Carbon Limits

FINAL REPORT

Assessment of flare strategies, techniques for reduction of flaring and associated emissions, emission factors and methods for determination of emissions from flaring

For the Norwegian Environment Agency

CL-2013-29, M-82|2013 (Norwegian)

M-312|2014 (English)

BIBLIOTEKSKJEMA

Utførende institusjon	**ISBN-nummer**
Carbon Limits AS	

Oppdragstakers prosjektansvarlig	**Kontaktperson i Miljødirektoratet**	**M-nummer**
Anders Pederstad	Sissel Wiken Sandgrind	312|2014

År	**Sidetall**	**Miljødirektoratets kontraktnummer**	**SPFO-nummer**
2015	95	7012018	

Utgiver	**Prosjektet er finansiert av**
Miljødirektoratet	Miljødirektoratet

Forfatter(e)

Anders Pederstad, Joseph D. Smith, Robert Jackson, Stephanie Saunier, Tore Holm

Title - Norwegian and English

Evaluering av faklingsstrategi, teknikker for reduksjon av fakling og faklingsutslipp, utslippsfaktorer og metoder for bestemmelse av utslipp til luft fra fakling

Assessment of flare strategies, techniques for reduction of flaring and associated emissions, emission factors and methods for determination of emissions to air from flaring

Sammendrag - summary

Denne rapporten beskriver resultatene av arbeidet som er gjort i forbindelse med Miljødirektoratets «Fakkelprosjekt 2012». Prosjektet har hatt som formål å kartlegge sentrale problemstillinger knyttet til fakling og relaterte utslipp til luft fra olje- og gassvirksomhet i Norge. Rapporten beskriver og evaluerer status og utviklingstrekk for fakling i Norge, dagens fakkelstrategier og fakkelløsninger, opprinnelsen og kvaliteten på de utslippsfaktorer og metoder som anvendes for å bestemme utslipp til luft fra fakling, resultater av gjennomførte tiltak de siste ti årene, og tiltaksmuligheter og begrensninger for å ytterligere redusere fakling og relaterte utslipp til luft.

4 emneord	**4 subject words**
Fakkelteknologi, fakkelstrategi, utslipp, BAT	Flare technologies, flare strategies, emissions, BAT

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1. Summary

This report summarises the project “2012 Flaring Project” undertaken for the Norwegian Environment Agency. The objective of the project was to assess a number of themes associated with flaring and emissions from the oil and gas industries in Norway:

- The status and trends of gas flaring in Norway;
- Flaring technologies/systems:
    - Flaring technologies/systems suitable for Norwegian conditions,
    - Criteria for choosing flaring technologies/systems,
    - Technologies in use compared to BAT requirements.
- Opportunities and barriers for flare reduction measures;
- Quality of methodologies and factors used to determine emissions from flaring.

The project team gathered information on the design of flaring systems, existing flaring practices, measures implemented and evaluation methodologies used by companies flaring offshore and onshore in Norway. Suppliers of flaring technologies, as well as relevant public agencies (Norwegian Environment Agency, Norwegian Petroleum Directorate, and the Petroleum Safety Authority Norway), were also consulted and provided input to the analysis. In order to increase understanding of parameters affecting emissions from flaring, the project team also undertook a literature review focusing on particulate matter (PM), methane (CH_4), non-methane volatile organic compounds (nmVOC), carbon monoxide (CO), nitrogen oxides ($NO=NO+NO_2$) and sulphur dioxide (SO_2).

Status and trends of flaring in Norway:

There is little flaring per unit of oil and gas produced in Norway compared to other oil producing countries. Norway began regulating flaring associated with exploration and production of oil and gas in the 1970s. The Petroleum Act (Petroleumsloven §4-4) contains provisions prohibiting flaring except for safety reasons and unless otherwise approved by the Ministry of Petroleum and Energy. Flaring, as the primary use of associated gas, is prohibited; any need for flaring must be detailed in the facilities development plans, which are reviewed by the Norwegian Petroleum Directorate (NPD). The Government regulates flaring through issuance of flaring permits in annual production licenses. The introduction of the CO_2 tax in 1991 provided further incentives for the oil and gas industry (operators on the Norwegian continental shelf) to reduce flaring. During the 1990s, there was a significant overall decrease of flaring. Since 2003, however, the picture is less clear-cut. Older installations have fewer reductions and new facilities have large variations in flaring rates. Overall, there has been a slight decline in flaring over the last ten years, with yearly variations.

Some 15 to 20 years ago a number of measures were implemented in Norway to reduce continuous flaring through development and use of new technologies. These measures were considered economically profitable for businesses. A large portion of the remaining reduction potential is associated with limiting flaring at start-up and shutdown of installations/facilities and pressure relief of equipment during maintenance and breakdowns. Low oil prices and limited investment activity have also resulted in fewer reductions during the early 2000s. Renewed attention on flaring and its emissions have increased both politically and within industry.

A review of industry’s efforts to limit flaring and associated emissions in the last decade has shown that more than 200 measures were implemented after 2001. These efforts focused mainly on reducing non-continuous offshore

flaring, both indirectly through measures that improve regularity and directly through improvements in operating procedures and training of operating personnel. Measures taken for onshore facilities are often linked to noise, odour and soot emission reduction (combustion efficiency).

In recent decades, the oil and gas companies undertook several assessments of potential emissions reduction measures focused specifically on flaring systems. Most of these measures were not considered economical, with only 14 measures implemented since 2001. Companies have only to a limited extent quantified the effect of these measures. Nor have effects of the measures been estimated as part of this project.

Applied flaring strategies:

Companies that operate on the Norwegian continental shelf, as well as onshore have established overall goals for reducing energy use, and have worked out procedures for operations and maintenance that limit flaring at individual facilities. A survey of flaring strategies in 2012/2013 showed that operating companies do not have clear objectives and timeline/timeframes for implementing measures to reduce flaring. This survey also showed that gas flaring, to an extent greater than in the past, is an integral part of energy efficiency improvement processes where all possible measures are identified and prioritized against other investments in a systematic way. Based on interviews for this project, there is still potential for improving industry’s work on this aspect by ensuring that the energy management is anchored both locally and centrally in the companies. However, field and plant specific flaring strategies were being developed and implemented in several places.

Flare technologies/system:

The flare system is an important element of the installation’s safety system. It is part of the over-pressure protection for the processing plant and used to relieve pressure. The flare system is also used during scheduled start-up/shut-down operations and depressurization for maintenance of process equipment. The flare system can also be used to continuously handle toxic or corrosive gases and other flammable gases that are, for various reasons, not considered attractive for use. The primary function of the flare is to ensure safe and efficient handling of gas in accordance with relevant safety requirements. Design of the flare system also affects noise and emissions of various components (CO_2, NO_X, CH_4, nmVOC, CO, SO_2 and particles).

Flare vendors have developed new technologies that flare gas in a safe and environmentally friendly way. From an environmental perspective the focus until recently has been achieving high combustion efficiency and smokeless operation. Many technologies have been developed during the course of the last 60 years to achieve this. Today there is an increased focus on NO_x, SO_x and particulates.

Selection and design of flare systems depends on the specific application. Technical and safety criteria, as well as relevant environmental requirements/criteria impact flare system choices. In this context, it is important to note that environmental requirements are never emphasized at the expense of safety. In addition, costs are critical factors in selecting the design of the flare system. For onshore flare systems, impacts on neighbours (noise and light) are also considered when designing the system.

Detailed information on high-pressure flares, low-pressure flares, vent flares and other flares with specific applications (among others maintenance flares, tank flares and H_2S flares) in Norway was gathered. Analysis of trends in use of flare technologies shows that most of the recent offshore facilities have flare gas recovery systems installed, and operate without a pilot flame. In general, older facilities still use pilot flames. Use of nitrogen as a purge gas is common in newer facilities, both onshore and offshore, but many older facilities also use this. Offshore practices lean toward higher gas velocity in the burner (improved combustion efficiency). Onshore, many facilities that started-up within the last 15 years, use multi-nozzle flares. This technology is less common offshore. The survey of flare technologies in Norway shows a wide range of designs, custom installations and site-specific conditions.

When assessing “Best Available Techniques” (BAT) it is important to note that the flare system, together with the pressure relief system constitute a critical part of the security system at a processing plant. In this project, existing techniques that meet these safeguards were assessed against what is regarded as BAT in terms of flaring and emissions reduction. When undertaking BAT assessments, the costs of applying alternative solutions shall be considered. These costs are dependent on local conditions, in particular for older installations, which were not assessed by the project team. With these caveats, the following are considered BAT for new offshore installations and onshore facilities:

- Maintenance, modifications, start-up and shutdown of process plants and wells should be planned and implemented to minimize flaring.
- In situations where the primary gas utilization option is temporarily unavailable, production should be scaled down following an established plan that balances safety, environmental and economic considerations.
- Flare gas recovery:
    - Gas from high-pressure relief systems should be captured during normal operation,
    - Gas from low-pressure relief systems should be captured during normal operation where this is considered technically and economically feasible and environmentally efficient.
- Use of purge gas:
    - Nitrogen should be used as a purge gas when it is considered safe.
    - When using hydrocarbon gas as a purge gas, technical solutions should be implemented to reduce purge gas volume to a minimum.
- Fuel consumption by the pilot flame should be minimized to the extent possible without compromising the ability to ignite the flare under all conditions.
- When using air and steam assisted flaring, the amount of the assistance medium used for assisted flaring should be controlled to minimize risks for both under- and over-use of the medium.
- The design and maintenance of the knock-out drum should ensure that there constantly is sufficient capacity to remove liquid drops from the gas stream, thereby reducing smoke formation in the flare.
- All flaring events should be registered and classified by root cause, to ensure effective identification, analysis and prioritization of potential measures associated with flaring.

Optimal design of the flare tip, in most cases, depends on local installation and site-specific conditions. There is limited knowledge on the effect of alternative flaring technologies in relation to the emissions component of this project (particulates, CH_4, nmVOC, CO, SO_2 and NO_x). As a result, it is not possible to define specific design aspects of these as BAT.

Potential measures and limitations:

Assessment of potential measures to reduce flaring and associated emissions is difficult due to the lack of detailed information:

- Measurement data: The scientific understanding of the parameters that govern formation of emissions in gas flares and the amounts emitted are somewhat limited, specifically for particulates matters (PM), including black carbon (BC). This is due to the challenges in conducting measurements, as well as limited access to measurement data to calibrate models that can estimate the amounts of emissions.
- Knowledge: Selection of flare technology has an impact on emissions (particles, methane, nmVOC, CO, and NO_X). The quantity emitted varies based on operating conditions and type of gas flared. Most flare designs when used within design specifications achieve good combustion efficiency and expected amounts of associated emissions. Limited access to quantitative information from flare operators means, however, that in practice it is difficult to compare flare technologies and therefore, select optimal designs in terms of actual operations and emissions.
- Non-continuous flaring: Changes in process design and use of new flare technology (including unlit flares) has led to non-continuous or relatively limited flaring at many facilities. Research and hard data (practice) indicate that low gas flaring rate and large variability in flaring rates may affect emissions of unburned hydrocarbons, carbon monoxide and particulates. As previously mentioned, it is challenging to quantify the effects of changes in process design and use of new flare technology on emissions. In order to assess the impact of actions taken or evaluated, representative emissions data for Norwegian conditions should be obtained.
- Analysis: The majority of companies do not systematically register information on incidences and root causes for flaring. Systematic registration of flaring events including cause for the incidences will contribute to increased knowledge, highlight potential reductions, and enable prioritisation of flaring measures in relation to other types of measures.

Information on plans and analysis of potential measures by operators was gathered and more than 150 measures were reported. Information on these measures were of varying quality, which has unfortunately provided an insufficient basis for analyzing the feasibility of these measures and their reductions potential within this project. An important condition for undertaking analysis of potential measures is to better understand the magnitude of CH_4, BC, NOx, CO and nmVOC emissions under variable flaring conditions.

Since the 1970’s Norway has regulated flaring associated with the exploration and production of oil and gas. Several laws regulate flaring: Petroleum Act, CO_2 Tax Law, Excise Law, Pollution Control Act and Greenhouse Gas Emissions Trading Act and its regulations. The Norwegian Environment Agency has instruments at its disposal to limit emissions from flaring, including through setting requirements in permits under the Pollution Control Act. As a party to the “Agreement on the European Economic Area” (EEA), Norway must also comply with EU Directives. The Industrial Emissions Directive (EU Directive 2010/75/EC) regulates industrial emissions and contains provisions on energy production and use of best available techniques (BAT). The project team considers the directive to be adequate for regulating emissions from flaring. Effective regulation, however, is contingent on quantitative data on emissions levels that are representative of Norwegian conditions, and the understanding of the relationship between emissions and the selection of flare technology is adequate.

The project team believes that available quantitative information is insufficient to identify the best potential measures to limit particulates (especially BC), CH_4, nmVOC, NO_x, and CO from flaring. Therefore, the team’s primary recommendation is to increase quantitative information on emissions.

Quality of methods and factors used to determine emissions from flaring:

Comparison of methods and factors used in Norway with other comparable countries show that there are relatively large differences in the emissions factors used for some emissions components. The review of data gathered from companies show that there is no technological or operational reason for the differences in the level of emission factors used. For some gases, it is currently impossible to determine emissions factors without significant uncertainty in the resulting emissions estimates. This is due to lack of access to measurement data from full-scale flares that are representative for Norwegian conditions. The project team therefore recommends the following:

- When estimating emissions factors for CH_4, nmVOC, CO and particles from flares a consistent set of assumptions should be used for gas composition and efficiency.
- To verify that the level of estimated emissions factors for CH_4, nmVOC, CO and particulates are reasonable, measurements on full-scale flares or control tests of flares under conditions representative of Norway should be carried out.
- The emissions factor for NOx, $1.4gNO_x/Sm^3$, recommended by SINTEF for offshore use should be revised to better reflect offshore flaring conditions in terms of flaring rates and energy content.
- The emissions factors recommended for methane, CO and nmVOC seem low and should be revised (increased) based on conservative assumptions for real combustion efficiency during flaring. This is supported by measurements of flares at onshore facilities with DIAL LIDAR and is in line with the principle of applying a conservative estimate until better information is available on actual levels of emissions.
- The basis for estimating emissions factors for particulates (including BC and Organic Carbon) is very thin, and the factors presented for Norway are very uncertain. They should be revised when test results for conditions more representative of flaring in Norway are available. In addition, an initiative should be taken to facilitate and organize measurement programs that are relevant and useful in both the Norwegian and international context.

2. Introduction

The Norwegian Environment Agency is the principal public authority conducting work on emissions from Norwegian petroleum installations, both onshore and offshore. This includes development of guidelines for reporting on relevant emissions, continuous monitoring of operations based on reported data, preparation of emissions inventories, monitoring of national targets and international commitments, implementation of evaluation measures and assessment of what is regarded as best available techniques (BAT). In addition, the Norwegian Environment Agency, as part of its portfolio, is developing a proposal for a national action plan to reduce short-lived climate pollutants (SLCP). To support the work with the national action plan, the Norwegian Environment Agency commissioned Carbon Limits AS to undertake a project to review a broad set of issues related to flaring and emissions (the “2012 Flare Project”). Carbon Limits AS undertook the project in cooperation with Combustion Resources Inc. (Utah, USA). This report summarizes the work done in connection with the project.

The “2012 Flare Project” aimed to increase knowledge on gas flaring and associated emissions. The project covered the following topics:

- Strategies and techniques used to reduce flaring and associated emissions,
- Available flare technologies/systems suitable for Norwegian conditions,
- Criteria for selection of flare technologies/systems,
- Current flaring situation and status of technologies against BAT requirements,
- The quality of methods and factors used to determine emissions[1],
- Potential measures, including cost-benefit analysis of potential barriers.

The project was divided into two main phases. “Phase 1” was completed in the autumn of 2012, and “Phase 2” was completed by the end of the first quarter of 2013. The final report summarizes the information, analysis and recommendations from both phases.

The analysis and recommendations in this study are from data collected through a survey conducted in two phases in parallel with the project phases. Questionnaires were sent to offshore installations and onshore facilities (altogether 66 facilities representing 114 flares). Follow-up interviews were conducted with representatives of companies. Additional interviews were also conducted with six different suppliers of flare technologies, and relevant information from the Norwegian Environment Agency, the National Petroleum Directorate (NPD), and other government agencies were gathered. The Norwegian Environment Agency assisted the project team for the information collection.

In “Phase 1” of the project, a comprehensive survey of flare strategies and flare technologies/systems used within the Norwegian petroleum industry was carried out. The purpose of the survey was to obtain information on the sources of flaring, typical flaring situations (including flare rates, gas composition and duration) and technical design for each of the 114 flares in operation. **Table 1** provides an overview of the response rate.

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[1] The project focused on the following emissions associated with flaring: particulates, methane, nmVOC, CO, SO_2 and NO_X.

Table 1: Response rate for "Phase 1" survey for plants where gas is flared

	Number of flares (facilities in operation)	Number of responses received	Percentage of flaring in 2011 covered by the responses (%)	Responses from facilities due to become operational shortly
Offshore installations	88	87	99 %	4
Onshore facilities	26	21	84 %	-
Total	**114**	**108**	**~ 93 %**	**4**

The "Phase 1" survey answers covered facilities that account for a significant portion of flaring in Norway, both offshore and onshore, and responses were generally of good quality. Responses provided an overview of the status of flaring in Norway and were a sufficient basis for detailed analysis of the data.

"Phase 2" sought to obtain information on companies' views on potential measures (including potential for emissions reductions, costs and benefits and potential barriers) and collect data and assessments of measures implemented in the last ten years to reduce flaring and associated emissions. Table 2 provides a summary of responses received in "Phase 2".

Table 2: Response rate for "Phase 2" survey for plants where gas is flared

	Number of flares (facilities in operation)	Number of responses received	Percentage of flaring in 2011 covered by the responses (%)	Responses from facilities due to become operational shortly
Offshore installations	88	88	100 %	-
Onshore facilities	26	18	69 %	-
Total	**114**	**106**	**~ 93 %**	**-**

The project gathered information on 388 different measures from companies; this included approximately 200 measures implemented from 2002 to 2012 and over 150 potential measures (under consideration, planned or rejected). Quantified data on costs and benefits and impacts on flaring and emissions were available for only 15 of the 388 measures; therefore, information received during "Phase 2" is primarily qualitative. Company descriptions provided a good overview of efforts and developments over the last ten years, and provide a basis for understanding the priorities behind assessments of potential measures for further flare and emissions reductions at the national level.

Chapter 3 contains a description of flaring and different aspects related to health, safety and environment (HSE) which serves as a background for the remainder of the report. **Chapter 4** summarizes strategies used in offshore and onshore facilities in Norway to control and reduce flaring. Results of implemented measures and current status on flaring are presented in **Chapter 5**. An overview of flare technologies suitable for Norwegian conditions, based in information from flare technology suppliers, is presented in **Chapter 6.** Assessments of flare technologies used in Norway compared against BAT are presented in **Chapter 6.4**. The quality of methods and factors to determine emissions are discussed in **Chapter 7**. Assessments of potential measures are presented in **Chapter 8**.

References used in the report are included in the text as "(X)," and the reference list is presented in **Chapter 9**. References to emails, phone calls and links to internet pages are provided directly in the text.

3. Flaring and HSE

The purpose of this chapter is to summarize factors that affect health, safety and environmental aspects associated with flaring, including heat radiation, noise, combustion conditions and emissions of various components. These factors can be influenced through design and modifications of flare systems and processing plants, and therefore these relationships are important to understand the content of the remaining sections of this report. As the project's objective is to identify key issues related to flaring and emissions, this chapter concludes with a review of the laws and regulations relating to emissions from flaring.

3.1 Heat Radiation

The flare system together with the pressure relief system form a critical part of the safety system at a processing plant. The flare system is designed to prevent escalation of dangerous and accidental situations, and thus must meet a number of technical and operational requirements to ensure safe and reliable operation. The flare system's design reduces the occurrence of emergencies as well as ensures safety during maintenance. In order to ensure safe and reliable operations, flare systems must meet many requirements. The Facilities Regulations[2] and those standards referenced in these regulations serve as guidelines for the design of offshore flare systems, including acceptable heat radiation in relation to objects and personnel.

As waste gases burn, a certain portion of the heat produced transfers to surroundings by thermal radiation. Estimating radiation from gas flares is an important part of flare design, governing, for example, flare stack height. Radiation from the flare to another object is determined by flame temperature, concentration of radiant emitters (in particular BC), size, shape and position of the flame compared to the object, and properties of the space between the flame and object (2).

Because of the importance of flame temperature in the radiation equation[3], any parameter influencing the flame temperature (including heating value of the gas, and combustion efficiency) leads to an increase in the flare's radiation.

