the period 2003–2009, a MODIS-based regression model was developed and tested. Achieved results indicate that such a model is able to estimate, with a good level of accuracy (R^2 of 0.83), emitted gas flaring volumes at COVA.

1 Introduction

The Petroleum Industry includes a wide range of activities and equipments (EPA, 2012), which affect the regional and global air quality status. The production of oil and gas, in fact, generates waste gases that need to be controlled in a manner that protects the environment. In all industrial plants, such as petroleum refineries, chemical plants, natural gas processing plants as well as oil/gas production sites, gas flares are used as a gas combustion device. Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, of waste gases deriving from industrial operations. The primary purpose of a flare is to act as a safety device to protect

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of satellite data have the potential for systematic observation of flares and estimation of flared gas volume emissions globally (Elvidge et al., 2012). To this aim, given the wide spatial distribution and the possible gas flaring fluctuation over time, particular attention has to be given to sensors able to collect data globally, on a frequent basis, and having a spectral capability suitable to detect gas flaring and/or related phenomena. Moreover, long-term data archives, together with a prospect for a time continuity of homogeneous observations in the future, have to be preferred in selecting the proper satellite technology to be employed for this purpose.

Although none of the currently available Earth Observation satellite sensors has been primarily designed for gas flaring observation, several systems have a capability to indirectly detect gas flares, based on the radiative emissions of sources (Elvidge et al., 2007). Gas flares are point-sources of persistent fire activity, occurring with high percent frequency and lower average Fire Radiative Power (FRP)/km² values than other fire types (Elvidge et al., 2011). Being objects with a high temperature (> 800 K), they radiate at all wavelengths of the electromagnetic spectrum. In particular, as shown in Fig. 1, the higher temperature of the body the higher total amount of the emitted radiation, according to the Plank’s law (area under the different curves in Fig. 1), while the wavelength relative to the peak of the maximum emission decreases inversely with temperature, according to the Wien’s “displacement” law.

The first satellite gas flaring survey, at global level, was assessed by the National Oceanic and Atmospheric Administration (NOAA), with the aim to improve the reliability and consistency of gas flaring data, as part of the GGFR (Global Gas Flaring Reduction) partnership fostered by the World Bank in 2002. Firstly, the DMSP (Defense Meteorological Satellite Program) OLS (Operational Linescan System) data, acquired during the night in its very sensitive visible band (0.5 to 0.9 μm, at 2.7 km of spatial resolution), were collected and analyzed to derive the magnitude of the gas flaring on the basis of its light (Elvidge et al., 1997, 2001). Calibration models were then developed to estimate gas flaring volumes for individual countries. Since 2005, NOAA and GGFR have been continuing to exploit such data to produce annual estimates of gas flaring

volumes at both national (about 60 countries worldwide, not including Italy) and global scale (Elvidge et al., 2009).

To overcome some shortcomings of such data (e.g. coarse spatial resolution, limited dynamic range and lack of in-flight calibration, more detail in Elvidge et al., 2009), MODIS (Moderate Resolution Imaging Spectroradiometer) records, acquired in medium (MIR) and thermal infrared (TIR) channels (at 1 km of spatial resolution) have been exploited. In particular, a combination between such bands was used. The MIR channels at 3–4 μm (i.e. bands 20 or 22) are more sensitive to the presence of high temperature sources (hot spots, fires or flares) than the thermal infrared bands (at 11–12 μm , i.e. channel 31) (Fig. 1). This is why the difference between Brightness Temperatures (BT) in the MODIS MIR and TIR bands is generally suitable and largely used to identify possible hot sources (Flasse and Ceccato, 1996; Dehn et al., 2000; Wright et al., 2002; Giglio et al., 2003; Baldassarre et al., 2009; Van Manen and Dehn, 2009; Elvidge et al., 2011; Marchese et al., 2011, 2012; Steffke and Harris, 2011). In the last recent years, the NGDC (National Geophysical Data Center) suggested a pure MIR-based MODIS algorithm for flare detection at night (using band 20 minus band 22) and characterization (Elvidge et al., 2011, 2012).

Since 2011, the NGDC staff has been working on Visible Infrared Imaging Radiometer Suite (VIIRS) data, offering a substantial number of improvements over its predecessors in terms of spatial resolution (375–750 m), dynamic range, quantization, calibrations and the availability of spectral bands suitable for discrimination of thermal sources. Based on these data, NGDC has developed a system called “Nightfire”, which detects and characterizes sub-pixel combustion sources worldwide using VIIRS night-time multispectral data. The utilized spectral bands span visible, near-infrared, short-wave infrared (SWIR) and MIR (Elvidge et al., 2013; NOAA-NGDC, 2013).

Recently Casadio et al. (2012a, b) demonstrated that the combined use of SWIR night-time radiances acquired by the Along Track Scanning Radiometer (ATSR) and the ASAR (Advanced Synthetic Aperture Radar, ENVISAT) sensors can be exploited for the detection, characterization and monitoring of off-shore oil/gas extraction platforms.

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These studies and pioneering works are generally developed to investigate gas flares at a global or country scale, analyzing multi-sources data-sets jointly and looking for major, very intense sources, characterized by large flares emissions (from few to some hundreds of BCM, Billion Cubic Meters per year) in countries where the gas re-injection or monetization is not provided. To our knowledge, no studies have been proposed up to now to investigate, by satellite observations, a single gas flare source characterized by low/moderate emission rates (less than one million of cubic meters per year), trying to provide a comprehensive analysis of the source, from its thermal characterization to the estimation of flared gas volumes. This work moves in this direction because, for the first time, a satellite based analysis of waste flaring activity from a single on-shore gas and oil pre-treatment plant (i.e. the Ente Nazionale Idrocarburi – ENI – Val d'Agri Oil Center – COVA), located in the Basilicata Region (South of Italy) with moderate emission rates (i.e. with flaring volumes emissions of some hundreds of thousands of cubic meters per year) was performed.