Wind has two conflicting effects on the flame; it both cools down the flame and causes the flame to bend (thereby increasing radiation since the distance between the flame and other objects decreases). These two effects result in a decrease of radiation with increasing wind speeds (3).

Use of assistance medium (described in **Chapter 6.2**) also has two conflicting effects on radiation. On the one hand, it increases efficiency and thus flame temperature. On the other hand, injection of steam or air increases destruction of BC particles. The second effect is dominant (4).

Various parameters effects on radiation from flaring are summarized in **Table 3.**

Table 3: Parameters ("A") that effect radiation from flaring ("B")

An increase in parameter "A" gives an increase (↗), a reduction (↘), no effect (→) or unclear effect (?) on "B"

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[2] The Facilities Regulations ("Innretningsforskriften") apply offshore and are one of five HSE regulations. HSE regulations: integrated special regulation for safety in petroleum activities offshore and some onshore facilities; developed and enforced by HSE authorities jointly in their respective areas of authority.

[3] Radiation is related to the absolute surface temperature to the fourth power.

«B» ↓ «A» →	Combustion efficiency	Flame temperature	Gas density	Heating value of the gas	Gas velocity	Diameter of flare tip	Turbulent mix	Crosswind speed
Radiation	↗	↗	→	↗	↗	↘	↘	↘

For safety reasons, acceptable radiation levels on objects and personnel are strictly regulated.

3.2 Noise

Noise from flaring is a safety issue and sustained high noise levels may also have an effect on health. Noise levels from flaring are regulated in order to minimize dangerous situations (for example on offshore helicopter platforms) and to reduce stress and illness on personnel and communities. The latter applies to onshore facilities. Noise from flaring is generated mainly through three mechanisms: (i) the flow of gas through the flare tip (jet or flow noise), (ii) steam/air injection (jet noise), and (iii) combustion (combustion noise).

There is a positive correlation between gas velocity and flow noise (i) in the flare tip (5), while (iii), combustion noise, increases with improved combustion efficiency and a high flame temperature (6). Flaring of hydrocarbons gives high flame temperatures and high noise levels (both high frequency flow noise [“jet screech”] and low-frequency combustion noise [“combustion roar”]. At the same time, the surrounding atmosphere’s ability to transmit noise is reduced due to changes in gas density around the flame (2). The wind cools flare effluents thus increasing gas density that may in turn increase noise propagation (2).

Steam or air injection in the flame aggravates flare noise by producing high frequency jet noise (ii). Jet noise can be reduced by use of small multiple steam jets and if necessary, by acoustical shrouding (7).

Various parameters effect on noise from flaring are summarized in **Table 4.**

Table 4: Parameters (“A”) that effects noise from flaring (“B”)

	An increase of parameter “A” increases (↗), reduces (↘), has no effect (→) has an unclear effect (?) on “B”							
«B» ↓ «A» →	Combustion efficiency	Flame temperature	Gas density	Heating value of the gas	Gas velocity	Diameter of flare tip	Turbulent mixing	Crosswind speed
Noise level from flaring	↗	↗	↗	→?	↗	↘	↗	↘

Noise from flaring can be reduced by modifying flare tip design, both through use of low-noise burner designs as well as other control measures (optimal solutions are dependent on flare specifications) (6).

3.3 Emissions associated with flaring

Gas flaring is a major source of air pollution and results in the release of a number of different components. The most important components, in terms of amount and potential impact, are CO_2, NO_x, VOC[4], CO, SO_2 and particulate matter.

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[4] Unburned hydrocarbons, including methane and non-methane Volatile Organic Compounds (nmVOC).

The combustion process in a flare is complex. In simple terms, it is an uncontrolled flame open to external influences. It can generally be understood by studying the different physical and chemical processes that occur during the gas combustion. The order of magnitude of emissions is dependent on a number of physical and chemical reactions, governed by conservation of mass, momentum and energy principle. This in turn is influenced by gas composition, flare rate, design of the flare system and external influences. The following text contains brief descriptions of two key concepts related to efficiency of the combustion process, as well as a summary of governing parameters of combustion efficiency and emissions from flaring of CO_2, NO_x, VOC, CO, SO_2 and particulate matter. The summary encompasses a review of available literature and discussion with international experts.

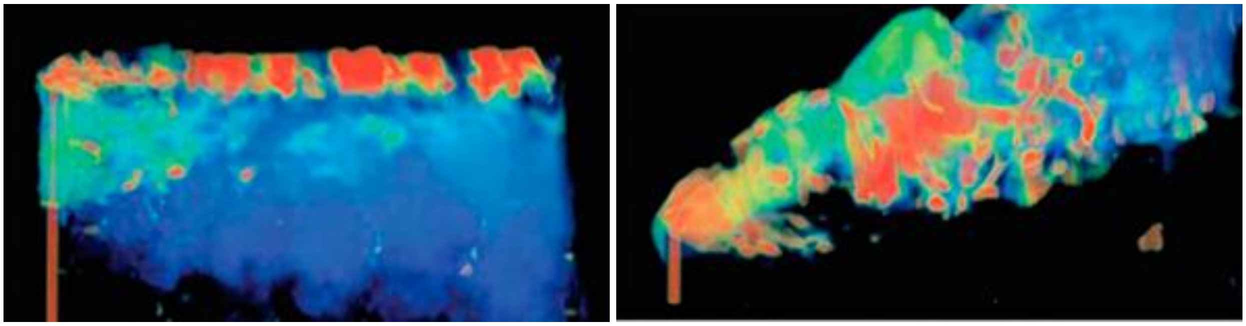
Combustion efficiency and destruction efficiency

The terms combustion efficiency and destruction efficiency are often used interchangeably and therefore, are confused. Destruction efficiency is a measure of how much of the original hydrocarbons are destroyed (to form CO_2 and CO), while combustion efficiency is a measure of how much of the original hydrocarbons burn completely to CO_2 and water vapour. Destruction efficiency is always larger or equal to combustion efficiency (2).

Parameters effecting combustion efficiency by flaring

Combustion in an open flare is characterized by an inhomogeneous distribution of local combustion efficiencies that evolve over time (8) (9) (see Figure 1[5]). To obtain an accurate determination of the combustion efficiency of a flare, one must know the distribution both horizontally and vertically over the plume. This has important implications in terms of requirements for models quality as well as flame combustion efficiency measurements.

Figure 1: Model of combustion efficiency in flaring



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[5] Figure 1 shows a volume rendered image of a large eddy simulation (LES) of two flares, and distribution of the combustion effect in the flare/plume for the two flares. The red tones show areas with low combustion efficiency while the blue tones show areas with high combustion efficiency.

Generally, lighter gases and gases with high heating value tend to burn more efficiently (7). Since the temperature of the flame is directly related to the reaction rate, the flame temperature increases at higher combustion efficiency.

In terms of flare design, flare tips with a large diameter may reduce combustion efficiency locally near the flame centre due to low oxygen levels while higher gas velocity generally increases the mixing with air thereby increasing combustion efficiency. The flare tip can also be designed to enhance mixing gas and air, thereby increasing combustion efficiency (10).

Combustion efficiency, can to some extent, be influenced through certain flare operating parameters. For example, experience with assisted flares show that both too little and too much consumption of an assistance medium (steam or air) can reduce combustion efficiency (11). (See **Chapter 6.1** for further details).

The reduction in combustion efficiency caused by wind has been measured on small-scale lab flares for relatively low wind speeds (12). Measurements carried out on large scale flares indicate, however, that combustion efficiency is not significantly affected by crosswind speeds up to about 10 m/s (13). At higher speeds, wind has a significant effect on combustion efficiency of a flare as it causes the flare flame to tear. The effect of higher wind speeds on larger flares (large diameter in the flare tip) is currently being discussed in the USA[6].

Various parameters influencing combustion efficiency of gas flaring are summarized in **Table 5**.

Table 5: Parameter (“A”) and its effect on flare combustion efficiency (“B”)

	An increase of parameter “A” increases (↗), reduces (↘), has no effect (→) has an unclear effect (?) on “B”							
«B» ↓ «A» →	**Combustion efficiency**	**Flame temperature**	**Gas density**	**Heating value of the gas**	**Gas velocity**	**Diameter of the flare tip**	**Turbulent mixing**	**Crosswind speed**
Combustion efficiency	▨	↗	↘	↗	↗	?	↗	↘ ?

3.3.1 Emissions of CO_2

Flaring constitutes a significant source of Norway’s CO_2 emissions (about 1.3 million tonnes in 2011, representing 10.9% of CO_2 emissions on the Norwegian continental shelf (14)). Emissions of CO_2 from flaring have been subject to specific regulation and a great deal of attention over time. The purpose of the “2012 Flaring Project”, therefore, was to increase knowledge of other gases associated with flaring. As such, this report briefly describes CO_2 emissions from flaring.

Emissions of CO_2 from flaring are directly related to gas composition and combustion efficiency. Combustion converts the total carbon content in the flare gas to CO_2. Emissions of CO_2 from flaring, while undesirable (as CO_2 is a greenhouse gas), are necessary as flaring is both a safety measure and a method for protecting the environment by reducing emissions (through efficient combustion) of other more harmful gases. Parameters that positively affect the formation of other pollutants may lead to an increase of CO_2 emissions. For example,

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[6] This was discussed at length at the American Flame Research Committee’s (AFRC’s) annual meeting in Utah, September 5-7, 2012.

higher combustion efficiency levels leads to CH_4, CO and nmVOC emissions reduction and an increase in CO_2 emissions.

3.3.2 Emissions of NO_x

Nitrogen oxides (NOx) increase the risk of respiratory disease. They contribute to acidification and corrosion, and in the presence of sunlight and VOCs contribute to the formation of tropospheric ozone. Nitrogen oxides are formed four ways during combustion: thermal NOx, prompt NOx, via N_2O (nitrous oxide), and so-called fuel NOx. Typically, flare gas contains no chemically bound nitrogen; therefore, fuel NOx has little significance for emissions from flaring (15). Studies have shown that NOx formation via N_2O is also of little importance in flaring (16) (17).

Measurements show that NOx emissions increase with higher flame temperatures, higher combustion efficiency and higher gas heating values (18). Improved mixing of hot combustion gases through steam/air assistance leads to higher efficiency and flame temperature, which, in turn, increases NOx levels. Studies carried out by SINTEF shows that NOx emissions from flaring increases with higher gas velocity in the flare tip and decreases with increased flare tip diameter (19). In the experimental “scaling law” for NOx emissions presented by SINTEF in 2008 (“d-scaling law”), NOx emissions per mass unit of flare gas is negatively correlated with gas density (20)). Data from Discroll et al (1992) shows that emissions factors for NOx is positively correlated to the burner’s diameters (Burner size from 1.6 to 5.2mm) (21). SINTEF, however, found the opposite effect, i.e., NOx emissions reduce by increasing flare tip diameter (19). SINTEF points out, however, that the effect of diameter is uncertain as the scaling law has not been verified experimentally for large flare tips (>50mm).

Hydrocarbon-rich (oxygen poor) fire or flame zones reduce NOx emissions. The same applies to air, which cools the flame and reduces NOx emissions.

Various parameters effecting NOx emissions from gas flaring are summarized in **Table 6**.

Table 6: Parameters (“A”) effecting NOx emissions from gas flaring (in g/kg)

	An increase of parameter “A” increases (↗), reduces (↘), has no effect (→) has an unclear effect (?) on “B”							
«B» ↓ «A» →	**Combustion efficiency**	**Flame temperature**	**Gas density**	**Heating value of the gas**	**Gas velocity**	**Diameter of the flare tip**	**Turbulent mixing**	**Crosswind speed**
Emissions of NO_x (g/kg)	↗	↗	↘	↗	↗	↘ ?	↗	↘

3.3.3 Emissions of VOC (methane and nmVOC)

Emissions of VOCs (volatile organic compounds) are primarily due to incomplete combustion in flares. The same parameters governing combustion efficiency therefore govern emissions of VOCs (methane and nmVOC) (see **Table 7**). Methane and nmVOC emissions depend on the proportion of methane and other hydrocarbons in the flare gas (in percentage by volume or mass depending on the emissions unit). Methane is a potent greenhouse gas with a relatively short lifespan in the atmosphere, while nmVOC are carcinogenic and contribute to the formation of tropospheric ozone.

Table 7: Parameters ("A") effecting emissions of methane and nmVOC ("B") from gas flaring

	An increase in parameter "A" increases (↗), reduces (↘), has no effect (→) has an unclear effect (?) on "B"							
«B» ↓ «A» →	Combustion efficiency	Flame temperature	Gas density	Heating value of the gas	Gas velocity	Diameter of the flare tip	Turbulent mixing	Crosswind speed
Methane & nmVOC emissions	↘	↘	↗	↘	↘	?	↘	↗ ?

3.3.4 Emissions of CO

Carbon monoxide (CO) is also a source of emissions associated with inefficient combustion of flares (see **Table 8**). Emissions of CO, therefore, should be measured to determine combustion efficiency. Measurement data from flare studies show that emissions of CO increase almost linearly as combustion efficiency decreases. Steam-assisted flares, where the gas flared has a low gas heating values, are, however, an exception (22) (23). Emissions of CO have health consequences and contribute to tropospheric ozone.

Table 8: Parameters ("A") effecting emissions of CO ("B") from flaring

	An increase in parameter "A" increases (↗), reduces (↘), has no effect (→) has an unclear effect (?) on "B"							
«B» ↓ «A» →	Combustion efficiency	Flame temperature	Gas density	Heating value of the gas	Gas velocity	Diameter of flare tip	Turbulent mixing	Crosswind speed
Emissions of CO	↘	↘	↗	↘	↘	?	↘	↗ ?

3.3.5 Emissions of SO_2

Sulphur dioxide (SO_2) acidifies soil and water, causes corrosion and increases the risk of respiratory disease. Normally, sulphur is not present in air around the flare. Sulphur in the waste gas converts to SO_2 during combustion; emissions of SO_2 are directly related to the sulphur (H_2S) content in the flare gas.

3.3.6 Particulates

Particulate matter (PM) comprises many different chemical compounds; the specific chemicals are determined by pollutant source. Emissions of PM influence local air quality, the global climate[7], and can be transported over great distances along with other pollutants (24). Related to flaring, emissions of PM are primarily "Black Carbon" (BC) and "Organic Carbon" (OC) that arise from incomplete combustion of gas.

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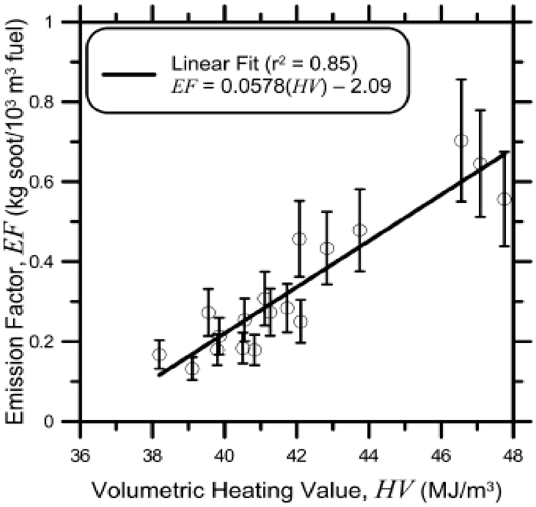
[7] Climate effect varies with particle composition. Emissions of BC contribute to global warming by absorbing sunlight (in particular when BC is deposited on snow and ice). On the other hand, OC has a cooling effect on the climate because sunlight is reflected.

The black carbon formation process is very complex, involving several steps of chemical and physical particle growth and then destruction[8]. The final amount of BC emitted from a flare is a result of the competing effects related to the formation and oxidation of these particles (25).

Compared to other types of emissions presented in this report, information on BC from flaring is relatively limited. This was confirmed recently in work undertaken by (among others) "CLRTAP Ad-Hoc Expert Group Black Carbon" and the "Artic Council Task Force on Short Lived Climate Forcers" (26). Various international research groups are actively working to understand the relationship between the complex formation process of particulates and turbulent conditions in a gas flare. Although the governing parameters are not yet fully understood, some important relationships have been identified.

Laboratory experiments undertaken by Carleton University in Canada have shown that soot formation tends to increase with gas density, flare tip diameter and gas heating value, where the best correlation is between soot formation and gas heating values (25) (see **Figure 2**). According to the US EPA (2002), all hydrocarbons heavier than methane can cause BC formation.

Figure 2: Emissions factor for soot as a function of volumetric heating value[9] (25)



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[8] There is extensive work on formation of soot/PM formation, including F. Mauss (Lund Univ), M. Frenklauch (Univ of Calif-Berkely), and R. Lindstedt (Imperial College). BC is formed through a chemical reaction mechanism that starts with the formation of acetylene (C2H2) leading to a benzene ring which grows into a multi-ring Poly Aromatic Hydrocarbon (PAH) compound. The heavy PAH molecules form primary soot particles. These particles then grow (via the addition of gas phase molecules and/or other PAH) and aggregates (via particle-particle collisions). Oxidation decreases the mass of soot particles and forms CO and CO_2. BC can also be formed as graphitic carbon which is quite different from the PAH form.

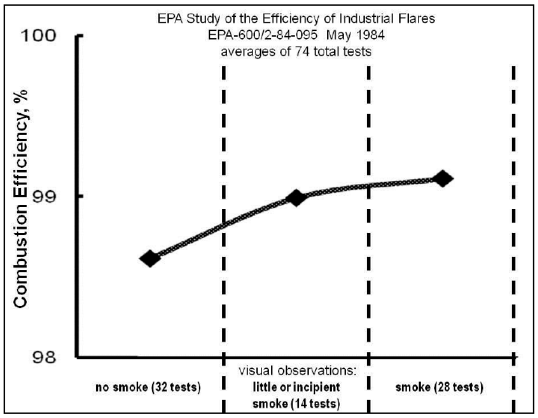
[9] Based on measurement data of burners («jet diffusion flames») with diameter from 38.1 mm to over "fire Froude numbers" greater than or equal to 0.003.

Long, unsaturated and branched hydrocarbons have a higher propensity to create soot than saturated and less branched hydrocarbons. In tests, ethylene and other alkalis (olefins) have a high propensity for soot formation than Ethane and other alkanes.

According to experts consulted during this project, there is no direct relationship between PM formation and combustion efficiency of flares. In 2010, Aerodyne Research[10], in conjunction with Montana State University, conducted a study on behalf of the Texas Commission on Environmental Quality (TCEQ) on flare emissions at the John Zink test laboratory in USA (27). During the study, emissions of particulates (BC and OC) from assisted flares showed increased levels at high(er) destruction efficiency(ies). The measurements showed that particulate emissions from flaring are not always a function of low combustion efficiency. These results align with a much older US EPA publication (see **Figure 3**). James G. Seebold concluded in a recent article: “data actually suggest that for the best combustion efficiency, you should run (the flare) at least slightly smoking all the time” (8). “Smoke-free” operations are therefore no guarantee of maximum combustion efficiency.

The impact of wind on particulate emissions is quite uncertain. In theory, wind shortens flame length and thus combustion products cool faster and can exit the combustion zone before oxidization. On the other hand, the TCEQ study (discussed above) showed that moderate wind had no significant effect on particulate emissions.

Figure 3: US EPA Study on the Efficiency of Industrial Flares - 1984



Higher gas velocities in the flare tip increases air mixture, improving the mix of air and gas. This leads to increased oxidation of PM (increased consumption of air) and lowers particle concentrations. Use of steam/air assistance also significantly reduces concentrations of particulates. Measurements from the Aerodyne TCEQ study for steam and air assisted flares confirmed this in the case of propane and propylene flare (23).

The influence of various parameters on particle emissions from flaring is summarized in **Table 9**.

Table 9: Parameters (“A”) that effect particulate emissions (BC&OC) (“B) from flaring

An increase in parameter “A” increases (↗), decreases (↘), has no effect (→) has an unclear effect (?) “B”

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[10] http://www.aerodyne.com/

«B» ↓ «A» →	**Combustion efficiency**	**Flame temperature**	**Gas density**	**Heating value of the gas**	**Gas velocity**	**Diameter of the flare tip**	**Turbulent mixing**	**Crosswind speed**
Utslipp av partikler	**?**	**?**	**↗ ?**	**↗**	**↘ ?**	**↗**	**↘**	**→ ?**

Based on available measurements, it is assumed that a high proportion (>95%) of particulate emissions from flaring is characterized as PM2.5[11] (27). Various studies using different methods to quantify particle emissions[12] have shown that the distribution between BC and OC emissions from flaring varies somewhat. The proportion of BC emissions from flaring is, however, significantly higher than from combustion engines and gas turbines. Johnsen et al estimate that BC and OC emissions from flaring constitute 80% and 20% respectively, of total particulate emissions (based on the use of two different measurement methods) (25). The TCEQ study, however, showed that the proportion of OC emissions constituted between 4 to 20% of total particulate emissions (27).

3.3.7 Laws and regulations related to emissions from flaring

Domestically, emissions from flaring fall within the scope of the Pollution Control Act. Norway, as a member of the EEA Agreement[13], is also obligated to comply with EU Directives (28). Under EU law, industrial emissions are regulated by the European Directive 2010/75/EC (IED). The Industrial Emissions Directive replaced EU Council Directive 97/61/EC concerning integrated pollution prevention and pollution control (IPPC Directive). Norway implements the IED through the aforementioned Pollution Control Act. The Directive sets requirements for pollution authorities (the Norwegian Environment Agency) to monitor operations and obligations of businesses in relation to the environment (through inspections and inspection plans), defines sectors covered by the Directive, and environmental requirements. The Directive also sets out detailed specifications for permits covered by the Pollution Control Act[14].

The IED provisions for large industrial facilities include requirements for integrated emissions permits, i.e. licenses covering pollution of water, air, waste, etc., and requirements for use of best available techniques (BAT)[15] and energy efficiency (29).

The IED aims to "prevent, reduce and as far as possible eliminate pollution arising from industrial waste." As such, the definition of BAT emphasizes the use of measures, which prevent the formation of emissions over

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[11] Fine particulate matter with an aerodynamic diameter less than or equal to 2.5 micrometres.

[12] Studies undertaken by Johnsen et al at Carleton University are based on measurement of BC emissions with the help of a proprietary laser-based technique (sky-LOSA) and a sampling method collecting soot filters for determination of total particle volume (25). Aerodyne Research collected and analyzed samples of non-tab (soot particle aerosol mass spectrometer and scanning mobility particle sizer), and have quantified the distribution of both BC and OC in relation to particle size.

[13] The Agreement on the European Economic Area brings together EU Member States, Iceland, Liechtenstein and Norway into a single Market. The Agreement provides for inclusion of EU legislation in certain areas.

[14] Chapter 36 of the 2004 Pollution Control Act implements the IPPC directive under Norwegian law.

[15] A guiding principle in the IPPC Directive is that those responsible for a business are obliged to use "best available techniques" (BAT), and that emissions limits contained in permits are based on BAT. Article 9 of the Directive states that the permit does not prescribe use of a particular technology, but that the technology is chosen taking into consideration local conditions.

measures that capture them[16]. The EU prepares BAT reference documents (BREF documents) for defined activities within a particular sector and across sectors. The BREF documents include BAT conclusions that describe considerations for BAT within a specific sector. BAT conclusions contain information to assess applicability, related monitoring, consumption levels and emissions level associated with BAT. The IED obliges pollution authorities to apply similar or more stringent emissions limits in industry permits. The IED also requires pollution authorities to ensure requirements are in place no later than four years after the publication of new or revised BREF.

The BREF documents adopted under the IPPC continue to be in force until updated under the IED process; BREF documents are updated at least every eight years. Permits issued by the Norwegian Environment Agency are set based on adopted BAT conclusions (whenever available), and contain all necessary measures to ensure compliance with the IED, including emissions limits. BREF documents are, however, not available for all activities within a sector. When BAT conclusions are not available, installations are to meet the standard of environmental control based on BAT and related BREF documents. Offshore energy facilities are covered by BREF documents under large combustion plants (LCP BREF) but flaring is not specifically addressed. BAT considerations related to the process design and design of flare systems are included in BREF documents for refineries and gas processing plants (REF-BREF)[17]. This does not, however, include activities related to exploration, production, transportation and marketing of products. Therefore, large portions of flaring in Norway are not directly covered. BREF documents for the production of organic chemicals (LVOC BREF) contain BAT assessments related to flaring. There is also a horizontal BREF document related to management of waste gas in the chemical industry that includes flaring (CWW-BREF, pages 573-585)[18].

New facilities and development projects are required to comply with the terms of the IED (including use of BAT) from commissioning. Choices made during the planning phase can have technical and economic consequences for reducing emissions. Operators must therefore inform the Norwegian Environment Agency on its BAT assessments well before decisions are taken and before binding contracts are made (28). This is due to the impact decisions made during the development phase can have technically and economically for reducing emissions. BAT assessments must also include an environmental impact assessment. In an application for emissions permits under the Pollution Control Act, operators must substantiate their chosen solutions as BAT. The Norwegian Petroleum Directorate, in their treatment of development plans (PUD and PAD[19]), must include an assessment of the facilities design with regard to flaring requirements including the BAT assessment.

Through this project, the Norwegian Environment Agency hoped to assess what qualifies as BAT for flare operators in Norway. The assessment was undertaken to minimize flaring requirements (process design and

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[16] "BAT is defined in the IED as "the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole."

[17] http://eippcb.jrc.es/reference/BREF/ref_bref_0203.pdf

[18] http://eippcb.jrc.es/reference/BREF/cww_bref_0203.pdf

[19] Plan for development and operation (PUD) and plan for construction and operation (PAD).

operating procedures) and techniques for optimizing the combustion process to reduce emissions of NOx, CH_4, nmVOC, SO_2, CO and particulates[20].

The combustion process and governing parameters presented above for various emissions are influenced the by design of the flare system. One challenge in assessing flare technologies against BAT are the design requirements for the flare system (including safety, health and environmental regulations). Performance, in relation to limiting emissions, is only one of many relevant considerations when choosing a flare design. Based on interviews with the Petroleum Safety Authority, suppliers and companies, Carbon Limit concludes that reduction in emissions is not currently an important performance criterion (see **Chapter 6.1** for a more in-depth discussion). It is not straight forward, methodologically and practically, to evaluate whether a minor increase in safety risk is acceptable against an environmental improvement. In the absence of proper pricing of social costs associated with all types of emissions[21] it is also fundamentally challenging to make reasonable judgments of cases where measures have opposite effects on emission components (e.g. increased emissions of NOx and particulates versus reduced CO_2 emissions).

Chapter 6.4 contains summaries of BAT assessments.

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[20] Techniques to minimize flaring requirements are described in **Chapter 8.2** while techniques that can be used to optimize the combustion process is presented in **Chapter 8.3**.

[21] CO_2 emissions from offshore flaring have been covered by the CO_2 tax law since January 1, 1991, and are now covered by the Emissions Trading Law. The Emissions Trading Law also covers onshore flaring. A tax on NOx was introduced in 2007. Offshore flare installations have tax obligation on NOx emissions. Onshore facilities with less emissions source (flares) are subject to environmental agreements on NOx. Environmental Agreements on NOx regulate trade association's obligations to the Government to reduce total NOx emissions. A NOx fund was established to .provide investment projects with verified emissions reductions. The company pays voluntary contributions to the fund based on their emissions (equivalent to 15 NOK / tNO_X).

4. Flare Strategies

An objective of this project was to document existing flare strategies used in oil and gas companies to gain an understanding of current practices and approaches used in flaring. The project team gathered information on:

- Strategies used (if any) in offshore fields and onshore facilities in Norway to control and reduce flaring
- How these strategies may be linked to the companies' operations management and energy management
- Companies' specific objectives for reducing flaring and emissions of greenhouse gases and other associated emissions

Carbon Limits interviewed 12 representatives from offshore and onshore installations in Norway, including key personnel in head offices. The interviewees selected provided a representative sample of Norwegian and foreign, large and small companies. Several of the interviewees also had responsibility for more than one facility. In total, information on 20 different facilities was made available. Most interviewees had environmental responsibilities for facilities, and some process managers also participated to the interviews.

The interviews showed that flaring strategies, both objectives and measures for reducing flares, vary between sites and operators, but commonalities exist. It is worth noting that the majority of offshore fields on the Norwegian continental shelf and onshore facilities have achieved significant reductions in flaring, showing that the most accessible emission reduction potentials have already been achieved.

In general, those interviewed stated that gas flaring, to the extent possible, should be reduced and unnecessary flaring should not occur. The majority of those interviewed, however, found it difficult to formulate an overall objective and rational for reducing or minimizing flaring.

Larger companies have clearly defined objectives and strategies at the company level, but implementation at the installation/facility level have varied. Based on the interviews, it was difficult to identify clear implementation plans for achieving the overall objective. The project team surmised that company objectives and strategies did not filter down to installation/facility level. This could be due to several factors. The objectives and strategies were only at least partially known, the company's strategy was not yet fully implemented or communicated, or was under preparation (during the time interviews took place) and overall flaring strategies for individual installations or facilities were not yet in place.

Some larger companies have key policies and procedures covering onshore facilities and offshore fields. These are concrete targets determining how long and how much flaring occurs before shutdown or other measures are implemented. If limits are exceeded (i.e., flaring rates offshore and specific emissions limits for onshore facilities) they are reported and explained internally as well as to the relevant authorities. Flaring permits, granted under the Petroleum Act, appear to be an important management tool for all offshore operators. Almost all interviewees mentioned it as a key tool for managing flaring volumes.

Currently a high percentage of flaring is due to unplanned shutdowns and events. It is the project team's assessment that, while management closely monitors and have clear guidelines on decreasing such incidences, the primary reason for minimizing flaring is safety and production rather than actual minimization of flares (which becomes a positive side effect). Prescribed routines (at shutdown, maintenance, and so forth) seem to focus on safety, operating efficiency and productivity rather than minimizing flaring.

Energy plans normally include assessments for flaring, of which environmental plans are also a part. Flaring is not a key focus of such plans. The level of awareness on the impact of these plans on energy management varies between companies (both offshore and onshore) and in general seems to be in an initial stage of understanding.

The companies interviewed, with the exception of one, did not categorize the cause for flaring; all flaring was classified as "safety flaring." Daily reports contain flaring data along with other operational data and events. Retrospective systemization is possible, for example by going through archived daily reports (as the project team have done for this study). Companies with offshore installations are concerned with flared volumes, but less concerned with causes of flaring. Flare permits pursuant to the Petroleum Act control focus on minimizing flaring volumes, to the extent possible. Given that systematized information on flaring causes is not readily available, there is cause to question how management can effectively prioritize resources between various mitigation measures. A systematic overview on continuous flaring, divided by gas source such as pilot flame, purge gas, glycol regeneration, and waste gas from produced water, would be a useful assessment tool in prioritizing emission reduction measures.

A significant portion of non-continuous flaring offshore is due to unforeseen disruptions (approximately 80%). Since this normally implies a loss of production, it is reasonable to assume that most companies systematically review these events. About 30% of this flaring is attributed to depressurization for maintenance and start-up/shutdown of plants and compressors. This category of activity presents a potential source for improvement. Many facilities have taken steps to improve site-specific strategies and procedures to minimize this type of flaring.

In assessing information gained through this phase, the project team determined that the offshore CO_2 tax regime introduced in 1991 achieved significant emission reductions; flaring measures that otherwise would not have been implemented were, due to the CO_2 tax. Further improvements by companies to reduce flare volumes are deemed economically demanding, and in terms of prioritization must be carefully weighed against unintended consequences. There is currently less pressure than in earlier decades to reduce flaring; this partly explains why few flare reduction measures have been implemented. Attention has increased recently, which was confirmed through the interviews; a number of interviewees referenced newly initiated plans. Energy efficiency is a prime example. One company stated that flare strategy has been included as part of the governing documents of the company since 2012. It contains a requirement for preparation of local flare strategies for all operational units (this is an ongoing process).

Expectations over climate policy may have led to increased awareness on the importance of flare reduction and linkages to energy efficiency. One company stated they have had long-term goals since the 2008 KonKraft report was issued[22], in which the petroleum industry undertook to reduce CO_2 emissions by a total of 1 million tons by 2020. The company is now working to put in place strategies for individual fields and onshore facilities. This shows that these types of processes and resulting measures are time consuming to implement. Upon completion of the "2012 Flare Project" it became clear, however, that a significant gap between strategies at the company level and the situation at individual fields exist. This gap demonstrates the time required for processes to result in concrete actions and behaviour changes[23]. It also shows the need for constant attention, visibility and clarity at all levels.

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[22] http://www.konkraft.no/default.asp?id=1005

[23] In several cases, the project team considered the relationship between key strategies and objectives at the company level and specific goals and plans at the facility level, to be weak or non-existent at completion of the interviews.

Recommendations:

Technical and operational measures to reduce flaring can have negative effects on other environmental goals. A recommendation on measure to reduce flaring rates may lead to an increase in fuel consumption for individual flares, increasing both methane emissions (so that flares choke and extinguish) and particulate emissions as combustion efficiency deteriorates. Other parts of this report address these negative correlations, whose effect are dependent on installation specific conditions. The project team, therefore, cannot provide specific recommendations on technical and operational measures related to existing plants and offshore installations.

The project team recommends that flaring be systematically categorized, classifying either by flaring cause or by systems in which the flaring occurs. The phrase “that which is measured gets attention” is valid for this practice. Increased attention enables companies to run a more systematic prioritization for both offshore and onshore.

Improvements in energy efficiency are also possible, and must be anchored both locally and centrally. This ensures that flaring occurs as part of a more centralized energy management plan. Responsibility for improvements lies with management. Without clear and continuous attention by management, strategies and plans are inefficient and end up shelved. The gap identified by the project team between stated company-level strategies and objectives, including emphasis on target (incentives) and how these filter down within a company needs to be closed in order to achieve lasting improvements in the operations.

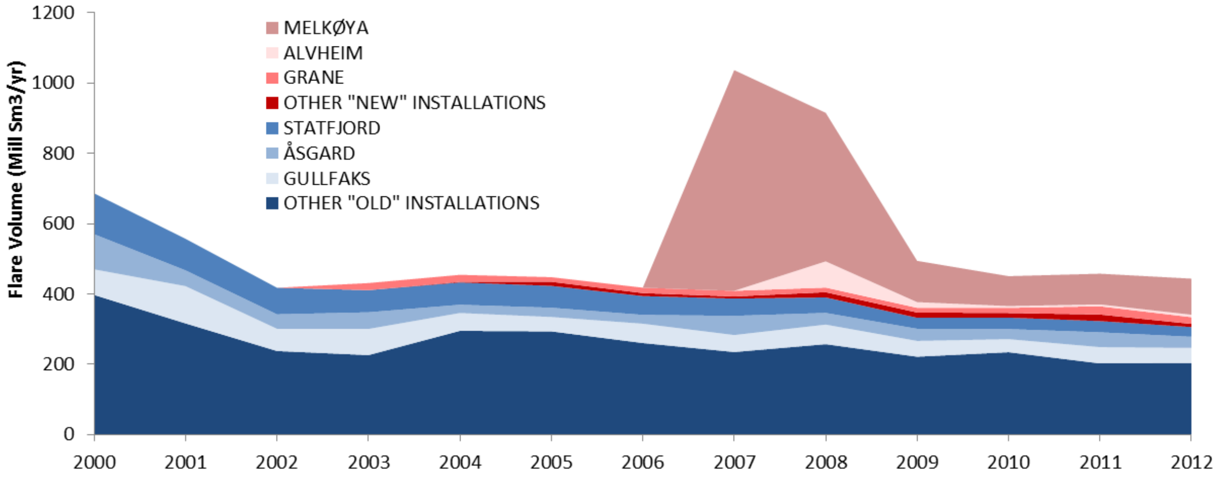
5. Flaring in Norway

There have been many measures implemented in Norway to minimize flaring, at both offshore installations and onshore facilities. Flaring volumes declined slightly over the past decade, varying from year to year. "Flaring intensity" (defined as flared volume per Sm3 o.e. produced) showed slightly rising trends during the same period. **Chapter 5.1** provides an overview of actions taken over the last ten years. This chapter briefly covers techniques for reducing flaring and related emissions, and is described in more detail in **Chapter 6**. The status of flaring on Norway, based on latest available information, is presented in **Chapter 5.2**. Chapter 5.2, combined with an assessment of available technology, formed the basis for BAT assessments; these are presented in **Chapter 6.4**.

5.1 Trends in Flaring and Measures Implemented within the Last Ten Years

Regulations on flaring associated with exploration and production of oil and gas were enacted in the 1970s in Norway. Petroleum legislation (the Petroleum Act §4-4) contains provisions prohibiting flaring except for security reasons, unless permitted by the Ministry of Petroleum and Energy. Norway prohibits flaring as the only option for the use of associated gas. A facility's design, with respect to flaring, is assessed by the Norwegian Petroleum Directorate (NPD) as part of the overall assessment of a company's development plans (PUD and PAD[18]). The Government regulates flaring through issuance of flaring permits by the Ministry through annual production licenses. The long-term, predictable and strict regulation of flaring has undoubtedly contributed to the low level of flaring in Norway, particularly compared to other oil and gas producing countries (14). **Figure 4** shows the change in amounts of gas flared in Norway from 2000 to 2012, including the largest contributors and other "new"[24] and "old" installations.

Figure 4: Development in the amount of gas flared in Norway since 2000



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[24] In this context, "new" installations are defined as installations that were not in operation at the start of the period

Following the introduction of the 1991 CO_2 tax regime, companies introduced a number of measures to reduce continuous flaring; these included developing and adopting new technologies such as flare gas recovery and unlit flares (with automatic flare ignition when required). Total volumes of flaring in 1993 were almost 30% lower compared to flaring volumes in 1989, despite an increase in the number of fields during that period[25]. Since the introduction of the CO_2 tax regime, new field developments have largely applied technologies limiting flaring from continuous sources (including flare gas recovery and use of nitrogen as a purge gas). Various studies conducted since the early 90's have shown that approximately 60-80% of flaring is now due to operational and safety reasons ("non-continuous flaring") (1).

During the project's "Phase 2" survey, information on measures implemented during the last ten years were gathered from companies that flare gas in Norway (i.e., a total of 52 different offshore and onshore installations). Companies reported more than 200 completed measures that reduced the amount of gas flared or the emissions from flaring. There is only a qualitative description for the majority of these measures, i.e., no information was provided on quantified costs, reductions in volumes flared or in emissions. While quantification of impacts from measures implemented in the last ten years was an objective of this project, it was not possible due to lack of data. Data gathered on implemented measures was categorized and is presented in **Table 10**.

Table 10: Overview of reported measures implemented during the period 202 to 2012

Category:	Sub-category:	# reported measures:
Technical measures	Technical measure to improve regularity	33
	(increased) flare gas recovery	18
	Various measures to reduce amount of gas sent to flare	18
Operational measures	Improved procedures and flaring strategies	93
	Personnel training	24
Changes in flare design	Measures related to pilot burners/ignition	4
	Reduced use of hydrocarbon gas as purge gas	2
	Other measures	10

Presented below are evaluations of implemented measures. Potential measures, based on the categories in **Table 10**, tied to further reductions in the gas sent to flares and associated emissions are described in **Chapter8.**

5.1.1 Measures to reduce non-continuous flaring

Technical measures - Improvements in operational regularity:

In 2002, the NPD noted that many facilities were pushed beyond design rates in order to increase earnings and net present value from production. In some cases, this has led to disruptions, more irregularities and more flaring (1). As there are significant win-win situations related to avoiding unplanned downtime and loss of production,

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[25] In 1989, there were 10 fields while in 1993, there were 20 (1).

companies largely focus on maintaining regular production. Measures increasing regularity are not necessarily aimed directly at flaring, rather they are considered by companies to represent some of the most important measures and can directly or indirectly reduce gas flaring.

Companies reported 33 technical measures implemented to improve operational regularity. According to the companies, however, the answers to the questionnaire did not provide a complete picture of efforts made to improve regularity in the last ten years. This is due to challenges associated with filling in the questionnaire, as it did not capture all relevant measures.

The majority of measures within this category reduce flaring. Examples of measures implemented include:

- Upgrades of control/logic/control systems
- Optimization of maintenance (for example water washing of turbines)
- General upgrading of equipment
- Improved robustness of power supply (production and/or distribution)[26]

Data submitted through the survey did not provide a basis for quantifying effects of these types of measures. This is because operational units only to a limited extent undertook quantification/analysis of the flare reductions component of these measures.

Operational measures - Improvements in procedures and flare strategies:

Companies reported 93 implemented measures to improve routines and procedures and flare strategies at individual installations. Nearly half of these measures (40) were implemented in the last three years (2010-2012). Examples of measures include:

- Improving start-up /shutdown procedures (i.e., changing the sequence of start-up activities)
- Optimizing procedures for operations and maintenance.
- Implementing installation specific flare strategies (including establishing methods/plans for undertaking flaring during unplanned events/operational stoppages).

Companies quantified effects for 14 of the 93 measures. Estimates of total reductions achieved through the 14 measures are 30 million Sm^3 per year (equivalent to approximately 7% of total volumes flared in 2002). It was not possible to quantify the effects of the remaining 79 measures during the course of this project. The reductions reported in the survey show that these measures contributed significantly to flare reduction over the last ten years.