In detail, thirteen years of nighttime Aqua and Terra MODIS thermal data were analysed implementing the Robust Satellite Techniques (RST) approach (Tramutoli, 2005, 2007), with the aim to identify highly radiant records associated to the main blow down events (i.e. waste flaring) occurred at the COVA during the emergency discharges. Exploiting the data provided by ENI about flares emission volumes between 2003 and 2009, a MODIS-based regression model, able to give reliable and independent information on COVA flaring volumes emissions, was finally developed and tested.

2 The Val d'Agri Oil Center (COVA)

ENI, the largest Italian company producing oil and gas, is the operator of the Val d'Agri concession in the Basilicata Region. Its oil/gas gathering and treating center in such an area is the COVA plant (Fig. 2). It is located in the industrial area of Viggiano (PZ), a small village in the South of Italy and covers an area of 171 700 m².

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It is worth noting that the COVA is not only the largest gas and oil pre-treatment plant in Italy but also the largest on-shore European reservoir, the only located in an anthropized area, characterized by a large environmental complexity, where naturalistic aspects coexist with anthropogenic activities, the last ones having potentially high environmental impacts. Besides, the considerable biodiversity which characterizes the Val d'Agri is partly included in the protected area of the Appennino Lucano Val d'Agri Lagonegrese National Park.

COVA started to operate in 1996 with the name “Monte Alpi”; in the following years (from 2001 to 2006), with the upgrade of the production lines (from 1 to 5), it became the Val d'Agri Oil Center (i.e. COVA). Such a plant is aimed at the separation and the further processing of the three phases present in the extracted fluid (crude oil, gas and water). In 2009 COVA infrastructures were modified to treat a higher gas amount, having also higher values of acidity and GOR (Gas Oil Ratio) (Rapporto Istruttorio, Regione Basilicata, 2011) as well as to optimize combustion processes. These recent upgrades modified the emission framework of the plant, compared to its original configuration (Local Report ENI, 2012). The crude oil is extracted from 26 wells, currently in production in the area and conveyed to the COVA through about 100 km of pipelines. The nominal capacity of treatment authorized for the entire plant is equal to $16\,500\text{ m}^3\text{ day}^{-1}$ of oil (corresponding to about $104\,000\text{ barrels day}^{-1}$) and $3.1\text{ million Sm}^3\text{ day}^{-1}$ of associated gas (to the crude oil). Oil produced is carried to ENI's refinery in Taranto via a 136 km long pipeline, while gas produced is treated at the COVA and then delivered to the SNAM (Società Nazionale Metanodotti) national grid system. To better understand the COVA entity at national scale, in Fig. 3 the 2012 COVA oil and gas productions are shown: the first one represents about the 82 % of the Italian amount (Fig. 3a) while the natural gas production is equal to the 50 % of the national one (Fig. 3b).

3 Data

In this section, all the data used in this work, both the satellite records and the validation data provided by ENI, are described.

It should be stressed that for the aims of this work, both satellite and in situ data, available at different temporal scales, were aggregated on an annual basis, according to all literature studies devoted to the gas flaring volumes estimation by satellite (Elvidge et al., 2009, 2011). Such works are focused on annual estimates of gas flared in order to monitor the trend of this phenomenon over the years, with the aim both of filling the gap about such data handled only by governments and petroleum companies and of better assessing the efficacy of efforts made to reduce it. This temporal aggregation, although possibly affecting the accuracy of the regression model, allows us to reduce the observational issues (e.g. cloud cover, high satellite zenith angles) of the used satellite system.

3.1 MODIS data

In this study, images acquired during the night by MODIS sensors, aboard EOS (Earth Observing System) Terra and Aqua satellites, passing over the area of interest between 20:00 GMT and 01:30 GMT were collected and processed. Specifically, the MODIS data multi-annual archive, available at the Institute of Methodologies for Environmental Analysis (IMAA) of the National Research Council (CNR), Tito Scalo (Italy), was used. The brightness temperature (BT) measured in the MODIS MIR and TIR bands, i.e. channels 20 (3.660–3.840 μm), 22 (3.929–3.989 μm) and 31 (10.780–11.280 μm) (see Fig. 1), at 1 km of spatial resolution, were analyzed to identify major thermal emissions as well as to quantify the radiant energy emitted by the investigated pixels. In detail, multi-year datasets of MIR and TIR BTs measured from 2000 to 2012 (about 10 000 images) were created for three pixels: two covering the COVA site and one representing an unperturbed area nearby (Fig. 2). By the re-projecting, re-sampling and co-locating procedures, in fact, the COVA area falls within two MODIS pixels (Fig. 2); therefore,

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the contribution of both these two pixels was taken into account in the study. Besides, the response of an unperturbed area, i.e. not impacted by the presence of industrial facilities (Fig. 2), was investigated to better assess the accuracy and the reliability of the proposed methodology in characterizing the thermal activity at COVA site. The unperturbed pixel is located in slight N–W direction, about 6 km far from the COVA, and it is a predominantly vegetated area, which ensures that no adverse impacts to environment due to anthropogenic activities can modify its spectral response. To better assess the effectiveness of such a choice the range correlation analysis suggested by Noguchi et al. (2011) was computed. Achieved results show that, for all the 13 investigated years, ρ is lower than 0.95, confirming the effectiveness of this selection. For each year and each day of the year the BT values in MIR and TIR channels for the three investigated pixels were extracted; data were analyzed on an annual basis, considering only cloud free records (Cuomo et al., 2004; Pietrapertosa et al., 2001) acquired at a zenith angle lower than 40° (to reduce the impact of the re-sampling and path radiance effects). After the cloud and the zenith angle filters application, 7 200 values (as the sum of those acquired in bands 20, 22 and 31) were finally analyzed for each pixel.

3.2 ENI data

To support this research activity, ENI provided data about: (i) gas (Standard cubic meter, Sm^3 , daily values) and (ii) oil (m^3 and barrel, daily values) production from 2000 to 2012, (iii) gas flaring emissions from 2003 to 2009 (monthly values in Sm^3).