Operational measures - Personnel training:

Companies reported on 24 measures implemented to improve operational personnel’s handing of normal and irregular operational situations (including shutdown and irregularities in processes, start-up/shut-down of processing facilities and operation of compressors). These measures are largely tied to training and use of simulators from shift personnel at ten installations, seven offshore and three onshore. Quantitative impact from one installation was reported; estimated at 600 tons gas/year per planned shutdown.

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[26] For example, power sharing between installations and fields. A specific example are Gullflaks and Snorre, where stoppage in one place does not mean that the entire installation must shut down. This provides opportunities for optimal turbine operation in terms of energy demand, which leads to less flaring and reduced fuel gas consumption.

5.1.2 Measures to reduce continuous flaring

Technical measures - Flare gas recovery:

During the last ten years, 18 measures related to recovery of flare gas were reported in the survey (all offshore). Eleven of these measures are tied to design choices of new installations. Flare gas recovery for these installations are considered BAT. The seven remaining measures were implemented at older installations and cover, among others, increased recycling from degassing of produced water, degassing of glycol regeneration and a power unit. The resulting flare reductions are estimated for three measures (Statfjord A Veslefrikk B and Snorre B), totalling 11.8 million Sm^3/year. There are no estimates for flare reductions for the remaining four measures at older installations.

There was also a report of a measure taken in 2002 to install a system for flare gas recovery, which was not a success. The measure proved technically unfeasible based on process conditions. The measure was thus abandoned due to lack of technology.

Changes in flare design - Measures related to pilot burners:

In total, companies reported five measures related to pilot burners. Three measures covered (re-)installation of pilot burners, while two related to changing pilot burners to reduced fuel consumption.

To ensure a stable flame, some installations periodically use substantial amounts of hydrocarbon gas (as purge gas) to keep the flame going. Three offshore installations have (re-)installed pilot burners to limit the amount of gas needed to sustain the flame particularly in foul weather[27]. Using a pilot burner reduces the amount of hydrocarbon purge gas needed to sustain the flame. Two pilot burner (re-)installation measures reduced flaring by an estimated 3.5 million Sm^3/year (implemented in 2010 and 2011).

In 2010, a new pilot and electric ignition system was installed in connection with the replacement of all flare burners on Balder FPU. The new pilot uses approximately 1/10th of the fuel used by the least efficient pilot in Norway, and uses approximately 1/3rd of average reported fuel consumption. An optimistic estimate therefore suggests that this measure may have reduced flaring by up to 100 000 to 300 000 Sm3 / year.

Changes in flare design - Reduced use of hydrocarbon gas as purge/blanket gas:

Numerous new installations chose to use nitrogen (N_2) as a purge gas. Within the last ten years, there has only been one reported concrete measure in which hydrocarbon gas was replaced with N_2 in an older installation. The measure was implemented at a methanol factory at Tjeldbergodden in 2012, and estimated to reduce gas flaring by 1 million SM^3/year.

5.1.3 Summary

Companies flaring gas in Norway reported more than 200 measures implemented to reduce flaring and related emissions in the period 2002 to 2012. The emphasis of these measures were on flare reduction tied to individual incidents or occurrences, both indirectly through various measures increasing regularity and directly through improved procedures and training of operating personnel. Companies rarely quantify effects of measures (reductions achieved). Regardless, there is reason to conclude that the measures contributed to significant flare

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[27] For two of the installations the pilot burner was out of service or removed due to corrosion.

reductions during the last ten years. Companies provided estimates for 26 of the 150 measures that together represent a gas flaring reduction of approximately 90 millionSM^3/year.

Prior to the ten-year period assessed in this study (during the 1990s) a number of measures were carried out to reduce continuous flaring (including flare gas recovery at Gullflaks A and C, Oseberg A, Heidrun, Varg FPSO and Troll C). During the period 2002 to 2012, many older installations reported completed reassessments of measures to reduce remaining continuous flaring. This included measures for flare gas recovery and use of nitrogen as a purge/blanket gas but many were uneconomical. Only 14 reported measures were completed at older installations during this period. These measures relate to the flare system (for example, flare gas recovery, pilot burners or use of purge/blanket gas). Based on the information submitted, estimated effects on the amount of gas flared are approximately 15-30 million SM^3/year. Technologies and flare design solutions reducing continuous flaring are considered as BAT by companies. Most new installations have adopted it over the last decade. BAT assessments are presented in **Chapter 6.4**.

5.2 Status of flaring in 2011

In 2011, flaring in Norway totalled 337 million Sm^3 offshore (938,000 tCO_2) and 203,000 tons onshore (396,000 tCO_2). To gain an overall understanding of the flaring situation at various plants, companies were asked as part of the survey in “Phase 1” to estimate the distribution of flaring in 2011 among various sources. It turned out to be a relatively challenging exercise for companies as causes of flaring are not normally systematically evaluated and reported (see **Chapter 4**). Companies, in most cases, had to manually review daily reports to identify causes of flaring retrospectively. Many companies pointed out that answers given were partly based on a combination of actual data, measurements and calculations, and partly qualified estimates. It was also noted, that submitted estimates for 2011 were not representative of future flaring at the facilities. The latter is natural as flaring varies considerably from year to year.

Despite challenges associated with estimating a distribution of sources of flaring in 2011, companies submitted estimates for 81 of 108 flares for which information exists. The results shown in **Figure 5** are for offshore installations and in **Figure 6** for facilities onshore. The contribution from high-pressure flares (HP) and low-pressure flares (LP) is also illustrated for each source. A relatively large proportion of flaring is listed as “other sources.” There is reason to believe that this is due to incomplete registration of flaring events and causes. These flare volumes should be allocated to other sources, which would likely modify the “snapshot” presented in this report. Although **Figure 5** and **Figure 6** show, at best, a partial snapshot of the situation, which is not suitable for drawing conclusions, they provide interesting indications of further opportunities to reduce flaring. Rough estimates by companies suggest that approximately 80 percent of flaring could be attributed to unexpected/unplanned events or occurrences (i.e., non-continuous flaring). Approximately 30% of flaring can be attributed to depressurization for maintenance and start-up and shut-down of plants and compressors. Continuous flaring accounts for approximately 20% and is related to a limited number of sources (use of pilot gas and purge gas/blanket gas, degassing of produced water systems and glycol regeneration). For onshore plants, approximately 95 percent of flaring is attributed to non-continuous sources and five percent from continuous sources (pilot and purge gas).

Figure 5: Estimated distribution of flaring from offshore sources (2011) [28]

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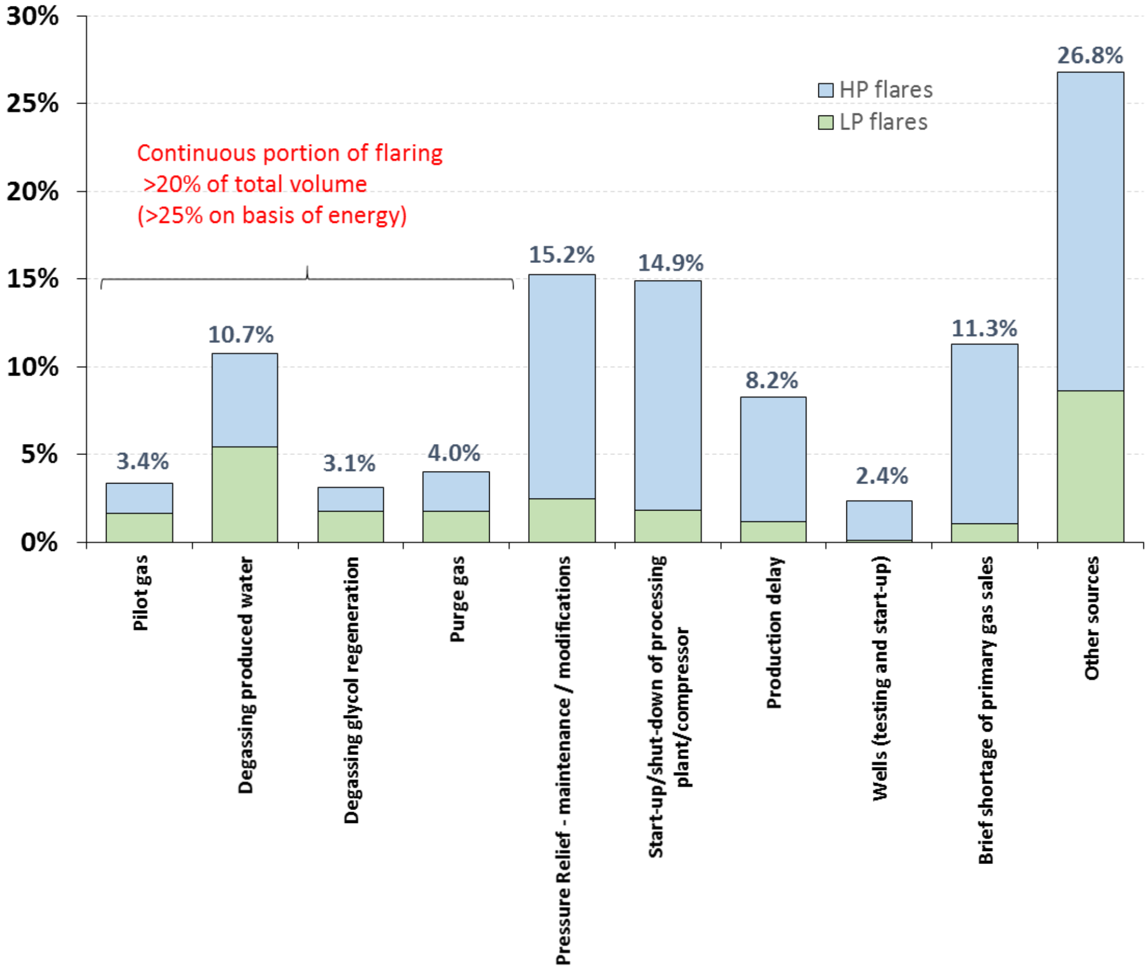
[28] Based on estimates provided by facilities' for the distribution of flaring of hydrocarbons (i.e. after deduction of nitrogen used as purge gas). The proportions in the figure are based on data related to a total flaring rate of 292 million Sm^3 (for a total of 337 million Sm^3 flared in 2011). Reported amounts of purge gas using N_2 were corrected by Carbon Limits as part of quality control of the reported data



Offshore installations had a relatively large percentage of flare volumes in 2011 due to temporary unavailability of the primary gas utilization option (estimated at about 11%). This was cited as a cause of flaring for 32 of 81 flares. For most installations, this constituted a relatively small proportion of overall flaring volumes; the comparatively large contribution (11%) was due to a small number of events resulting in significant volumes flared (and a high percentage of annual flaring for respective installations). Three onshore facilities reported that a significant proportion of the total volumes flared were due to temporary unavailability of the primary gas utilization option. Available techniques to reduce flaring and detailed assessments of potential measures are described in **Chapter 8**.

Figure 6: Estimates of volumes flare by onshore facilities by source (2011) [29]

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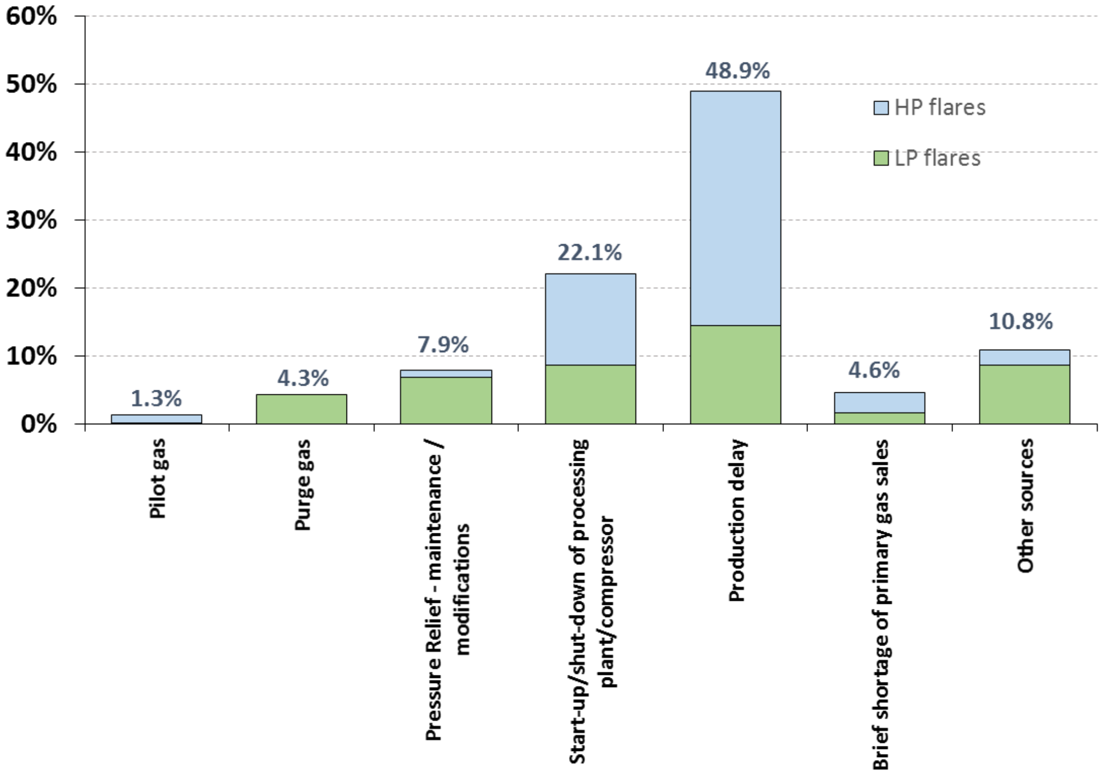
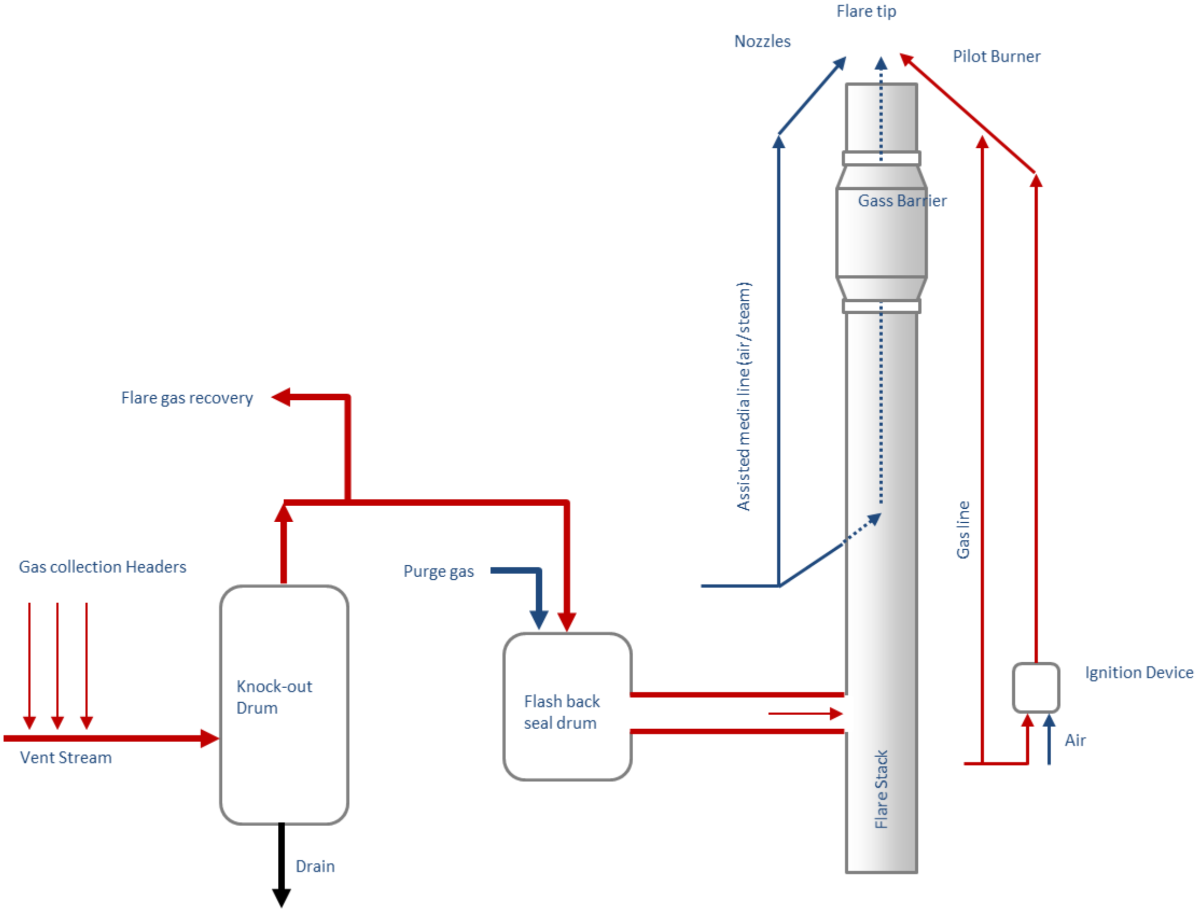
[29] Based on estimates provided by facilities' for the distribution of flaring of hydrocarbons (i.e., after deduction of nitrogen used as purge gas). Percentages in the figure are based on data related to a total flaring rate of 144,000 tons (of a total of 202,000 tons of volume flared by onshore facilities in 2011) Reported amounts of purge gas using N_2 were corrected by Carbon Limits as part of quality control of reported data.


60%
50%
40%
30%
20%
10%
0%
1.3%
4.3%
7.9%
22.1%
48.9%
4.6%
10.8%
HP flares
LP flares
Pilot gas
Purge gas
Pressure Relief - maintenance / modifications
Start-up/shut-down of processing plant/compressor
Production delay
Brief shortage of primary gas sales
Other sources

6. Flare Technologies/Systems

The flare system, together with the pressure relief system forms a critical part of the security system at a processing plant, and are designed to prevent escalation of accidents and dangerous situations. Gas flows through the safety valve, pressure relief valves, control valves and manual drain valves are routed through the gas collection headers to the knock-out drum and on to the flare stack where the gas burns (or is emitted into the atmosphere (vented) when there are limited quantities of gas). The flare system is also designed to handle gas for short time periods such as at start-up and shut-down. Flare systems can be used for continuous handling of toxic or corrosive gases and other flammable gases that for various reasons are not considered attractive for productive purposes. **Figure 7** shows a schematic overview of a typical flare system where important concepts are introduced.

Figure 7: Schematic overview of a typical flare system



The primary function of a flare is to ensure secure and effective handling of gas in accordance with relevant safety requirements. As described in **Chapter 3.3**, the design of the flare system also affects noise and emissions.

An important part of this project was to prepare an overview of current flare technologies/systems appropriate in the Norwegian context and assess the implications of the use of these technologies on various emissions related to flaring (NO_x, CH_4, nmVOC, CO, SO_2 and particulates).

Up until 1940, it was common to vent gas into the atmosphere. As this practice was replaced by gas flaring, there arose a need for improvements in burner design, combustion systems and other equipment. This led to the establishment of industrial suppliers of flare technologies. Due to irregularities in operations and the need for pressure release, flares typically operate over a wide range of operating conditions; from maximal flare rates to very low gas volumes consisting of only purge gas. Flare technology vendors have worked to develop new technologies to flare gas in a safe manner, and do so as environmentally friendly as possible. From an environmental perspective, the main purpose, until recently, has been achieving high combustion efficiency and smoke free operation. Many technologies developed over the last 60 years achieve this. Today, however, there is increasing focus on emissions reduction of NO_x, SO_x and particulate matter.

The project team undertook interviews with six well-known vendors of flare technologies (Argo Flares, Callidus, John Zink, MRW, Tornado and Zeeco) as well as discussions with a number of international experts in this area. Through these discussions, as well as a review of literature, test results and websites, relevant flare technologies were catalogued with regard to design criteria, costs and performance in relation to emissions. The project team also considered general trends and different views on best available techniques for reducing emissions.

Norwegian companies that flare gas provided data on existing flare systems, as part of the survey for this project. This information was reviewed, and analyzed. **Chapter 6** contains a summary of the data review and interviews, concluding with an overall assessment of flare technologies applied in relation to Norway, including what is considered as BAT.