In detail, in reference to the gas flaring volumes, the flare system at COVA (consisting of three elevated flares and one on the ground, see Fig. 2) is used for emergency discharges to burn the gas excess sent to the flares as well as during normal operations for ensuring the safety of the plant (Local Report ENI, 2012). Note that the volumes of gas flared provided by ENI are referred to the main blow down events (i.e. waste flaring) occurred in the investigated temporal range. The peculiarity of such plant is that the 60–80 % of gas is flared during emergency depressurization operations.

4 The methodology

Literature papers on gas flaring with MODIS data suggested the use of BT difference between channel 22 (more recently channel 20, Elvidge et al., 2012) and channel 31 (e.g. Elvidge et al., 2009, 2011) (gray bars in Fig. 1 enhance their spectral location) to discriminate flares presence and quantify their radiant energy. In particular, Elvidge et al. (2012) proposed the use of MODIS channel 20 rather than channel 22 for improving the discrimination between different types of hot sources as it is more sensitive to the presence of emitting bodies at very high temperatures.

Generally speaking values of the MIR-TIR BT difference greater than 5 K have been arbitrarily defined as thermal anomalies of the investigated signal and used in literature to discriminate the presence of hot sources at night (Flasse and Ceccato, 1996; Dehn et al., 2000; Wright et al., 2002; Giglio et al., 2003; Kervyn et al., 2006; Van Manen and Dehn, 2009; Elvidge et al., 2011; Steffke and Harris, 2011). In contrast to such fixed threshold methods, in this paper an automatic change detection scheme (named RST, i.e. “Robust Satellite Techniques”, Tramutoli, 2005, 2007), based on the analysis of multi-year series of satellite data, co-located in the space time domain, is used. The RST methodology may assure, in fact, an automatic and reliable identification of highly radiant values associated to the flaring of gas. In detail, the methodology implemented to define a satellite based regression model for estimating the gas flaring volumes emitted by the COVA in emergency conditions (i.e. waste flaring) was based on the following steps:

1. pre-processing (e.g. calibration, geolocation) and analysis (e.g. cloud detection, zenith angle filtering) of MIR (channels 20 and 22) and TIR (channel 31) MODIS radiances between 2000 and 2012;
2. implementation of the RST approach to select the highly radiant records associated to the gas flaring activities; according to its definition, as explained in the following section, RST should be able to pick up in the time series only the most

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“anomalous” thermal emissions, i.e. the ones which are likely to be associated to the main flaring events;

3. computation of the FRP for the anomalous records previously identified by RST;
4. FRP correlation with the actual gas flaring volumes (provided by ENI) to define a MODIS-based regression model for an indirect estimation of COVA gas flaring emitted volumes.

Figure 4 shows the flowchart of the developed methodology.

4.1 The RST approach

The Robust Satellite Techniques approach is a change detection scheme, based on the analysis of multi-year series of satellite data acquired in homogeneous spatio-temporal conditions (i.e. same geographic area, same month and hour of acquisitions) for a previous characterization of the signal to investigate ($V(x, y, t)$) in terms of expected value and natural variability (i.e. the “reference fields”) for those specific conditions. Such reference fields are usually expressed by the monthly temporal mean $\mu_{V(x,y)}$ and the standard deviation $\sigma_{V(x,y)}$ of the signal V and are computed, for each pixel of the scene, processing all cloud-free records and removing, by an automatic and iterative procedure, outliers from the series (Tramutoli, 2005).

Signal anomalies are automatically identified in the space-time domain by the ALICE (Absolutely Llocal Index of Change of the Environment) index, defined as follows:

$$\otimes_V(x, y, t) \equiv \frac{V(x, y, t) - \mu_V(x, y)}{\sigma_V(x, y)} \quad (1)$$

which provides, at pixel level, a measure of the deviation of the recorded signal $V(x, y, t)$ from its expected (in unperturbed or normal conditions) value (μ_V) and automatically compares this deviation with its normal variability (σ_V), which includes all the possible

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noise sources not related to the event to be monitored. The signal $V(x, y, t)$ to be analyzed is chosen according to the phenomenon to be studied and may correspond to the measurement made in a single spectral band or can derive from a proper combination of several channels (Tramutoli, 1998).

For its construction, the ALICE index is a standardized variable characterized by a Gaussian behavior (i.e. with mean equal to zero and standard deviation equal to 1). This means that the probability of occurrence of values higher than ± 2 standard deviation is less than 2.28 % and it becomes lower than 0.13 % for values higher than 3.

The RST approach has been largely used in the past to study several environmental phenomena and, in particular to investigate sources at high temperature, characterized by a 1-D, time dependent, distribution (e.g. volcanoes) and a 2-D dependence, in both the space and time domains (e.g. fires) (Baldassarre et al., 2009; Filizzola et al., 2010; Marchese et al., 2011, 2012).

For studying the gas flaring phenomenon, following the indications of Elvidge et al. (2009, 2011, 2012), the signals to investigate are the combinations $MIR_{22} - TIR_{31}$ and $MIR_{20} - TIR_{31}$, so two ALICE indices were defined and analyzed:

$$\otimes_{20-31}(x, y, t) = \frac{BT_{20-31}(x, y, t) - \mu_{20-31}(x, y)}{\sigma_{20-31}(x, y)} \quad (2)$$

$$\otimes_{22-31}(x, y, t) = \frac{BT_{22-31}(x, y, t) - \mu_{22-31}(x, y)}{\sigma_{22-31}(x, y)} \quad (3)$$

Generally, for both the indices, high values are expected to be detected in presence of significantly (on a statistic basis) anomalous hot spots. Considering that the COVA is a stable source, persistent in space and time, ALICE indices are not expected to reach very high levels in case of normal operation of the flare system. On the other hand, the highest ALICE index values should be related to the most highly radiant records associable to the major fluctuations in the COVA combustion operations and/or to the gas flaring in emergency conditions (extremely high and intense burst of flames are

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generally associated to these anomalous situations). Therefore, from this point of view, the COVA represents a significantly different hot source compared to previous RST applications. Thus, in order to study the ALICE index behaviors for such a source and to investigate the reliability of this approach to describe the flaring phenomenon eight values of both the ALICE indices, from 1.0 up to 4.5 (with an increase of 0.5), were analyzed.