6.1 Criteria use in selection of flare technologies

Each flare system is selected and designed for a particular application. This process requires that suppliers have access to data on a sufficient level describing relevant operating conditions. Jackson et al (31) prepared an overview of data initially sought from various vendors. Flare systems are chosen and designed based on customer's technology needs/criteria and cost expectations. Design criteria can be categorized into five groups:

Technical criteria[30]:

- Design capacity (maximum flare rate)
- Flare rate
- Flare gas composition
- Gas pressure and temperature
- Local climate (air temperature, humidity and wind)
- Space and weight limitations
- Access to electricity, steam, air, and so forth
- Height (with respect to fallout and ground level concentrations)

Safety criteria:

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[30] Specified in, among others, NORSOK standard P-100, ISO 23251 og ISO 25457

- Safe handling of gas (flaring is a part of the pressure relief system and needs to function together with the rest of the system to avoid system failure)
- Safe ignition (to ensure gas ignites and does not accumulate, causing an explosion or venting of large amounts of unburnt hydrocarbons)
- Heat radiation (designs must operate within safety margins, for example heat radiation on personnel and the environment
- Noise (design must operate within acceptable noise levels from a security perspective)

Environmental criteria:

- Emissions limits (established by the competent authority). Depending on the facility's geographic location, this may include varying requirements for combustion efficiency, destruction efficiency and limits for different emissions.
- Limits related to smoke. As emissions from open flares (in particular "smoke") from flares are difficult to measure, the environmental goal for flare operations has historically been defined qualitatively as "smoke free". For example, the USA's regulations for flaring: "Flares shall be designed for and operated with no visible emissions, except for periods not to exceed a total of 5 minutes during any 2 consecutive hours." [31]
- Noise. Noise levels of 130dBA are a security issue; in addition, noise must be tempered by consideration of neighbours and local communities. Noise levels are an environmental problem, regulated under the Pollution Act for onshore facilities, and must be taken into account in flare design.

Cost criteria:

Design choices have implications for equipment, installation and maintenance costs.

- Type of flare (elevated, at ground level or closed).
- Type of flare tip ("utility"/pipe flare, sonic, Coanda, number of nozzles, steam-/air-assisted, staged).
- Support structure (self-supporting, rope or tower/crane).
- Knock out drum
- Purge gas system and equipment for reducing use of purge gas.
- Ignition system (manual/automatic pilot, ballistic).
- Measurement and control systems (for example for ignition and monitoring pilot burners).

Local environment criteria:

(Aspects that affect the local community. These are important elements taken into account requirements of the Pollution Control Act.)

- Light (flares can illuminate the sky for miles depending on size). Complaints can trigger requirements for stricter light minimisation measures including gas flaring reduction.
- Odours (can trigger requirements).

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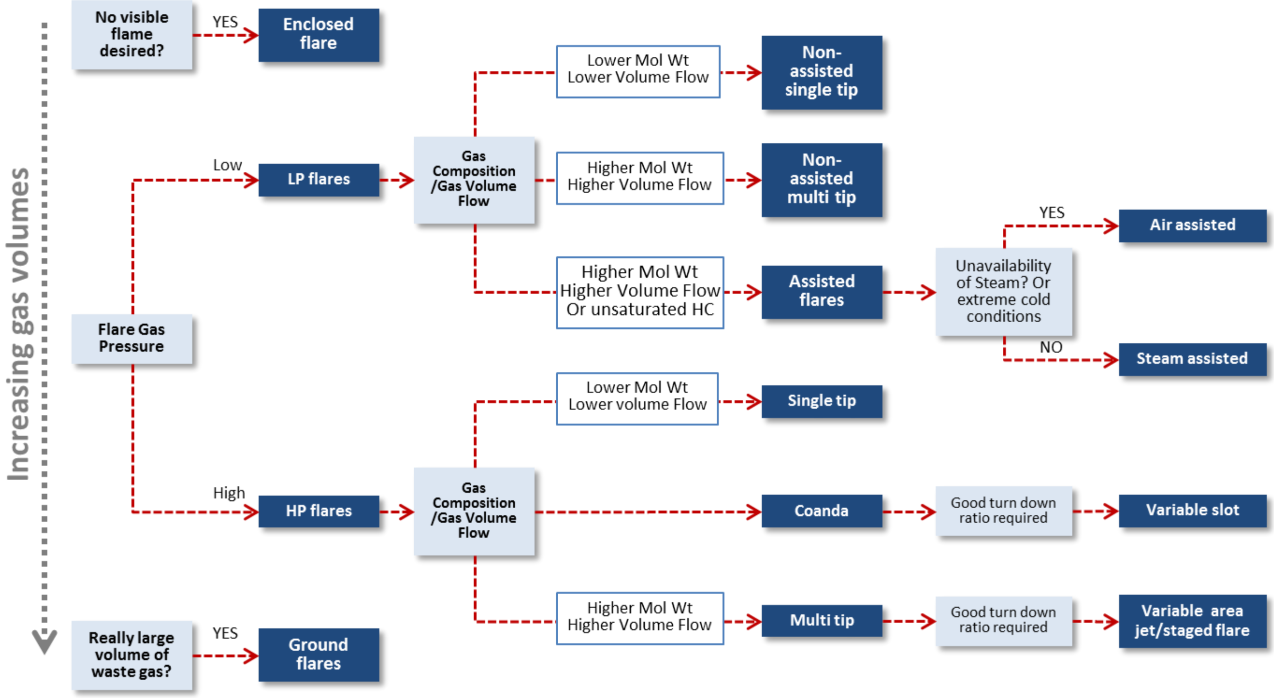
[31] USA Code of Federal Regulations, Title 40: Protection of Environment, PART 63.11

- Appearance (some neighbours might react to the sight of a naked flame even in daylight).
- Noise levels (can trigger requirements).

As part of the design process, all of the above criteria should be considered. A simple overview of various technology options is illustrated in **Figure 8**, (flare technologies/systems referred to in the figure are described in the next chapter).

Figure 8: Simple overview of various flare technologies and design choices



Flare systems are chosen based on technical and safety criteria, as well as relevant environmental requirements/criteria. In addition, costs are of crucial importance for selected solutions. For flare systems onshore, considerations for neighbours also affect the choice of design.

There is general agreement that high combustion efficiency (and limiting VOC, CO and particulate emissions) is desirable as long as flaring occurs within design specifications. It is therefore essential that the variability in flaring rates and gas composition is considered during the design phase and in selection of the flare design.

Figure 9 illustrates actual variations in daily flaring volumes for a low-pressure flare (LP flare) with pilot over a three-year period. The flare has a design capacity of 5.2 million SM^3/day. Flaring rates typically are 1500-2000 SM^3/day (including the pilot) and major flaring events measure at up to 70,000 SM^3/day. **Figure 10** shows daily flaring volumes for a high-pressure flare, where a significant proportion of the total flare gas amount is from continuous sources (degassing of produced water).

Figure 9: Daily variations in flare rates, low-pressure flare example

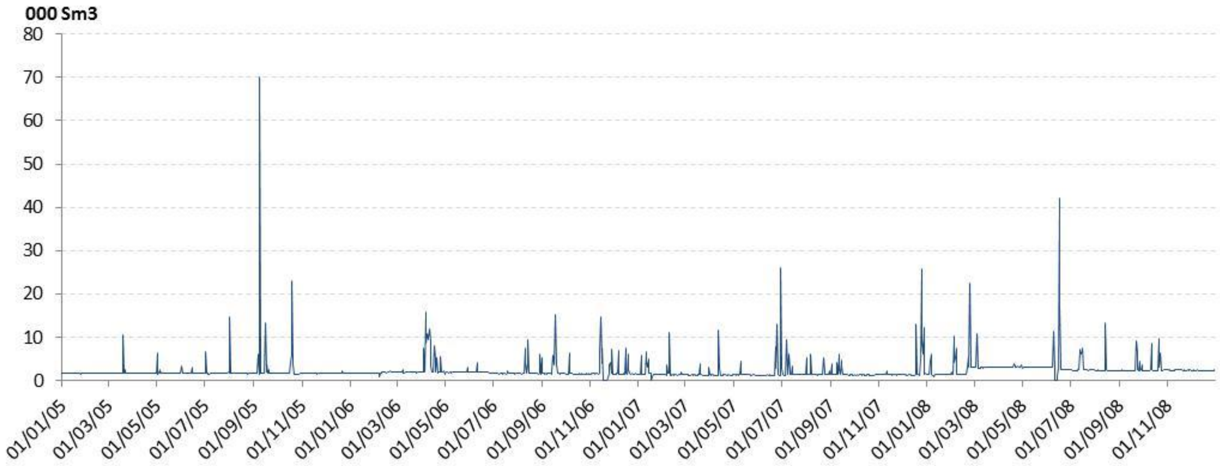
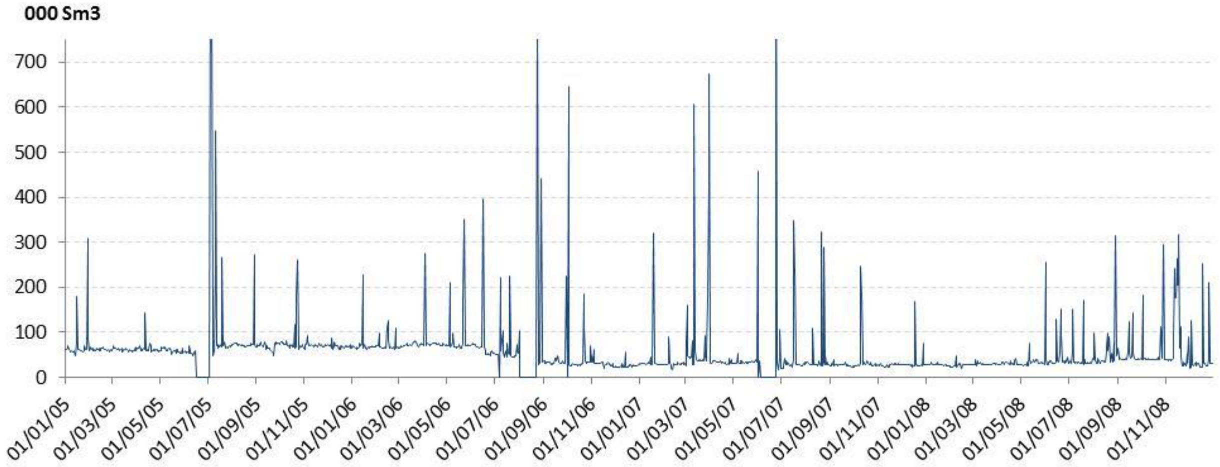


Figure 10: Daily variations in flare rates, high-pressure flare example



Vendors provide a number of patented flare technologies. These are described in **Chapter 6.2**. The Chapter also contains a general overview of existing flare technologies.

6.2 Existing flare technologies/systems

Most flares in Norway are located on offshore installations (88 flares). The installations are usually equipped with a high-pressure flare and a low-pressure flare. A number of installations also have a vent flare. There are various types of flares installed by petroleum companies and petrochemical plants onshore (26 flares). **Table 11** lists available flare types currently used in Norway. Vendors of flare technologies consider these to be suitable for Norwegian conditions. Following the table is a presentation of applications, advantages and disadvantages of different flare technologies. **Chapter 6.3** provides an overview of flare technologies/systems used in Norway.

Table 11: Overview of existing flare-technologies/systems in use and recommended by vendors for Norwegian conditions

General description of flare type	**Flare design**	**Estimated cost**[32]	**Combustion Efficiency (CE)** (CH_4, nmVOC, CO)	**Flame temperature** (NO_X)	**Smoke and particulate emissions** (BC)	**Other benefits**	**Other Conditions**	**Suitable offshore**
Non-assisted, raised LP-flare	Flare tip with a nozzle (pipe flare)	100	**Reference case**			Long lifespan Simple design	Suitable for low rates, low Mol Wt.	Yes
	Flare tip with multiple nozzle ("multi-tip")	150[33]	Increased CE compared with stack flare	Increased temperature compared with stack flare	Reduced smoke relative to pipe flares	Reduced heat radiation	More complex design, incremental operation	Yes
Non-assisted, raised HP-flare	Flare tip with multiple nozzle (stack flare)	120	Increased CE compared with LP pipe flares	Increased temperature compared with LP pipe flares	Reduced smoke relative to LP pipe flares	Less sensitive to wind, lower heat radiation	Suitable for low Mol Wt. Saturated hydrocarbons	Yes
	Flare tip with multiple nozzle ("multi-tip")	150	Increased CE compared med HP pipe flares	Increased temperature compared with HP pipe flares	Reduced smoke relative to HP pipe flares	Stiv/kort flamme (vind), redusert varmestråling	More complex design, incremental operation	Yes
	Coanda flare tip (tulip shaped nozzle)	200	Increased CE relative to pipe flares due to better mixing	Air turbulently mixes with the gas flow leading to higher flame temperature	Reduced smoke for many types of gas	Bra for gas-væske blandinger, lavere varmestråling	Small slots that can clog up	Yes
	Coanda flare tip with variable slot	300	Increased CE relative to Coanda with lower flaring rates	Air turbulently mixes with the gas flow leading to higher flame temperature	Reduced smoke with lower flaring rates	Less sensitive to wind	Shorter life expectancy	Yes
	Flare with water injection		Uncertain. Too much water can reduce CE	Reduced flame temperature	Reduced smoke	Significant reductions in radiation and noise	High CAPEX, complex operation, Increased maintenance	Yes
Assisted, raised flare	Steam assisted flare	100 – 130	Better mixing increases CE Poor CE when using too much or too little assistance medium	Better mixing gives higher local flame temperature. Steam assistance gives lower NO_X then air assistance	Reduced BC-emissions, especially heavier gases and unsaturated hydrocarbons		Use of steam/air can increase noise problems (high-frequency jet noise).	Steam often not available
	Air assisted flare	150 – 200						Not usual
Flares at ground level	Ground level, multiple nozzles	300 – 600	Very high CE for variable rates	High local flame temperatures	"Smoke-free" at all flaring rates	Reduced noise and heat, hidden	Requires large parcels of land	No
	Enclosed flare	300 – 1000	Very high CE can be achieved	High temperature - NO_X can be controlled	Limited BC for all rates	Not visible, low noise and heat	Limited capacity	Yes

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[32] Relative costs (pipe flares were used as reference case) provided by technology providers during interviews in autumn 2012.

[33] Depending on equipment specification (valves, control systems) related to incremental use ("staging").

High pressure flares:

High-pressure flares are generally flares with backpressure close 1 barG or higher. A high backpressure allows use of "sonic" [34] speed burners. The advantage of high-pressure flares is that high gas velocity gives good turbulent mixing of flare gas and ambient air, which provides good combustion conditions.

Use of flare tips with multiple nozzles improves mixture of gas and air. This type of flare tip provides many small jets instead of a large gas stream (with use of a pipe flare), which increases the surface of contact between gas and air. Flares with multiple nozzles also give a shorter and "stiffer" flame. Short flames reduce heat load compared to pipe flares with the same capacity[35], and in some cases, the reduction may be up to 40%[36]. Although shorter flames can provide high heat radiation from the flare, the total heat output from the flame is less than for longer flames[34]. The heat emitted from a smaller volume, will with improved mixture of gas and air, reduce particulate formation. Increased air intake also reduces local flame temperatures. These effects lead to an absolute reduction in heat load. The disadvantage of this type of flare tip is increased costs associated with a more complex design. Examples of a flare tip with multiple nozzles are:

- John Zink Hydra Flare
- Zeeco VariJet Flare
- NAO multi-jet sonic flare

The Coanda flare tip is another high-pressure design providing improved mixture of gas and air than that of pipe flares. Coanda flare tips have a unique design, comparable to a tulip (a tulip shaped nozzle). Waste gas exists the flare tip at high speed and follows the tulip shaped surface producing the "Coanda" effect. The gas adheres to a curved surface, creating a near vacuum that pulls in substantial amounts of air[37]. The Coanda flare tip typically provides sonic speed exit of the gas. It achieves generally good combustion efficiency and is a good design choice for normal natural gas. This type of flare tip also works well for gas-liquid mixtures with up to 75% liquid[38]. The flare tips can be equipped with an adjustable gas exit areas ("variable slots")[39]. The variable slots design provides excellent environmental performance since it achieves high gas velocity at variable flaring rates (33). They can therefore operate over a wide range of flaring rates without smoke and with efficient combustion[40]. Disadvantages of the Coanda flare tip are the cost and, to some extent, the complexity of using the variable slots technology (moving parts)[41]. Tulip-shaped nozzles can also be used in flare tips with multiple nozzles ("multi-point Coanda flare"), and may

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[34] The term "sonic" is used due to the flare gas reaching sonic speed (Mach1) at the end of the flare tip.

[35] John Zink HYDRA High Performance Sonic Flare Tip, http://www.johnzink.com/wp-content/uploads/HYDRA-flare-tips.pdf

[36] ARGO Flares' website, http://www.argoflares.com/research/introduction/flare-types/

[37] http://www.johnzink.com/products/flare-systems/products-2/coanda-flares/

[38] John Zink Flare Product Guide can be found at: www.johnzink.com/wp-content/uploads/production-flares.pdf

[39] The size of the output slots automatically adjust.

[40] Based on Jackson, R.E. and Smith, J.D.'s personal communication with Zeeco and NAO where advantages and disadvantages of Coanda flares were discussed.

[41] Some providers noted that the lifetime for this type of flare tip is shorter than normal.

include low-pressure pipe in the design. Another example of a "multi-point Coanda flare" is NAO's design (sometimes referred to as a "Hot Dog Tip").

Water injection is a technique used on high-pressure flare tips, particularly offshore. Water injection reduces flame temperatures, which in turn reduces heat load (radiation from the flame). Water injection also reduces noise from the flare. J.D. Smith, a project co-worker, experienced these phenomena testing a "Poseidon" flare tip at John Zink's testing facilities in the US. The oil company, BP, patented use of water injection for a Coanda flare in 1987, and has documented a reduction in both heat radiation and noise[42]. Water injection has also been used for other types of flare tips. The reduced flame temperature, achieved through injection also reduces NO_x emissions from flaring. The increased complexity associated with water injection results in higher investment costs and increased maintenance costs.

Low-pressure flares:

Low-pressure flares are flare that have a limited backpressure, and therefore do not have the same potential for air-gas mixing as high-pressure flares. As with high-pressure flares, there are alternative designs for low-pressure flares to increase combustion efficiency of waste gas. Following is a short summary:

To flare gas with limited propensity to smoke, the simplest design is a pipe flare. While a relatively simple design, pipe flares consists of more than just a pipe. In addition to the flare pipe, the design must include solutions to maintain a stable flame. The pilot flame must be able to withstand a crosswind. As with high-pressure flares, multiple nozzles flare tips (instead of a single nozzle) can be used to increase the gas-air mixing.

When additional mixing is necessary to achieve satisfactory combustion, an external medium such as steam, air or gas can be used to assist in the combustion process. The advantage of assisted flares is improved combustion efficiency and reduced emissions ("smokeless" operation is the criterion often referred to in relation to reduced emissions). Disadvantages of assisted flares are costs associated with the consumption of the assistance medium and complexity of design. Assisted flares are rarely used offshore due to their associated costs unless they are required to meet environmental requirements. Assisted flares are common onshore.

Steam assisted flares:

Jets of steam are injected into the combustion zone to draw air into the jet. The air mixes with flare gas and provides better combustion and reduced emissions.

Air assisted flares:

Low-pressure blowers are most comment with use of air assistance (2). Low-pressure blowers supply large volumes of air at low pressure through (relatively) large air pipe where the air mixes with flare gas. Air pipe/nozzles often have a larger diameter than the pipe that carries the flare gas up to the flare tip[43]. Even

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[42] US Patent Number: 4,634,370, David A. Chester, British Petroleum Company, Jan. 6, 1987

[43] See for example Zeeco's air assisted «AF Series flares» (http://www.zeeco.com/pdfs/AF.pdf), John Zink Air assisted Flaring Systems, http://www.johnzink.com/wp-content/uploads/air-assisted-flaring.pdf or Flare Industries' Slot-Flow Air-Assist Flares (SFVP),

if this type of design is the most common, there are also technical solutions where air pre-mixes with flare gas before combustion (i.e., John Zink's JZ ZFF flare). Another flare type applying this principle was developed by Saudi Aramco, and is available under the name "HPAAS" flare through Zeeco [44].

Ground level flares:

Ground level flares (i.e., flares that are not elevated) can be an interesting option when sufficient land is available[45]. This flare type is relatively large due to safety reasons.

The flare system can be designed with numerous flare tips ("staged") in order to obtain optimal combustion for very variable gas flow rate. Ground level flares are typically equipped with fence surrounding the flare to protect the flame from cross winds and, in some cases, to control heat, noise and flame visibility. Placing the flare at ground level reduces costs associated with support structures, which are necessary for elevated flares. Disadvantages of this type of flare are that it requires isolation due to safety considerations (heat radiation and noise) and requires larger surface of land available. The limited height of the flare can also cause environmental or health problems due to higher concentration of emissions.