As a first step, the two investigated signals (Eqs. 2 and 3) were analyzed both for the COVA and the unperturbed pixel in order to verify their capability in detecting and characterizing the investigated phenomenon. In detail, the behavior of the two signals for the unperturbed pixel was analyzed to define the residual error (i.e. false positives) for each index. It means that the same analysis carried out for the COVA site was carried out also for the unperturbed one, for which, obviously, no (or residual) anthropogenic thermal anomalies are expected. The possible error committed during the identification of thermal anomalies at COVA (false identifications, i.e. local warming effects not related to industrial processes) was then computed as the percentage of thermal anomalies identified over the unperturbed pixel at a specific confidence level (c) of the investigated index.

Figure 5 describes the occurrence (in percentage respect to the total number of analyzed images) of thermal anomalies detected over both the COVA and the unperturbed pixels. Results achieved by using the two ALICE indices, at all the different selected confidence levels, are reported.

Looking at the Fig. 5, some considerations can be done:

- regarding the COVA pixel, as expected, a higher number of thermal anomalies is detected compared to the unperturbed pixel, regardless the ALICE index and the confidence level used;
- over the COVA, the two ALICE indices behave in a very similar way, with a slightly better sensitivity of the $ALICE_{20-31}$ than $ALICE_{22-31}$ for $c \geq 1.5$;

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- concerning the unperturbed pixel, a more distinctive behavior of the two indices is instead observed, with a more reliable character of the $ALICE_{20-31}$ which, already at $c = 1.5$ and differently by the $ALICE_{22-31}$, shows very low rates of false positives. However, it should be stressed that the absolute maximum percentage of false identifications is 8.4 % (observed for $MIR_{22} - TIR_{31}$ at the lowest confidence level, confirming the high reliability of the RST approach);
- in general, a clear discrimination between the two sources can be observed at the lowest confidence levels of both the ALICE indices (i.e. between 1.0 and 2.0) as, for $ALICE \geq 2.5$, the number of thermal anomalies detected for both the pixels is very low. This circumstance, while obvious for the unperturbed pixel, for the COVA is likely to be ascribed to the stability of the thermal source.

In conclusion, this analysis reveals:

- *in terms of ALICE indices*: the most suitable index for studying the COVA flaring is the $ALICE_{20-31}$ (Eq. 2), because the rate of possible “false positives” is very low (i.e. less than 2.7 %), at whatever $c \geq 1.0$ (high reliability). Moreover, such an index shows a better sensitivity than the other one in identifying instances at very high temperatures (high sensitivity).
- *in terms of confidence levels*: the best confidence level range is between 1.5 and 2.0, where the best trade-off between statistical population and reliability seems to be assured.

Concerning the sources of thermal anomalies identified over the unperturbed pixel, apart from local warning effects, they could be related to: (i) clouds edges not correctly identified by the cloud masking procedure; (ii) low quality data; (iii) possible fires occurred in the area. Although fires can be considered “actual” thermal anomalies, not having any independent and reliable information about their possible occurrence in correspondence of detections, we preferred to consider all of them as false positives,

providing a more conservative analysis. Therefore, the analysis seems to suggest that, with the chosen ALICE index and confidence levels, a maximum residual error of about 3% in hot spot detection should be accounted for.

To better assess the nature of the detected hot spots and to verify their possible relationship with COVA plant operations and combustion processes, the excess of radiance (defined as the numerator in Eq. (2), i.e. the difference between the measured $MIR_{20} - TIR_{31}$ and the mean value expected to be observed for such a band combination in normal conditions) was computed for the identified “hot” pixels (i.e. the ones having values of $ALICE_{20-31} \geq 1.5/2.0$). In detail, as before explained (see Sect. 3.1), being the COVA plant inside two MODIS pixels (Fig. 2), for the computation of the excess of radiance, the contributions of both were summed only when both $ALICE_{20-31}$ were over 1.5 (or 2.0) (in 3% and 1% of cases, respectively), otherwise only the one over the selected confidence level has been considered.

Such excesses were then aggregated at annual basis, providing one value for each year from 2000 to 2012. Afterwards, a correlation analysis was carried out comparing achieved satellite-based radiance values with data provided by ENI about gas and oil production.

In Fig. 6 the excess of radiance computed for the two levels of confidence of $ALICE_{20-31}$ is reported, together with the COVA gas (in Sm^3) and oil (m^3) production values between 2000 and 2012 (histogram bars).

Firstly, observing temporal trends shown in Fig. 6, it is evident the good agreement between production and satellite data as well as a lower radiant power for COVA estimated for the year 2012 by satellite analyses, despite a gas and oil production higher than the one of the previous years. Such aspect can be explained considering the history of the COVA production. About gas (Fig. 6a), an increasing production is observed from 2000 until 2007, with a sharp decline in 2008, year after which the production returns to increase. For the oil (Fig. 6b), instead, there is a quite constant increasing in the production until 2006, later lower quantities of oil were produced, with the lowest peak in 2009, then in the following years the production starts to grow up. In 2010 and

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2011 the two productions seem to flatten out (both growing up with the same relative increase), while in 2012, compared with the immediately previous years, the gas increases with a rate higher than the one observed for the oil, because of the higher GOR of the produced hydrocarbons. Since 2011, the facilities of COVA have been affected by a series of adaptation and modernization activities (Rapporto Istruttorio, Regione Basilicata, 2011), still in progress, aimed at treating the crude extracted showing different chemical and physical properties (higher acid content and GOR). Such operations, obviously, have modified the emission framework of the plant, compared to its original configuration, resulting in lower emissions of some pollutants like CO₂ and NO_x and in a better management of emergency operations (Local Report ENI, 2012).

About the results referred to the correlation analyses between the two data series, the computed correlation coefficients (R) are reported in Table 1.

The R values reported in Table 1 show that, for both the considered ALICE levels, the thermal radiative power of COVA, identified by RST and characterized in terms of the BT excess, is well correlated with the production chains of the plant (both in terms of oil and gas productions). In particular, the records selected at $ALICE_{20-31} \geq 1.5$ show the highest correlation coefficients, with R equal to 0.84. So that the main conclusion of this analysis is that the RST approach, by using the $ALICE_{20-31}$ index at values ≥ 1.5 , allowed to select thermal features that, with a high level of accuracy and reliability, are likely to be associated to the COVA production chains. Therefore, thermal emissions selected, in this way, using RST, can be further used to better characterize the source in terms of gas emissions due to the flaring operations.

4.2 The FRP computation

To quantify the radiative energy emitted by the COVA during the flaring activity the FRP was computed using the simplified formula proposed by Kaufman et al. (1998). The MODIS FRP retrieval is based on the relationship between the emitted fire energy and the middle infrared brightness temperature and is expressed as (Kaufman et al.,

1998):

$$FRP = 4.34 \times 10^{-19} (T_4^8 - T_{4b}^8) \quad [W m^{-2}] \quad (4)$$

where T_4 and T_{4b} are the brightness temperatures (K) measured in the $4 \mu m$, MIR region (i.e. band 22, although band 21 is used when band 22 saturates) for the target (i.e. the COVA, in this case) and the background pixels, respectively. The constant in Eq. (4) is derived empirically for the spectral interval of MODIS channel 21–22 (Kaufman et al., 1998). The empirical derivation of Eq. (4) is valid for FRP retrievals of hotspots with flaming temperatures ranging from 600 to 1500 K (Wooster et al., 2003).

In this paper, the FRP (Eq. 4) was computed for the thermal anomalies previously identified implementing $ALICE_{20-31} \geq 1.5$, in the period 2000–2012, again aggregating values annually. To define the mean radiance of the neighboring pixels, images having at least 50 % of clear pixels in the box surrounding the COVA were taken into account.

The FRP temporal trend is reported in Fig. 7, where a clear increasing trend of FRP from 2000 to 2005 can be noted, with a maximum measured in 2005; in the following years, until 2012, FRP seems to be quite stable in time, with a mean value around $80 W m^{-2}$.

4.3 The flaring regression model

As previously explained (see Sect. 3.2), ENI provided data about the volumes of gas flared associated to the main blow down events (i.e. waste flaring) occurred between 2003 and 2009. Satellite-based FRPs were then correlated with waste flaring volumes, for the whole temporal range they were available. In Fig. 8 the temporal behavior of the two observables is shown. Looking at the figure, a pretty good correlation seems to appear and, in fact, a linear correlation coefficient equal to 0.97 was obtained.

On these bases, a MODIS-based linear regression model (with an imposed zero intercept) was defined, exploiting the data between 2003–2008, as the ground truth, to

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estimate the flaring emitted in 2009. The regression model (see Fig. 9) is:

$$\text{Gas Flared Volumes (Sm}^3\text{)} = 2442.7 \times \text{FRP}(1.5)$$

where FRP(1.5) is the FRP computed over thermal anomalies identified for the COVA implementing the $\text{ALICE}_{20-31} \geq 1.5$. The derived R^2 is 0.83 (Fig. 9).

By exploiting the COVA FRP derived from satellite for 2009 (69 W m^{-2}), the gas flaring volume emitted for the same year was estimated by applying the above defined model and compared with the true value provided by ENI. Using the regression model, a volume of gas flared in 2009 was estimated equal to $167\,854 \text{ Sm}^3$. This should be compared to the actual value which, according to ENI measurements, is $171\,759 \text{ Sm}^3$. Therefore, the satellite derived waste flaring is underestimating the real measurement of about 2%. Considering all the possible limits (e.g. temporal sampling, spatial resolution) and noise contributions (e.g. clouds, residual false positives/negatives, missing data) of the satellite observations as well as that the analysis is referred to nighttime conditions, the achieved results encourage future investigations.

5 Conclusions

Recently, satellite-based methodologies have been developed to detect and monitor the flares and the emitted gas volumes, both at a global and country scale, mainly focusing on sources characterized by relatively large flares emissions (from a few to some hundreds of BCM).

In this paper a satellite based analysis of flaring activity of the on-shore crude oil pre-treatment plant (i.e. the ENI Val d'Agri Oil Center, COVA), located in the Basilicata Region (South of Italy), characterized by low/moderate emission rates (less than one million of cubic meters), mainly due to emergency depressurization, was assessed. To this aim, thirteen years of MODIS data, acquired in its medium and thermal infrared bands were processed. The RST approach was implemented for the first time to

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analyze such kind of phenomenon, allowing to select the highly radiant records (compared to the normal behaviour of the plant), which can be associated to the COVA flares emergency discharges. Once identified these anomalous values, the emitted energy was estimated through the FRP to quantify the COVA radiant power during these emergency flaring activities. Using such a parameter and exploiting the data provided by ENI about the volumes of gas flared in emergency conditions (i.e. waste flaring) occurred between 2003 and 2009, a MODIS-based regression model was defined for the COVA source and a very accurate estimation of gas flared in 2009 was obtained (error of about 2 %).

The achieved results are unique for the investigated area. They represent the first independent analysis of the area by using satellite data; in addition, they highlight the reliability of the proposed methodology for a thermal characterization of the site, with reference to the emergency flaring activity. Such outcomes are much more significant considering that the COVA, in contrast to most of similar industrial plants, is located inside a natural park, in an area (i.e. the Val d'Agri) where the main activities are based on agriculture and farming.