Enclosed flares:

Enclosed flares are used to reduce heat load on equipment and personnel, and consists of an insulated cylinder surrounded by wind protection. The flare operates with burners placed in the bottom, where air is sucked in through a vent. The cylinder is open at the top and can have air intakes on the sides, or when above the ground, air intakes at the bottom. Thermal buoyancy enables air to be sucked in and provides efficient mixing of air and flare gas. Closed flares are suitable for both high-pressure and low-pressure systems, but have limitations with regard to flaring volumes. This flare type is often used on FPSOs (Floating production storage and offloading) and onshore facilities.

Combustion in an enclosed flare is easier to control since the flame is not affected by ambient conditions in the same way as an elevated flare (i.e., wind). The enclosed structure also provides thermal boundaries that increase combustion efficiency[46]. Particulate emissions (BC) are also reduced. One of the advantages of an enclosed flare is that the heat load on the environment (equipment and personnel) is reduced. Since the flame is not visible, these flares are increasingly used in urban areas where visible, open flames are undesirable. This type of flare also provides efficient wind protection and enables measurement of emissions. The disadvantage is that the flare type has limitations in terms of flaring rates and represents significant costs (see **Table 11**).

Flare systems offshore vs. onshore:

Offshore installations have the same technical requirements as onshore facilities, but have additional space and weight limitations and limited access to utilities. Use of steam-assisted flares presupposes that

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http://www.flareindustries.com/products/elevated-flares/slot-flow-assisted-flares.php

[44] HPAAS Flare, http://www.zeeco.com/pdfs/HPAAS_Brochure_Web.pdf

[45] This type of flare is, for example, used in Australia (http://www.zeeco.com/case_studies/case_studies.php), Saudi Arabia (http://wikimapia.org/23719823/largest-ground-flare-in-saudi-arabia) and USA.

[46] Theradiant heat reflected back into the flame

steam is available. While air assistance is possible, it is difficult to install due to space limitations. Space limitations also present challenges related to placement of the flare tip which must be at sufficient distance from equipment and personnel in order to meet heat radiation and noise requirements. Special towers and flare booms have been developed to address these offshore challenges. Individual floating flare devices tied to fixed installations or drilling rigs with the help of flexible pipes have also been used. The water injected high-pressure flares discussed previously use a readily available fluid, water, to reduce both radiation and noise and thus reduce the structural support requirements for the flare. Due to reduced heat radiation, John Zink reported reductions in the length of flare booms by up to 70%[38]. This can sometimes lead to cost savings.

The logistics associated with installing, maintaining and replacing flares, are more challenging and costly offshore[47]. Often this will lead an operator to be more conservative in their approach to flare design, choosing a system with longer lifetime over a system that may perform better in other ways (e.g. optimal combustion efficiency and low emissions). Some operators prefer to avoid using flare design with variable geometry (variable slot areas) offshore based on experience with increased failure and maintenance associated with moving parts. Although noise may affect the health of birds and personnel, design requirements related to noise offshore are mainly associated with safety requirements.

Pilot burners and ignition systems:

Ignition systems for flares traditionally contain pilot burners. Many different types of pilot systems have been used on gas flare. The pilot flame is typically a pre-mixed stabilized flame with various sizes to keep the flare light, even under extreme conditions. API—and ISO—standards (API537/ISO25457[48]) require that the flames remain lit with wind speeds up to 100mph (45 m/s) in dry weather and 85mph (38 m/2) with precipitation of 55mm/hour. Pilot lights must also release sufficient heat (flame) to ignite the flare gas[49].

There are many factors taken into account in the design of a pilot burner, including gas composition and pressure, output speed of the flare gas (an interval) and design of the flare tip. There has been continuous development of pilot designs, primarily with a desire to improve stability under difficult weather conditions and for extending lifetimes (34). Pilot burners typically have a lifetime of approximately seven years, but can last up to 30 years.

Historically, a flame front generator ignites pilot lights. Flame front generators consist of a thin pipe (less than 2.5 cm in diameter) that contains a gas/air mixture. When the mixture ignites, a “fire ball” generates, travels through the pipe to the pilot burner were the pilot flame ignites. The pipe can be over 1500 meters long.

An alternative ignition system uses a guide tube, sending a pellet to the flare tip. At the end of the tube (the guide tube can be up to 2,000 meters long) the pellet explodes, producing a cloud of sparks, igniting the flare. The system is called a ballistic ignition system. The advantage of the system is that it can eliminate the need for a pilot burner, thereby reducing emissions associated with fuel gas consumption

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[47] There is also information about several critical safety events and loss of life associated with the replacement of flare tips in the North Sea (by helicopter).

[48] Referred to in the NORSOK S-001, cf. Instructions to § 10 of the Facilities Regulations.

[49] Recommended standard minimum is 45,000 BTU/hour for the majority of flares.

of traditional pilot burners. Disadvantages are primarily related to the logistics related to the supply of pellets and higher costs. Many offshore installations use this system.

Equipment for reducing use of purge gas:

Low flare rates can cause air to penetrate into the flare system and lead to internal combustion in the flare tip, and in the worst case farther down in the flare system. To prevent this, flare tips with variable slots and/or purge gas are used. Systems with variable slots, such as Coanda flare tips with variable slots or Zeeco's VariJet, allow flares to operate effectively over a wide range of flaring rates, and can minimize or eliminate the need for use of purge gas.

Purge gas can either be an inert gas such as nitrogen or a flammable hydrocarbon gas. Use of nitrogen as a purge gas is limited by the ignition conditions or "flammability limits" in the combustion zone. Due to this, flammable gases are often used, sometimes in combination with inert gases. If the composition of the purge and flare gases fall below the lower ignition limit, combustion becomes less efficient and can, in the worst case, lead to venting of unburned hydrocarbons. Use of hydrocarbon gas for purging increases costs compared with nitrogen, and may result in increased emissions (with the reservation mentioned above). Several offshore installations use hydrocarbon gas as a purge gas, but nitrogen is the most commonly used. For onshore facilitates the situation is reversed. The majority of facilities use hydrocarbon gas as purge gas.

There are two main types of equipment used for reducing the need for purge gas:

- Velocity seals: a velocity seal is placed in a flare pipe. It is designed for the air stream entering a flare tip to turn 180 degrees and exit the flare tip along with the reduced amount of purge gas[50].
- Molecular seals: a molecular seal utilizes two 180-degree bends to form a zone in which the purge gas is trapped. The difference in density between the purge gas and air prevents further air penetration. If purge gas flow is interrupted for a short time, the only possibility of air ingress is diffusion, which is a relatively slow process.

A molecular seal is substantially larger and more expensive than a velocity seal. On the other hand, a molecular seal is more effective at preventing ingress of air and reduces the need for purge gas. An analysis of costs from a life cycle perspective, will determine which solution is most economical. There are reports of use of velocity seals in Norway; there are no reports related to use of molecular seals.

Knockout Drums:

There are three basic types of knockout drums used in flare systems:

- Vertical settling drums
- Horizontal settling drums
- Cyclone separators.

Both the vertical and horizontal knockout drums remove liquid droplets in a similar mechanism. The flow of gas-liquid mixture expands into to the drum causing the flow velocity to slow. With proper design[51],

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[50] Tornado Technologies, Inc. website http://www.tornadotech.com/products/combustion/flares/purge-gas.html

[51] American Petroleum Institute's API RP-521contains guidance for design of liquid separators.

the velocity slows sufficiently so that with the proper residence time the liquid droplets separate from the gas due to gravity and the difference in density of the liquid and gas. The liquid falls to the liquid reservoir of the tank (horizontal knockout drums often maintain a liquid level such that the tank is about ½ full (2)) while the gases exit and proceed to the flare. This basic design has remained unchanged from several decades. Knockout drums successfully remove most of the liquid, but are not as efficient at removing small droplets as cyclone separators. Cyclone separators use a similar mechanism to particulate cyclone separators. The liquid-gas mixture is forced to proceed through a curved path, similar to a cyclone. Due to the higher density of the liquid it is not able to turn as rapidly as the gases causing a separation of the two. Knockout drums will allow some small droplets of liquid to exit the system and proceed to the flare where they can form larger droplets at the flare. Knockout drums are typically designed to remove droplets of 300 µm or larger, while cyclones usually remove droplets greater than about 20 µm (2).

Control systems for flares:

Satisfactory operation of flares requires a variety of control systems[52]. Control systems are necessary for, among other things, ignition and monitoring of pilot burners, and to ensure that the flare pilot(s) remain lit. It is also important to control fluid levels in the separators. For assisted flares, use of assistance medium must also be controlled. Use of water injection requires monitoring that the flare burns satisfactorily, i.e., is smokeless. Monitoring of flaring rates and gas heating value may also be required. Some flares (closed flares) measure oxygen to ensure adequate supply of air for combustion. Staged flares are dependent on control systems to manage the number of nozzles in use depending on the gas flow. Purge gas systems must be checked to ensure safe operation to, among other things, prevent ingress of air and ensuring that the mixture of flare gas and purge gas is above the flammability limits.

Measurement and control of the flame is important to ensure that the flame remains lit or to ensure that the flare gases burn. Due to location of the flame position, it is often challenging to check whether it is lit. Flames result in heat, ionization of gases, sound and light, which can be used for the monitoring.

- Thermocouples are widely used to measure heat dissipation, and require balance between achieving quick response and avoiding early burnout. If they are placed too near the flame, the probes may quickly burn up. Conversely, if the probes are placed farther away or behind protective materials, the response time becomes longer. Burning of probes can in many cases lead to closure of the facility, and thus should be avoided. Benefits of thermocouples are that they are widely used and relatively affordable.
- Probes have also been designed to measure ionization of gases caused by flare flame (“flame ionization detection probes”). This technique requires placement of two probes in the flame, and is not widely used for flares.
- Optical sensors can measure wavelengths from infrared to ultraviolet. Ultraviolet sensors, which are widely used for boilers, have also been used for closed flares. Most optical sensors used to detect the pilot flame, employ one or more bands in the infrared region (2). The disadvantage of optical sensors are that they cannot always distinguish between the pilot and flare flame, and

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[52] See, among others, Zeeco’s webpage, http://www.zeeco.com/flares/flares_fcs.php.

measurements can be disturbed by weather conditions (rain, fog, snow) or movement in the top of the flare/flare tip.

- Probes utilizing the acoustic properties of the flare have also been designed (35). These probes have no problems in relation to burnout, and can distinguish the pilot flame from other sources of sound including weather conditions.

Control of steam injection can be either automatic or manual. Some flares continue to use manual vents that open and close by an operator who observes the flame. This can be partly automated by using vents controlled from a control room, using a camera to observe the flame. In both cases, an operator adjusts the steam supply based on a visual assessment of the flare. This type of controller is often associated with excessive steam injection (“over-steaming”), especially at low flaring rates. To avoid over-steaming, optical sensors can be used to automatically control steam injection rates.

6.3 Flare technologies used in Norway

Information on flare technologies used in Norway was gathered through the survey of this project. Of the 108 flares surveyed (including four flares that are under construction in facilities not yet in operation) only two are at ground level, while two enclosed flares are installed on Skarv FPSO (HP and LP flare towers as back up). The remaining flares are raised, and are divided into high-pressure flares, low-pressure flares, vent flares and other flares with specific applications (including maintenance flares, tank flares and an H_2S flare). **Table 12** provides an overview of flare technologies applied in Norway.

Table 12: Overview of flare technologies in use in Norway[53]

	Total #:	Type 1:	Type 2:	Type 3:	Type 4:	Div. HP:	Type 6:	Type 7:	Type 8:	Type 9:	Type 10:	Div. LP:
Flare design:	122	16	7	4	4	29	4	9	7k	4	6	18
Gas pressure: (HP/LP)	60 HP 62 LP	60 HP					62 LP					
Closed: (YES/NO)	42 YES 62 NO	YES	NO			8 YES 15 NO	YES		NO			4 YES 14 NO
Pilot flame: (YES/NO)	61 YES 39 NO	NO	YES			16 YES 6 NO	YES	NO	YES			9 YES 7 NO
Purge Gas: (N2/HC)	64 N2 36 HC	N2	N2	HC	HC	10 N2 11 HC	N2	N2	N2	HC	HC	9 N2 7 HC
Velocity: (DESIGN)	40 HIGH 39 LOW	HIGH	HIGH	HIGH	LOW	7 HIGH 7 LOW	HIGH	LOW	LOW	LOW	LOW	5 HIGH 7 LOW
Assisted: (YES/NO)	11 YES 82 NO	NO	NO	NO	NO	5 YES 13 NO	NO	NO	NO	YES	NO	2 YES 13 NO
Assistance: (TYPE)	6 STEAM 4 AIR	▨	▨	▨	▨	3 STEAM 2 AIR	▨	▨	▨	3 DAMP 1 ANNET	▨	2 AIR
Ignition: (AUT/MAN)	44 AUT 49 MAN	13 AUT 3 MAN	1 AUT 5 MAN	1 AUT 2 MAN	1 AUT 3 MAN	11 AUT 10 MAN	7 AUT 2 MAN	2 AUT 2 MAN	1 AUT 4 MAN	0 AUT 4 MAN	1 AUT 4 MAN	5 AUT 9 MAN
# Nozzles: (PIPE/MULTI)	63 PIPE 27 MULTI	10 PIPE 5 MULTI	4 PIPE 3 MULTI	3 PIPE 1 MULTI	3 PIPE 1 MULTI	10 PIPE 9 MULTI	6 PIPE 2 MULTI	3 PIPE 1 MULTI	5 PIPE 1 MULTI	4 PIPE 0 MULTI	6 PIPE 0 MULTI	9 PIPE 4 MULTI.
Diameter: (cm/nozzle)	1.32 - 122.0	5.6 - 81.0	5.1 - 90.0	15.2 - 65.0	28.8 - 81.4	1.32 – 122.0	15.0 - 61.0	35.6 - 50.8	5.1 - 50.8	61.0 - 122.0	15.2 - 121.9	3.2 - 40.6
HV gas: (MJ/Sm^3)	12.5 - 85.3	39.4 - 54.6	41.3 - 45.1	40.1 - 57.3	36.7 - 37.5	27.7 - 52.0	45.4 - 83.3	47.7 - 74.9	38.2 - 48.1	38.9	12.5 - 64.1	31.6 - 85.2
Age: (design)	1978 – 2012	1988 - 2012	1999 - 2012	1992 - 1996	1982 - 2003	1979 – 2012	1999 - 2012	2007 - 2008	1986 - 2011	2004 - 2010	1982 - 2010	1978 – 2012
Number: (last 5 years)	52k	6	3	0	0	13k	5	3	4	1	1	3

Application of technologies related to the main types of flares, described in **Chapter 6.2**, are summarized below.

High pressure flares (HP-flares):

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[53] Various design parameters are used to classify flares into flare types with identical characteristics within these areas. The types where there is the greatest number of flares are presented as "Type X" in the table.

Technical descriptions for 43 high-pressure flares were available for the study. Of the 43 HP flares, 30 have a single nozzle flare tip (pipe flare); four are onshore and 26 offshore. Only two of the 43 flares have a Coanda flare tip with variable slot opening, one onshore and one offshore (Oseberg A and Tjeldbergodden (terminal flares)). Multi-nozzle tips that provide better mixing with air are used for 19 of 43 flares, of which 15 are offshore and 4 onshore. Five of the high-pressure flares are assisted (one offshore and four onshore), two of which are air-assisted and three steam-assisted. There is an air-assisted high-pressure flare offshore (Balder FPU).

Low pressure flares (LP-flares):

Technical descriptions for 36 low-pressure flares were available for the study. One flare is enclosed (Skarv FPSO), while seven of the 36 use multi-nozzle tips (four offshore and three onshore). Goliath (not yet operational) is the only offshore installation with multi-nozzle tip with variable slot openings. There are four flares that use assistance, two of which are air-assisted, one is steam-assisted and one is assisted by incorporation of high-pressure gas. There is an air-assisted low-pressure flare offshore (Balder FPU).

Vent flares:

There are in total seven vent flares in Norway; descriptions are available for only two of these. Both flares are raised pipe flares.

Other flares with specific applications:

Of the 12 flares with specific applications (including maintenance flares, tank flares and an H_2S flare), information is available for five flares, three onshore and two offshore. Three of five flares are installed with Coanda flare tips, one of which is located at ground level (at Kollsnes). Two of the onshore flares are steam-assisted (at Kårstø)

Pilot burners and ignition systems:

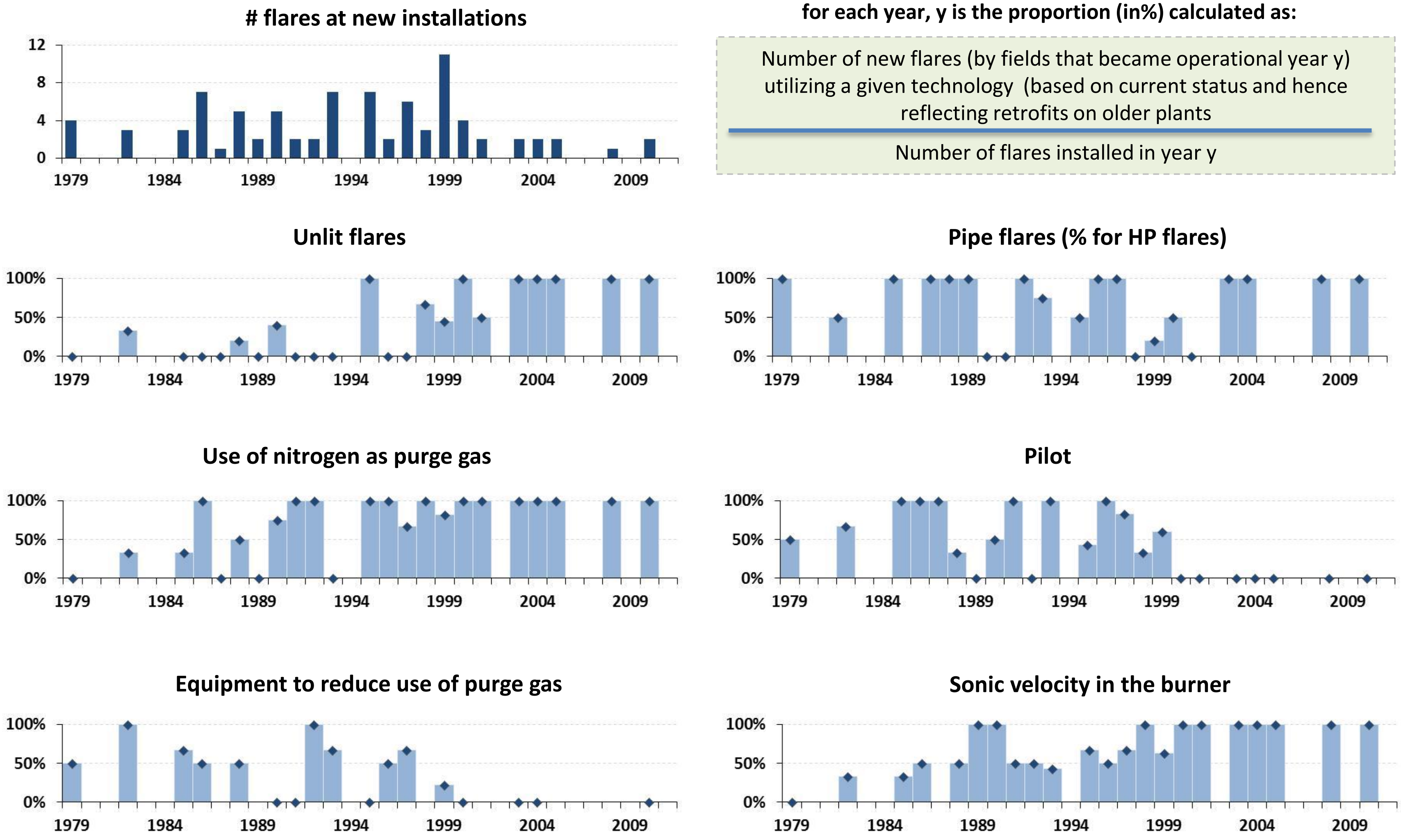
Sixty-one of 100 flares, for which there is information, use pilot burners to keep the flares lit; 43 are offshore and 18 are onshore. As can be seen in **Figure 5** pilot gas represents approximately 3.4% of the volume flared offshore in 2011, while the corresponding estimate for onshore facilities was 1.4%. Fuel pilot burners vary between 0.3 and 40 Sm^3/h, of which 17 of the 61 pilot burners have automatic ignition systems activated if the pilot flame blows out. It was stated that 33 flare systems operate without normally lit flares (unlit flares), and these are equipped with ballistic ignition system. All installations without lit flares are located offshore, with the exception of the facility at Nyhamna (Ormen Lange).