Starting from the very satisfactory results carried out by these preliminary analyses, further studies will be carried out in order to test the reliability and accuracy of the proposed methodology in estimating gas flared volumes of other worldwide oil plants, provided that in situ data (i.e. gas flaring volumes) are available. Besides, thanks to the intrinsic exportability of the RST algorithm on whatever satellite system and geographic area, also the performances of new generation satellite data (i.e. VIIRS) will be investigated. Moreover, the capability of the proposed RST configuration in daytime conditions to detect and characterize such combustion source will be also tested. In addition, the already proposed RST configuration for hot spot detection (i.e. RST_{VOLC}) will be tested and possibly adapted to this specific phenomenon.

Finally, the RST approach for hotspot detection may be applied on MSG-SEVIRI thermal data which, assuring the best temporal resolution today available from space (i.e. up to 5 min of refreshing time), might be tested as a space based “early warning”

system, to promptly identify anomalous event at COVA and activate intensive monitoring surveys and campaigns.

Acknowledgements. This work has been carried out in the framework of the scientific agreement among Basilicata Region, the National Research Council – Institute of Methodologies for Environmental Analysis and the Osservatorio Ambientale Val d’Agri.

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Table 1. Correlation coefficients (R) between excess of radiance measured by satellite and COVA gas/oil production in the period 2000–2012.

R	Radiance excess (ALICE _{20–31} \geq 2.0)	Radiance excess (ALICE _{20–31} \geq 1.5)
Gas production	84 %	84 %
Oil production	82 %	84 %

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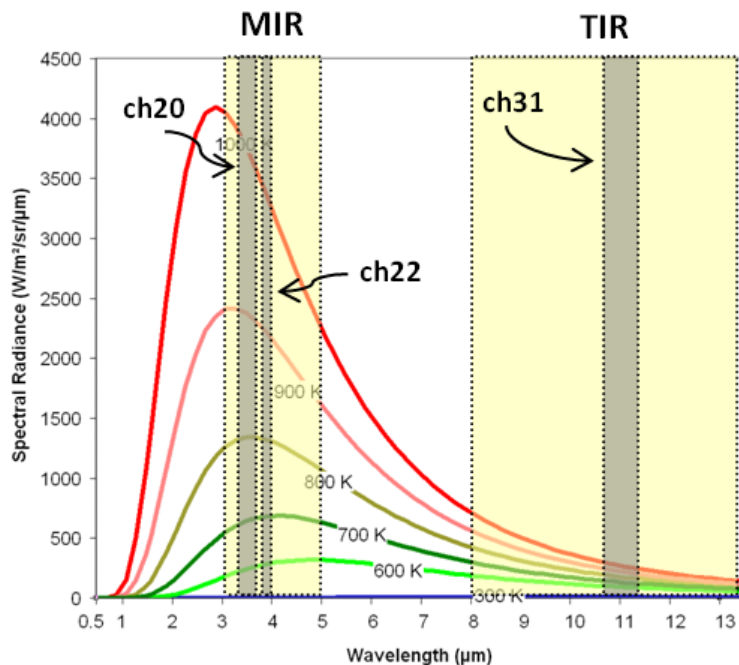
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ch20: 3.660-3.840 μm ch22: 3.929-3.989 μm ch31: 10.780-11.280 μm

Figure 1. Variation of the quantity of radiation emitted in the visible-thermal infrared region by an object at different temperatures. Yellow boxes identify the medium and thermal infrared regions of the electromagnetic spectrum used in the remote sensing for hot spot detection, being located in atmospheric windows, whereas gray bars show the spectral range covered by MODIS (Moderate Resolution Imaging Spectroradiometer) bands (i.e. ch20, ch22 and ch31) used in these analyses.

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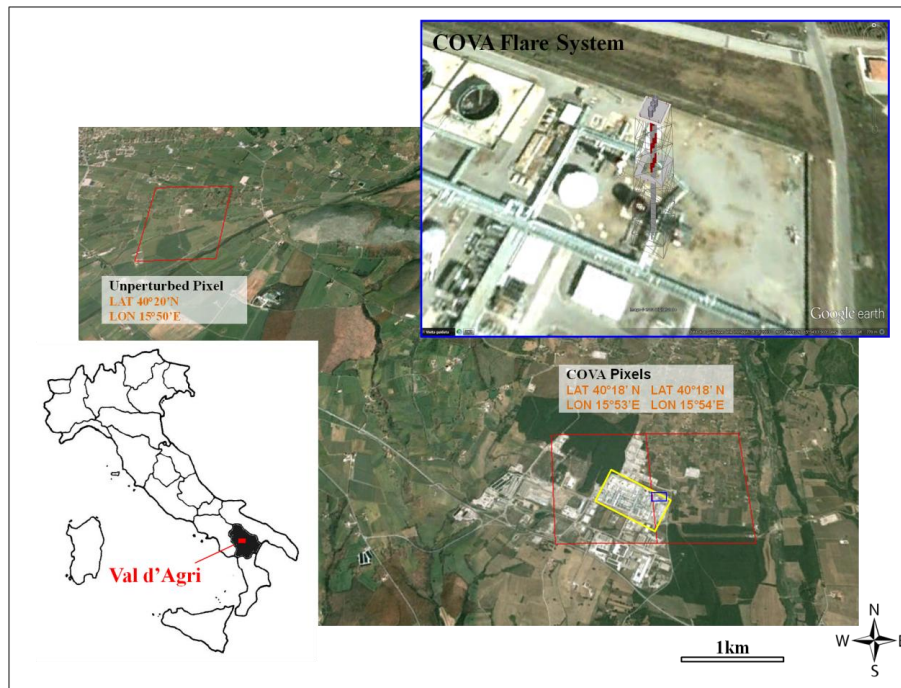


Figure 2. Framework of the COVA site, highlighted by the yellow box (adapted by Google Earth[®]); the red boxes represent the MODIS pixels position in the re-projected grid covering the COVA and the unperturbed area used in the analyses (see text); on the top right corner a detail about the COVA flare system (blue box).

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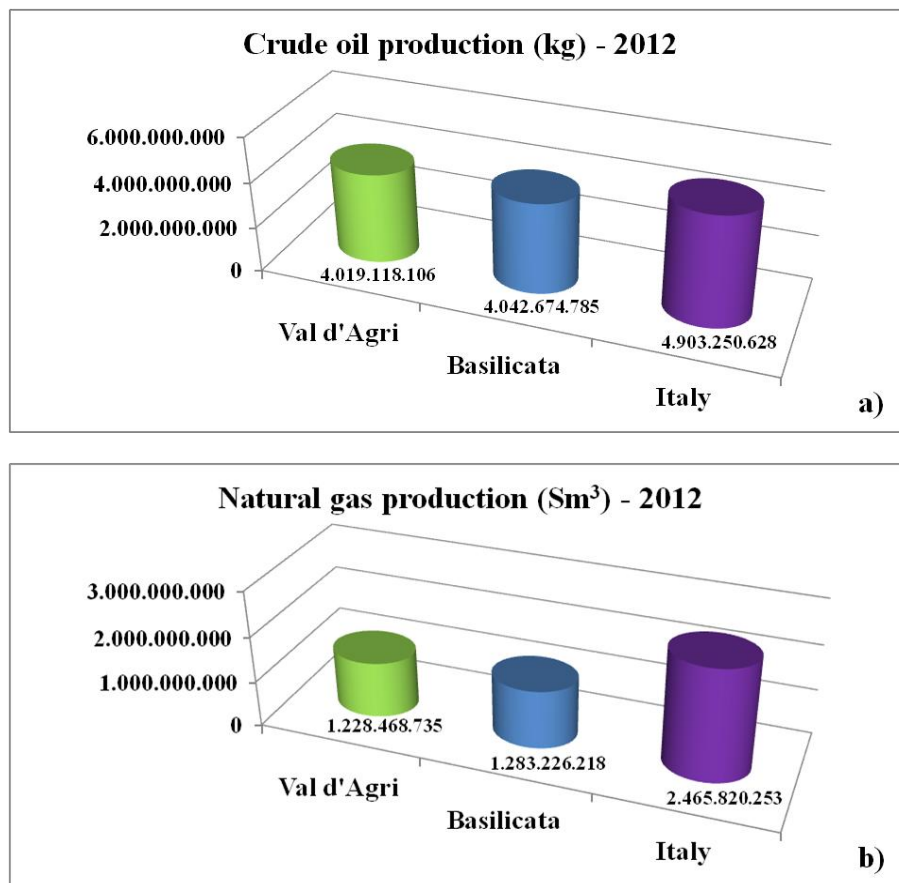


Figure 3. Oil and gas production for Italy, Basilicata Region and COVA (Data processed by <http://unmig.sviluppoeconomico.gov.it/unmig/produzione/mensile/elenco.asp>).

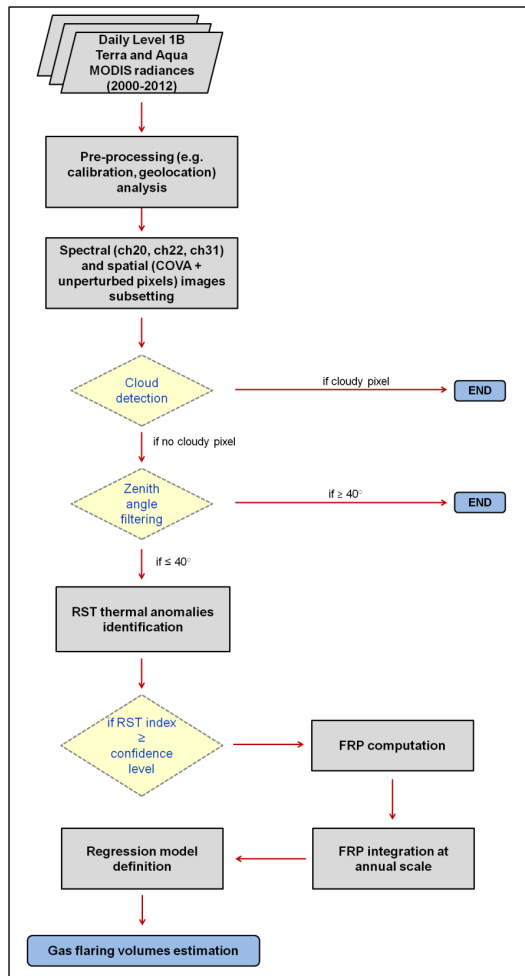


Figure 4. Flowchart of the developed methodology for gas flaring volumes estimation.

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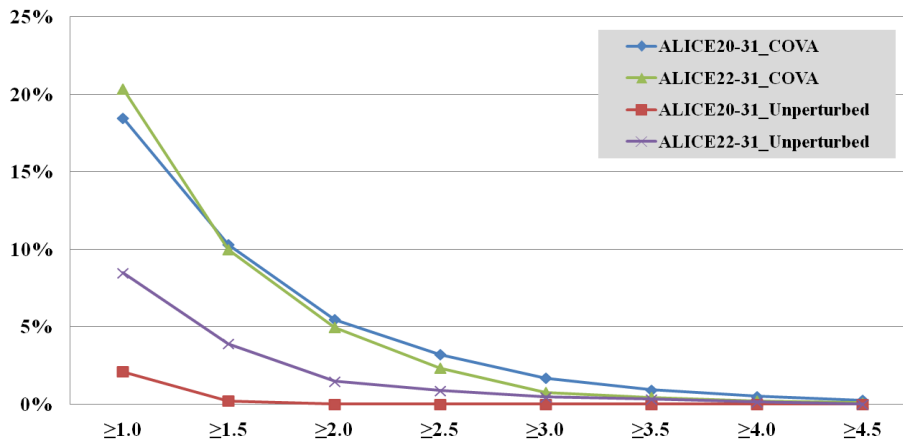


Figure 5. Percentage of anomalous value occurrence (i.e. $ALICE_{MIR-TIR} \geq c$) compared to the total number of analyzed images (in the 2000–2012 temporal range) over the COVA and the unperturbed pixel, for the two investigated signals (i.e. $MIR_{20} - TIR_{31}$ and $MIR_{22} - TIR_{31}$).