Purge gas:

Information was provided on the type of purge gas used for 100 flares. Of these, 64 employ nitrogen as the purge gas, while the remaining use hydrocarbon gas. Several respondents to the survey pointed out that hydrocarbon gas helps keep flares lit in addition to, or in substitution of, any pilot flame. Twenty-six flares employ equipment to reduce use of purge gas (two onshore and 24 offshore). All installations that have flare gas recovery and unlit flares uses N_2 purge gas, while 22 out of 58 installations that do not have unlit flares use N_2 as the purge gas.

Figure 11 shows a more detailed overview of today's technology status based on start-up dates to which the installations are tied.

Figure 11: Application of various technologies offshore based on system start-up (years)



for each year, y is the proportion (in%) calculated as:

$$\frac{\text{Number of new flares (by fields that became operational year y) utilizing a given technology (based on current status and hence reflecting retrofits on older plants}}{\text{Number of flares installed in year y}}$$

Figure 11 illustrates the use of various technologies offshore based on system start-up (years)/start of production. The figure shows, for each of the years in the period 1979 to 2011, the number of installations that became operational in the year in question, and what proportion of these are using a given technology. The overview includes only those installations for which information is available. The number varies from technology to technology, as the information made available is not consistent.

Of the flares that currently fall under the category "unlit" (i.e., without the use of pilot flame, and using a ballistic ignition system (see **Chapter 6.2** for description)), all are relatively recent. Since the early 2000s, all new development projects have applied this technology solution; the technology less frequently used on older installations. These still largely use still pilot flames.

Use of nitrogen purge gas is common for newer installations, but many older installations also use it. Use of equipment for reduced use of purge gas follows an opposite trend. There are few or no incentives to use these on installations, where nitrogen is used as purge gas. Information gathered shows that the practice offshore leans in the direction of higher speed burners. Furthermore, flare tips with sonic velocity are largely used by newer installations (high output speeds provides good turbulent mixing between flare gas and surrounding air, which in turn provides good combustion). There are no clear trends related to the use of more complex designs of flare tips for high-pressure flares. This is not surprising, since the advantages of complex designs are largely flare specific.

For onshore facilities, there is only one "unlit" flare (at Nyhamna (Ormen Lange)). Use of nitrogen purge gas has been the norm for newer onshore facility, with the exception of the methanol plant at Tjeldbergodden. In 2012, however, measures were implemented at the Tjeldbergodden plant to switch to nitrogen. Sonic velocity is not widespread in pilot burners onshore. Of the newer facilities, only the high-pressure flare at Nyhamna has this. All flare tips at onshore facilities, which started up in the past 15 years, employ multi-nozzle tips, except the low-pressure flare at Nyhamna.

6.4 Assessment of current technology status in relation to BAT

When assessing BAT, it is important to point out that the flare system, along with the pressure relief system, constitutes a critical part of the safety system at a processing plant. Flare systems must be designed to prevent escalation of dangerous and accidental situations, and must meet a number of requirements to ensure safe and reliable operations with limited impact on the environment, as described in **Chapter 6.1.**

In assessing BAT, cost of the alternative solutions limiting flaring and emissions should also be taken into account. Costs and profitability depends on local conditions, including processing plants remaining lifetime, flare gas quantities and flare gas quality handled under various operating and flaring scenarios. This is especially true for older installations (see **Chapter 8** for further descriptions of the technical and economic aspects related to various categories of measures).

Given the above, the following are considered BAT for new offshore installations and onshore facilities:

- Maintenance, modifications, start-up and shutdown of process plants and wells should be planned and implemented to minimize flaring.
- In situations where the primary gas utilization option is temporarily unavailable, production should be scaled down following an established plan that balances safety, environmental and economic considerations.

- Flare gas recovery:
  - Gas from high-pressure relief systems should be captured during normal operation,
  - Gas from low-pressure relief systems should be captured during normal operation where this is considered technically and economically feasible and environmentally efficient.
- Use of purge gas:
  - Nitrogen should be used as a purge gas when it is considered safe.
  - When using hydrocarbon gas as a purge gas, technical solutions should be implemented to reduce purge gas volume to a minimum.
- Fuel consumption by the pilot flame should be minimized to the extent possible without compromising the ability to ignite the flare under all conditions.
- When using air and steam assisted flaring, the amount of the assistance medium used for assisted flaring should be controlled to minimize risks for both under- and over-use of the medium.
- The design and maintenance of the knock-out drum should ensure that there constantly is sufficient capacity to remove liquid drops from the gas stream, thereby reducing smoke formation in the flare.
- All flaring events should be registered and classified by root cause, to ensure effective identification, analysis and prioritization of potential measures associated with flaring.

Balance between what is considered BAT and current practice:

The technical measures presented above, are largely consistent with designs chosen for new installations in Norway in recent years, both offshore and onshore. For older installations the situation is somewhat mixed. Many installations use hydrocarbon gas as purge gas and do not recycle flare gas. This could be a potential to improve procedures and routines affecting flaring. Potential measures are discussed in more detail in **Chapter 8.**

Optimal design of the flare tip will in large part be dependent on site-specific conditions. It is, therefore, difficult to generalize on specific design aspects as BAT. Choice of design should, at a minimum, take into account requirements related to safety, noise and nuisance, and include an assessment of possibilities for limiting emissions under realistic operational scenarios. In this context, it is important to define flaring scenarios that accurately describe the physical conditions applicable to the largest proportion of flaring, especially when there is an expectation of low flaring rates over time.

6.5 Recommendations

The project team recommends that, in the early phase of a new installation (EIA process), operators (offshore and onshore) inform the Norwegian Environment Agency of the choice of flare system and technical solutions that ensure that BAT is being implemented. To the extent possible, technical solutions and associated emission components should be documented for a realistic set of operating scenarios. When companies' procedures and strategies related to flaring are expected to have a major impact on the amount of gas flared, choices and trade-offs should be documented and assessed against best practices at installations in operation.

For older installations, the Norwegian Environment Agency should follow up that there are updated procedures and strategies designed to limit flaring related to individual incidents and malfunctions.

Planned replacement of flare systems and other major modifications resulting in changes in operating conditions should include an updated assessments and documentation related to flaring and related emissions against BAT for new plants, including measures carried out for technical and economic reason.

7. Methods for determining emissions from flaring

An important objective of the project was to assess methods and emission factors used to determine emissions from flaring in Norway.
Emissions can be determined in three ways:

- Direct measurements using detectors placed near the emission source,
- Remote measurements ("open path"), and
- Indirect estimation by quantifying parameters that govern emissions formation (using activity data and emission factors)

Historically, quantifying emissions from flares have been challenging due to large, intense and open (unbounded) flames often not easily assessable for direct measurement (e.g., high above offshore platforms). Remote locations make access difficult for measurements, and open flames and large smoke plumes make it difficult to define boundaries of the control volume using remote measurements. In spite of these challenges, there have been a number of attempts to characterize flare performance as described in **Chapter 3.3**. New measurement techniques are under development, such as Johnson's "sky-LOSA" technique for measuring BC emissions (25) (36) (37), passive FTIR (PFTIR) (38), DIAL LIDAR measurement of CH_4, nmVOC and NO_X and the unique sampling system developed by Aerodyne Research Inc., applied in the TCEQ study (23).

7.1 Current practice in Norway

Currently, direct measurement and remote measurement are not suitable for continuous measurement of emissions from flaring. Therefore, emissions from flaring must be estimated using activity data and emission factors (default emission factors and company-specific factors). Company specific factors are used for CO_2 emissions and in some cases for CH_4, nmVOC and NO_x where measurements are performed using the DIAL LIDAR technique (for onshore facilities). Activity data and emissions factors used to determine emissions from flaring in Norway are described below.

Activity data:

Different activity data can be used as parameters in emissions calculations (flaring can, for example, be expressed in amount of energy burned, gas volume or gas mass). The choice depends on both the factor(s) that governs emissions formations, and practical considerations relating to the availability of accurate measurement equipment to quantify the level of activity in a given period. In Norway, flare gas amounts are reported annually under the Pollution Control Act and Greenhouse Gas Emissions Trading Act. For offshore installations, the Petroleum Act and CO_2 Tax Law also apply. Activity data is primarily determined using ultrasonic meters (sound velocity meters). Activity data is expressed in volume unit (Sm^3) for offshore and/or mass unit (tons) onshore.

Measurement equipment used to determine flare gas amounts must satisfy requirements imposed by regulations under Greenhouse Gas Emissions Trading Act. For offshore installations, additional requirements are imposed through regulations on measurements[54]. Several companies, using nitrogen as a purge gas, subtract the amount of nitrogen passing measurement instruments to determine flare gas flow. Nitrogen amounts are measured upstream using flare meters or determined through mass balances or process simulations. These methods are highly uncertain and increase the uncertainty of the activity data. Companies cannot deduct the volume of nitrogen from the flared gas unless they first apply to the Norwegian Environment Agency in relation to Greenhouse Gas Emissions Trading Act regulations.

Emissions factors:

Emissions factors are typically defined as the mass of a given component (for example g CO, g PM or ton CO_2) per unit of energy burned, volume or mass unit. Emissions factors depend on gas quality, design of the flare tip, whether the flare uses assistance, air/gas ratio in the combustion zone, temperature, wind and other variables as described in **Chapter 3.3**. Given the number of factors affecting emission, emission factors are by nature uncertain which impact emissions data uncertainty reported through the emissions inventory.

In order to achieve an estimate of emissions that is as accurate as possible, emissions factors must reflect combustion conditions in the flare at the relevant facility/installation. In the Norwegian Oil and Gas Association's (Norsk Olje & Gas; NOROG) guidance on annual emissions reporting for offshore installations, it is generally recommended that measurements or field/equipment specific factors be use to the extent possible and only where this is not available, standard factors are to be used (39) (see **Table 13**).

Table 13: NOROG's recommended emissions factors for flaring (in kg/Sm^3 as presented in Table 24 in (39))

CO_2	NO_X	CO	N_2O	CH_4	nmVOC
3,73	0,0014	0,0015	0,00020	0,00024	0,00006

Onshore, default factors for flaring natural gas are specified in Table 3B in Appendix 2 in "the Guide to Self-Assessment for Land-Based Industries" published by the Norwegian Environment Agency (40). The factors may be when emissions are not measured or calculated by other means.

Table 14: Default factors for emissions from natural gas for flaring (in g/kg as presented in (40))

CO_2	NO_X	CO	N_2O	CH_4	nmVOC
undefined	1,4	undefined	0,020	0,24	0,06

A comparison of emissions factors in **Table 13** and **Table 14** shows that emissions factors for NO_x, CH_4 and nmVOC are the same given a gas density of 1.0 kg / Sm3. For N_2O the recommended factor for onshore facilities is 1/10 of the factor recommended by the NOROG. The discrepancy should be examined in relation to the data forming the basis for these emission factors, and the error corrected.

Offshore installations largely use standard emissions factors, except for CO_2 and SO_X, where field-specific factors are primarily used. For onshore facilities, the situation is somewhat different. In addition to CO_2,

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[54] See http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20011101-1234.html

company-specific emissions factors, have been established based on limited-time measurements, including for NO_x, CH_4 and nmVOC[55].

In **Chapter 7.2** methods and factors in use in Norway are compared to methods and factors used in other oil and gas producing countries. Assessments and recommendations related to estimate various emissions are described in **Chapter 7.3**.

7.2 Practices in other oil and gas producing countries

Currently, there are no suitable methods for continuous measurement of emissions from flaring. The approach used to estimate emissions in Norway is similar to those in comparable countries.

The emissions factors used for flaring are primarily in mass per unit of energy[56] or mass unit[57]. Test results show that for emissions of several gases (e.g., for NO_X emissions (40)), emissions factors which are energy- or mass-based are more accurate than volume-based. Other oil and gas producing countries also utilizes time-limited measurements to determine flare specific emission factors, both in terms of sampling smoke plume and remote measurements using, e.g. DIAL LIDAR or PFTIR. The scope for this type of measurement is not known, and it has not been possible to confirm whether these measurement technologies have been used for offshore flares. Most countries have established default emissions factors for the main emissions from flaring. A compilation of these is presented in **Table 15**.

Table 15: Default emission factors for determining emissions from flaring in different countries

Emissions component:	Recommended Norwegian factor:	Emissions factors (converted to mass[58] per kg gas flared)				
		Norway:	UK[59]:	USA:	Denmark[60]:	Russia:

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[55] DIAL LIDAR (a method that uses light to measure chemical concentrations in the atmosphere) has been used to measure concentrations/emissions of NOx, CH4 and nmVOC from flaring. These time limited measurements are the basis for establishing flare specific emissions factors.

[56] For example in the USA, where emissions factors for flaring presented in the US EPA's AP-42 is given in lb/10^6 BTU.

[57] For example in the UK.

[58] The CO_2 unit mass is quoted in kg, while other factors are given in grams (g). The average gas density for flare gas is not known. Based on information for 2011 a gas density of 1.06 kg/Sm^3 is assumed in the table (based on data for 69 flares).

[59] Default factors for flaring natural gas and associated gas are presented in Chapter 8.5 in (42). These factors are based on an assumption of 98% combustion efficiency.

[60] Emissions factors for Denmark are given in pass per GJ. The factors are converted for comparison with a given heating value of 48.4 MJ/ton.

CO_2	3,73	3,52	2,8		2,75	
NO_X	1,4	1,32	1,2	1,2	1,5	
CH_4	0,24	0,23	18,0	2,6	0,23	Flare specific[61]
nmVOC	0,06	0,06	2,0		0,12	
PM	0,856	0,81		(in µg/liter)	0,0048	
CO	1,5	1,42	6,7	6,8	1,16	
N_2O	0,02	0,02	0,081		0,02	
SO_X	Flare specific	Flare specific	0,0128		0,01	

As seen in **Table 15**, some gases have relatively large differences in recommended emissions factors, especially for unburnt hydrocarbons. The differences provide an indication of fundamentally different assumptions and/or data in different countries.

7.3 Assessing methods and default factors for use in Norway

Assessments presented in this chapter are based on data collected from companies that flare gas in Norway, interviews with flare experts and a thorough review of available literature related to quantifying emissions from flaring. Recommended methods and factors relate primarily to technological and physical conditions.

Several of the emissions factors in use are based on factors presented in the US EPA's AP-42 section 13.5 (41). These factors originate from the extensive flare study financed by the Chemical Manufacturing Association (CMA) in 1983 (22). Extensive research was carried out on small-scale "laboratory" flares in controlled environments, where flare tip diameter was 8 cm or less (23). In comparison, full-scale flare diameter of burner nozzle(s) typically exceeds 30 cm. Flares in Norway, based on information provided, have a diameter range of 5.8 to 122.0 cm. There is general agreement that small-scale "laboratory" flares with a diameter less than 9 cm are not representative of full-scale flares. The lack of emissions data for large-scale flares has resulted in many flare emissions factors that are based on non-representative sets of measurement data. Below, the project team reviews the methods and factors used in Norway.

7.3.1 Emissions of NO_x

Several onshore facilities have conducted verification measurements (remote measurements) with the DIAL LIDAR technique for determining emission factors for NO_X. Such measurements are difficult and costly to implement for flares, but is considered one of the most reliable methods for measuring these types of emissions. Onshore facilities undertaking these measurements, have established average emissions factors for NO_x based on measurements over limited period. It is unknown whether similar

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[61] Emissions of unburned methane from flaring is levied. Based on field-specific data provided in published "Project Design Documents" (PDD's) for projects registered under "Joint Implementation" (a project-based mechanism under the Kyoto Protocol) to reduce flaring in Russia the emissions factor was estimated from approximately 3 to 11 gCH_4/kg gas.

measurements have been made offshore or whether other measurement techniques have been used to determine specific emissions factors for NO_X.

The recommended emissions factor offshore for NO_x is 1.4g/Sm^3. The factor was reduced from 12g/Sm^3 in 2008 after recommendations from a study for NPD and NOROG prepared by SINTEF Energy and add Novatech (40) (hereinafter called SINTEF). The reason for the study was an increased focus on NO_x emissions (due to the introduction of a NO_X tax). In addition, the emissions factor of 12g/Sm^3 from 1993 did not take into account changes in flaring rates, gas compositions or flare technology. In addition, the emissions factor was approximately 10 times greater than emissions factors used in other comparable countries.

In the 2008 SINTEF study, an experimental scaling law ("d-scaling law") was developed. This showed a good correlation with available data from laboratory tests of small- and medium-sized flares (<50 mm in diameter) and the results of DIAL LIDAR measurements of flare emissions from four onshore facilities, especially when taking into account the flare diameter. Results for steam-assisted flares showed the greatest deviation from the experimental scaling law. Therefore, it was not recommended to use the "d-scaling law» for either steam- or air-assisted flares

Based on daily flaring data (2004/2005) and information about flare diameter from five offshore installations, SINTEF uses the "d-scaling law" (see Equation 1) to estimate the NO_x factor. The resulting NO_x factors ranged between 1.16 to 2.36g NO_X/Sm^3, with an average of 2.0g NO_X/Sm^3 for these five installations (40).

$$\mathrm{EI}_{\mathrm{NOX}} = 0.93 \times \frac{1}{d_0^{0.45}} \times \dot{V}_0^{0.2} \times \frac{1}{\rho_0} \qquad \textbf{(1)}$$

The recommended emissions factor of 1.4gNO_x/Sm^3 is in the lower portion of the range, which emerged in the SINTEF study. The value of 1.4g NO_x/Sm^3 is based on the US EPA's AP 42 factor (EFNOX) at 0.068 lb NOx/10^6 BTU (41) and an assumption of a constant flare gas heating value of 48 MJ/Sm^3 (see Formulas 2 and 3, and Chapter 8 in (40)).

$$0.068 \frac{\mathrm{lb\ NO_X}}{10^6 BTU} = 0.029 \frac{kgNO_X}{10^6 kJ} \qquad \textbf{(2)}$$

$$0.029 \frac{kgNO_X}{10^6 kJ} \times 48000 \frac{kJ}{Sm^3} = 1.4 \frac{gNO_X}{Sm^3} \qquad \textbf{(3)}$$

Data obtained in this project, however, shows a relatively large span in gross heating values offshore, from 35 to 112 MJ/Sm^3, with an average of 46.6 MJ/Sm^3 and a weighted average[62] of 41.2 MJ/Sm^3 (figures are based on data for 72 flares).

The data upon which the US EPA's EF_{NOX} is based is shown in **Table 16**. The data ranges from 0.018 to 0.208 lb NO_x/10^6 BTU, with the average value for the whole dataset being 0.068 lb NOx/10^6 BTU. The mean value for each category (i.e., steam-assisted (by high and low GCV) and non-assisted[63] (by high and low GCV)) are shown in **Table 17**. The table shows that the average value of the two categories, including

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[62] The amount of gas flared in 2011 is used to estimate the weighted average

[63] This also includes air-assisted flares.

gas with low energy content (low BTU) is relatively consistent with the overall average (all data), while the two categories of energy-rich gas (high BTU) differs. Steam-assisted flares give somewhat lower emissions than the average value of high BTU, while non-assisted flares have a significantly higher factor under such conditions, approximately twice as high as the overall average of 0.068. In the US State of Texas, four default factors are used that are comparable with the average factors in **Table 17** (42)[64].

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[64] The smaller deviations caused by the elimination of data points where combustion efficiency was less than 98%. CMA study in 1983 showed that properly operates ball flares typically had a combustion efficiency of 98%.