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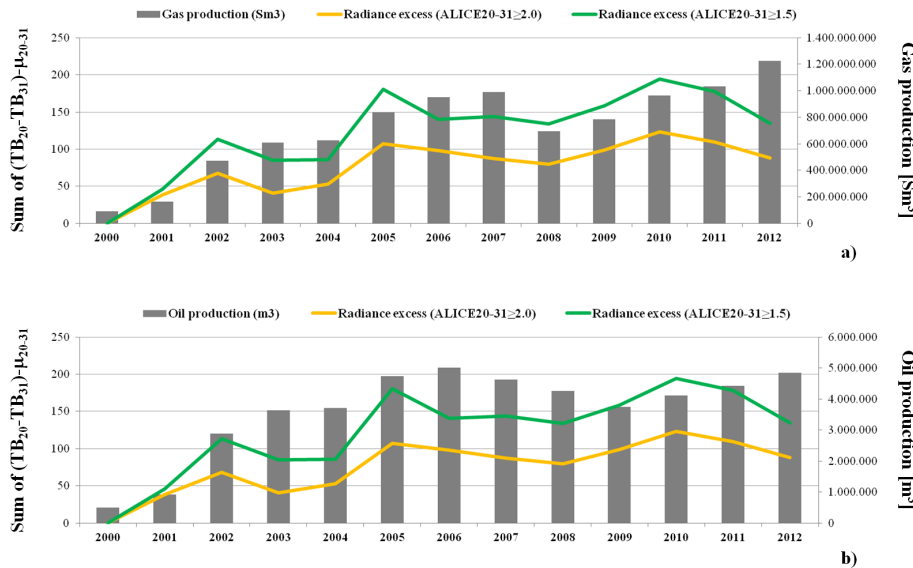


Figure 6. (a) Gas (in Sm³) and (b) oil (in m³) production in the period 2000–2012 and annual excess of radiance for COVA, computed in the same temporal range using the Eq. (2) at levels 1.5 (green line) and 2.0 (orange line).

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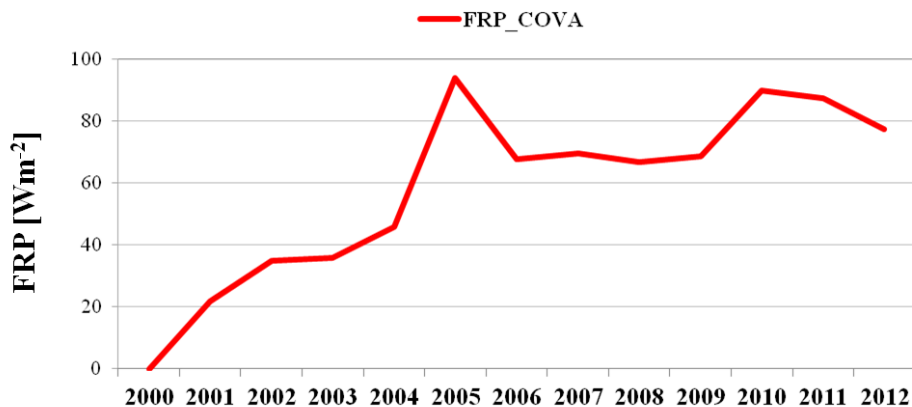


Figure 7. Annual FRP estimation for COVA.

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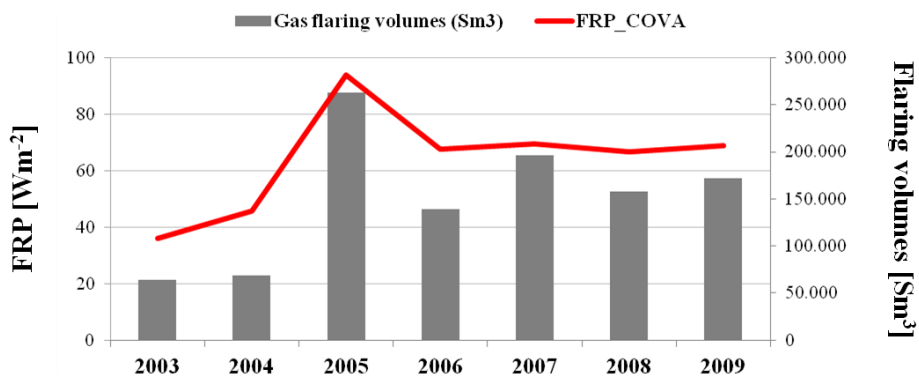


Figure 8. Temporal trends of gas flaring volumes (emitted during main emergency conditions) and COVA FRP, in the period 2003–2009.

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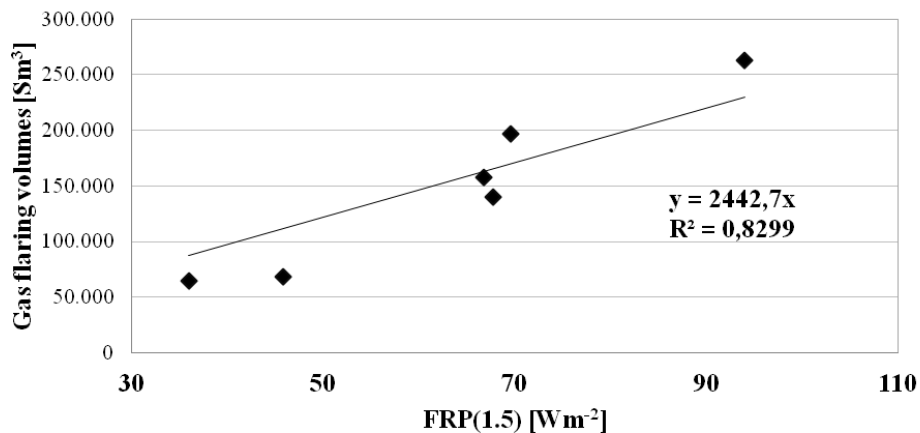


Figure 9. Linear regression model for gas flared volumes estimation.

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