Table 16: Data from 1983 CMA study (22)

Flare type:	**Test No.**	**Heating Value** BTU/SCF	**NO_X concentration** ppm	**CO_2 concentration** ppm	**Emissions factor NO_X (EF_{NOx})** $lb_m/10^6$ BTU	**Combustion efficiency (CE)** %
Steam Assisted High BTU	1	2,183	3,09	7,052	0,0680	99,96
	2	2,183	2,16	4,719	0,0710	99,82
	3	2,183	3,46	8,159	0.0658	99,82
	4	2,183	1,96	6,616	0,0459	98,80
	8	2,183	1,45	5,400	0,0416	98,81
	7	2,183	1,62	5,224	0,0481	99,84
	5	2,183	2,09	6,115	0,0530	99,94
	67	2,183	3,77	3,758	**0,1556**	
	17	2,183	1,00	3,493	0,0444	99,84
	50	2,183	0,50	4,220	**0,0184**	99,45
	56	2,183	0,58	3,120	0,0288	99,70
	61	2,183	1,32	6,273	0,0326	82,18
	55	2,183	0,38	2,012	0,0293	68,95
Steam Assisted Low BTU	57	294	2,68	6,945	0,0598	99,90
	11		3,69	5,269	**0,1086**	99,83
	11a	305	3,31	6,677	0,0769	99,93
	11b	342	4,17	8,158	0,0793	99,85
	11c	364	4,00	8,210	0,0756	99,82
	59		1,41	5,413	0,0404	98,49
	59a	192	1,30	5,575	0,0362	98,11
	59b	232	1,62	5,090	0,0494	99,32
	60	298	0,99	3,685	0,0417	98,92
	51	309	0.57	3,347	**0,0264**	98,66
	16		1,87	4,059	0,0714	99,75
	16a	339	1,39	3,236	0,0666	99,74
	16b	408	2,42	5,291	0,0709	99,75
	16c	519	1,57	3,419	0,0712	99,74
	16d	634	2,28	4,458	0,0793	99,78
	54	209	5,00	7,115	0,1090	99,90
	23	267	5,90	8,465	0,1081	100,00
	52	268	0,68	2,622	0,0402	98,82
	53	209	2,83	5,741	0,0764	99,40
Air- & Non-assisted High BTU	26	2,183	5,34	6,270	0,1321	99,97
	65	2,183	2,40	4,878	**0,0763**	99,57
	28	2,183	8,16	6,078	**0,2082**	99,94
	31	2,183	4,02	4,568	0,1365	99,17
Air-Assisted & Non-assisted Low BTU	66	158	0,97	2,432	0,0619	61,94
	29		1,06	2,179	0,0754	61,60
	29a	168	1,09	1,529	**0,1106**	55,14
	29b	146	1,04	2,808	0,0574	65,60
	64	282	1,24	3,282	0,0586	99,74
	62	153	0,68	3,076	**0,0343**	94,18
	63	289	1,57	4,184	0,0582	99,37
	33	83	0,74	1,857	0,0618	98,24
	32		1,75	3,702	0,0733	98,87
	32a	294	0,63	1,761	0,0555	98,91
	32b	228	2,39	4,811	0,0770	98,86

Table 17: Analysis of data presented in Table 16

	Steam assisted, high BTU	Steam assisted, low BTU	Air- and unassisted, high BTU	Air- and unassisted, low BTU	All data
Average	**0,047**	**0,068**	**0,138**	**0,060**	**0,068**
Maximum	0,156	0,109	0,208	0,111	0,208
Minimum	0,018	0,026	0,076	0,034	0,018
Standard deviation	0,021	0,032	0,054	0,015	0,039

In a recent study conducted in Texas (43) measurements of NO_x emissions from flaring with low flare rates and flare gas with low heating value (BTU) were carried out for full-scale flares for both air- and steam-assisted flares. A summary of the results are presented in **Table 18**. Results of the air-assisted flares are relatively consistent with the 1983 CMA data. Results from the steam assisted flare show considerably lower emissions than that which was found in 1983. The Texas study shows a good correlation with combustion efficiency. Reduced combustion efficiency is often associated with low flame temperatures that tend to lower NO_x production. In addition, more hydrocarbon radicals react with NO_x molecules to convert the NO_x back to N_2 and O_2.

Table 18: NO_x emissions factors for flare gas with low heating values from TCEQ study (43)

	Steam assisted, low BTU	Air assisted, low BTU	All data
Average	**0,017**	**0,056**	**0,030**
Maximum	0,033	0,083	0,083
Minimum	0,009	0,037	0,009
Standard deviation	0,0065	0,0167	0,0216

Based on the information from the 1983 CMA study it is possible to compare the measured NO_x emissions with estimated NO_x emissions for the same flare using SINTEF's d-scaling law. In order to compare the results the emission factors from the CMA study have been converted into a mass basis[65]. Based on flaring rate information and flare tip diameter from the CMA study, the NO_X emissions factors are calculated using the scaling law. The entire dataset from the 1983 CMA study was used for comparison, as the SINTEF study had limited access to data for full-scale flaring. The results of the comparison are shown in **Figure 12**.

Emissions factors calculated using the d-scaling law have similar mean values for each of the four groups presented in **Table 17**, when the hydrocarbon portion is used for conversion of the CMA emissions factor on a mass basis. The comparison shows that the greatest deviations are for air- and non-assisted flares with high BTU. For this flare type, calculations with the scaling law provides an average of 1.38g NO_x/kg

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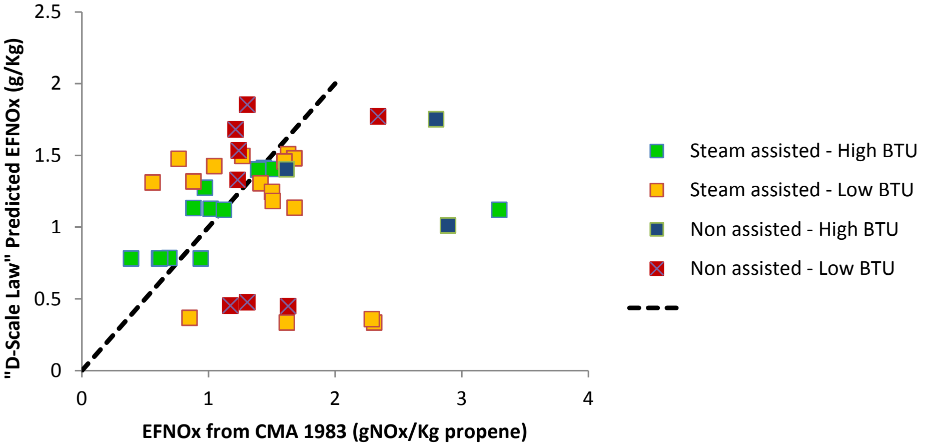
[65] Of the tests performed for gas with low heating value, propylene was mixed with large amounts of nitrogen in order to achieve low heating value. Since most flares in Norway have a low content of inert gas (high heating value), the CMA data was used to calculate the two emission factors for respectively the total amount of gas (including nitrogen) and only for propylene ratio.

(very close to the current Norwegian emissions factor of 1.4g NO_x/SM^3). The emissions factor presented in the CMA study for this flare category was 2.9g NO_x/kg (based on test data); this was over twice as high as the factor estimated by the d-scaling law.

Figure 12: Comparison of test results CMA (1983) and calculations with the "d-scaling law"



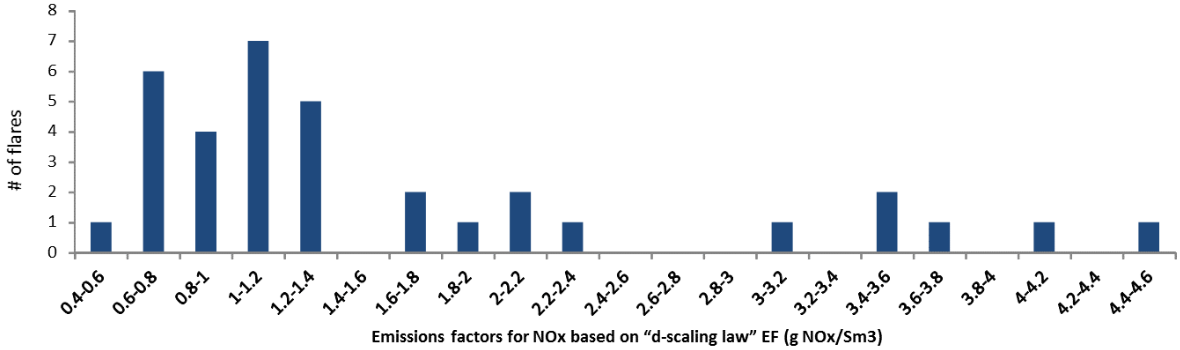
It is difficult to define which method is best in relation to establishing an emissions factor for NO_x for non-assisted flares. SINTEF's correlation seems robust. The d-scaling law has not been verified for full-scale flares with characteristics typical of offshore flares in Norway (in relation to diameter, gases with relatively high gas density and sonic speed in the flare tip). The d-scaling law should therefore be verified against a larger set of metrics than exists for offshore flares in Norway today. As mentioned in **Chapter 3.3**, other researchers have found partly the opposite effect than SINTEF as it relates to the importance of gas density and flare diameter on NO_X emissions. Comparison of the results from the 1983 CMA study and estimates of NO_x emissions using the d-scaling law, shows that the d-scaling law provides for low NO_X emissions for non-assisted flares at high BTU values, which is relatively typical offshore.

SINTEF recommends in their report that today's emissions factor of 1.4g NO_x/Sm^3 be used only for offshore flares, because onshore flares use gases with greater variation in energy content and many onshore flares are also steam-assisted (40). As can be seen in **Table 16**, the US EPA emissions factor of 0.068 lb $NO_x/10^6$ BTU, which is identical to the recommended emissions factor offshore under an assumption of an energy value of 48 MJ/Sm^3, is based on an average of a wide range of measurements undertaken by CMA in 1983 (22). A large proportion of the CMA measurements are undertaken for steam-assisted flares (32 of 47, or approximately 70%). Using the average factor for air/non-assisted flares and gas with high energy content (high BTU) as the starting point (0.138 lb $NO_x/10^6$ BTU), which is more presentative to the situation offshore, and the assumption of the average energy content of 48 MJ / Sm^3 used in SINTEF report, an emissions factor for offshore flares corresponds to 2.8g NO_X/Sm^3.

For onshore flares, the representative values presented in **Table 17** were used to calculate emissions for different categories of flares in the absence of results from flare specific measurements using DIAL LIDAR or other suitable measurement methods. Use of the values presented in **Table 17** assumes that the energy content of flare gas at individual onshore facilities is known, where the emissions factors is given as gNO_x per ton of gas flared for onshore facilities.

Based on daily flaring data for 35 flares in the period 2005-2011 (data for 12 to 36 months is available for each flare within this period), flare tip diameter and gas heating value, the d-scaling law was used to calculate flare specific emissions factors. The distribution of emissions factors, calculated for the 35 flares are shown in **Figure 13**. The flaring rates, in the absence of detailed data on flaring events, are assumed to be evenly distributed throughout the day (continuous flaring), which represents a conservative assumption. Calculations for the 35 flares result a weighted average of approximately 1.6 g NO_x/Sm^3.

Figure 13: Distribution of calculated emissions factors for NOx based on "d-scaling law"



The project team recommends the following for NO_x emissions factors:

Emissions factors for NO_x of 1.4g NO_x/Sm^3, as recommended by SINTEF for offshore use, should be revised to better reflect flaring conditions offshore when it pertains to flaring rates and energy content. The revision should be based on a review of updated measurements and calculations carried out with SINTEF's d-scaling law.

7.3.2 Emissions of Methane (CH_4)

Several onshore facilities carried out measurements with the DIAL LIDAR technique (remote measurements) to determine emissions factors for CH_4 from flaring. Those onshore facilities that performed measurements established average emissions factors for CH_4 based on measurements in the smoke plume over a limited period. It is unclear if similar offshore measurements have been made or whether other techniques have been used to determine specific emissions factors for CH_4.

For the majority of offshore flares the recommended NOROG emissions factor of 0.024g CH_4/Sm^3 is being used. As presented in **Table 10**, this emission factor deviates significantly from those used in other comparable countries. In NOROG's guidance on annual emissions reporting for offshore installations (39), it states the listed emissions factor is from a 1994 report by Norsk Energi (44). It is unclear how emissions factors in the Norsk Energi study were calculated. The 1994 report contains primarily flaring data associated with flaring of liquid from well testing, although Table 4.3 of the report shows data from gas flaring. The emissions factors presented in Table 4.3 of the 1994 report are also different from the default factors recommended by NOROG.

CH_4 emissions from flaring are mainly determined by two parameters[66]:

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[66] Heavier hydrocarbons may also be broken down to more volatile hydrocarbons, which could result in emissions of methane, although the flare gas originally contained no methane. This is reported by, among others, McDaniel's

- The proportion of methane in the gas flare (in gCH_4/Sm^3), and
- Combustion efficiency[67]

The first parameter is determined by flare gas composition, while the other is more difficult to quantify. According to experts, elevated flares can achieve a combustion efficiency of more than 98% when the flare is designed, installed and operated optimally (up to 99.5% according to some experts). This is confirmed by data from e.g. the 1983 CMA study presented in **Table 16**. Experts also agree on some conditions that may adversely affect emissions of unburned hydrocarbons. The following situations may result in reduced combustion efficiency and thereby increase CH_4 emissions

- Over use of assistance medium (only relevant for assisted flares)
- Flaring with very low flare rates
- Delayed ignition and poor combustion during ignition, particularly for unlit flares
- Flare gas with low heating value
- Flaring in strong winds

There is an abundance of research literature related to combustion efficiency for flaring. The most relevant were recently summarized in a report published by the US EPA[68]. Combustion efficiency was measured, in an important series of tests, for various types of flares with changes in gas composition, flaring rates, the design of the flare tip and use of assistance. Measurements performed were mainly for steam-assisted flares. In 1985, Pohl and Soelberg conducted tests for CMA for pressure-assisted flares, and published curves for the relationship between exit velocity and gas heat content that maintains flame stability. Tests were also conducted at John Zink's test laboratory in Tulsa (Oklahoma, USA) in collaboration with the TCEQ and the Dow Chemical Company. Test reports from this study concluded that pressure-assisted flares can achieve a combustion efficiency that is at least as good as steam and air-assisted flares. The weakness of this study is that it only included two different flare tip designs (Varner et al. (2007) referred to by EPA[69]).

Over use of assistance medium:

Challenges related to overuse of steam (for steam-assisted flares) or air (for air-assisted flares) has been widely studied in recent years in the United States. Based on data from more than 300 measurement, US EPA recently concluded the following:

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from the 1983 CMA study (22); unburnt hydrocarbons in the smoke plume containing up to 80 vol% methane even though flare gas consisted of a synthetic mixture of propylene and propane.

[67] The combustion efficiency is not a precise measure how much unburned hydrocarbons are emitted from the flare. With combustion efficiency of 99.5% there can be both more or less methane emitted than 0.5% of flare gases from initial methane content due to the effect described in footnote 63. Combustion efficiency is used in most studies to estimate emissions of unburned hydrocarbons. The project team is not aware of any alternative methods to quantify this type of emissions that have been determined to be more accurate based on measurement data.

[68] http://www.epa.gov/airtoxics/flare/2012flaretechreport.pdf

[69] http://www.epa.gov/airtoxics/flare/2012flaretechreport.pdf

> "Using too much steam in a flare can reduce flare performance. Given that many steam-assisted flares are designed to have a minimum steam flow rate in order to protect the flare tip, over steaming has resulted, especially during base load conditions. In addition, operators acting cautiously to avoid non-compliance with the visible emissions standards for flares have liberally used steaming to control any potential visible emissions, also resulting in over steaming in some cases. [Similarly] using too much air in a flare can reduce flare performance."

The US EPA (13) and other experts (11) prepared recommendations related to control of the operation of assisted flares. These relate to lower ignition limits in the combustion zone or net heating value of the gas/air mixture in the combustion zone. There is insufficient data to reflect on the situation of the 11 steam- or air –assisted flares in Norway. Most reported that there is some sort of optimization of injection rates of steam or air, including that the assistance medium volume is correlated to the flared amounts (in some cases also temperature) or that there are multiple blowers in which some start as needed (for air assistance). Based on the data available, it is not clear, however, whether optimization is manual or automatic.

Flaring with very low flare rates:

Flare designs require sufficient capacity to handle flaring scenarios that could withstand extreme events. Very often they operate, however, with a much lower flaring rate than they are designed, as illustrated in **Figure 9** and **Figure 10**.

Tests have been conducted showing combustion efficiency rapidly decreasing with very low flaring rates. The rates analysed, however, are so low they are not considered relevant for Norwegian conditions. Results from measurements made with the DIAL LIDAR technique by Norwegian onshore facilities, however, shows that combustion efficiency is less than 95% at very low flaring rates.

Delayed ignition when flaring is needed and poor combustion during ignition:

Emissions of unburned hydrocarbons can occur if ignition is delayed (for example in a system with an unlit flare or if a pilot flame blows out). There is also reason to believe that abnormally high emissions can occur for a limited time, from ignition to a stabile flame, depending on the ignition process. Practical experience shows that ignition period lasts from 10 to 30 seconds. Combustion efficiency is estimated conservatively to about 50% in this period.

The number of ignitions per year has increased in Norway as a result of the introduction of technologies for unlit flare. Based on daily flaring data it is estimated that the number of ignitions offshore is about 1100 to 1700 per year. This can result in up to roughly 700 tons of CH_4 emissions annually[70]. Distributed over flared volumes offshore in 2011, this gives emissions of 2.1g CH_4/Sm^3, which is almost nine times higher than the current recommended factor (i.e. 0.24g CH_4/Sm^3).

Flare gas with low heating value and flaring in strong winds:

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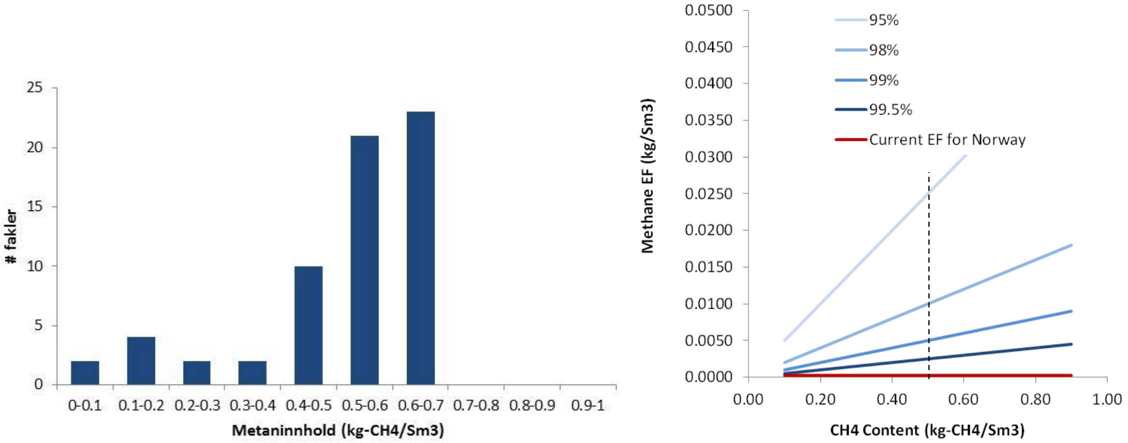
[70] Gas density is assumed to be 1.04kg/Sm^3 and Mol Wt. 25 kg/kmol based on available data for Norwegian flares.

Research results published by Johnson et al. (12) shows that combustion efficiency can be negatively affected when flare gases have very low heating value (for example when nitrogen is used as a purge gas and constitute a large proportion of the gas sent to the flare) or by strong winds. This is corroborated from measurements performed at Kollsnes. As mentioned in **Chapter 3.3**, the impact of wind on large flare/flaring rates is uncertain. Flaring in Norway is believed to be affected by wind conditions (especially offshore), but there is no data or robust correlations to estimate quantitatively the impact on methane emissions.

Assessment of default emissions factors for methane offshore and onshore:

Figure 14a shows the distribution of flares relative to methane content in flare gas, while **Figure 14b** shows the impact of methane content and assumptions on combustion efficiency on the emissions factor for CH_4. A weighted average of methane content in flared gas in 2011 is about 0.5 kg CH_4/Sm^3 (shown as dotted line in the figure at right).

Figure 14: Methane content in flare gas (a) and illustration of the impact on emission factor (b)



Measurements carried out with the DIAL LIDAR technique by onshore facilities gives significantly higher emissions factors than the recommended emissions factor of 0.24g CH_4/Sm^3 for offshore flares. The DIAL LIDAR technique is also used for verification of combustion efficiency. Measurements performed for onshore flares show combustion efficiencies in the area of 95.0 to 99.5%. For the low-pressure flare at the Melkøya processing plant emissions of methane were measured equivalent to 6.3g CH_4/kg, which corresponds to emissions of 8.5 gCH_4/Sm^3 [71]. Combustion efficiency for this flare was measured to be in excess of 99% in 2008, while that of the high pressure flare was measured to be 99.8%. At the gas processing plant at Kollsnes, combustion efficiency was measured at 99.5% for the high-pressure flare in 2009. The emission factor for the high-pressure flare at Kollsnes in 2009 is calculated at 2.95 gCH_4/Sm^3.

It has not been possible for the project team to set a representative combustion efficiency for flaring in Norway. This is due to lack of familiarity with real flaring rates and gas compositions, as well as limited knowledge over other factors that affect combustion efficiency. The project team has the following recommendations related to the default emissions factors for CH_4 in Norway:

- A consistent set of assumptions for gas combustion and combustion efficiency associated with flaring should be used in the estimation of emissions factors for CH_4 (and emissions factors for other components resulting from incomplete combustion such as nmVOC, CO and particulates).
- Implementation of measurements for full-scale flares or controlled tests of flares under representative conditions for Norway should be implemented and combined with results from model calculations to verify that the level of emissions factors for CH_4 offshore and onshore are reasonable.
- Emission factors used for CH_4 emissions from flaring offshore (0.24 gCH4 / Sm^3) and onshore seem low and should be revised (increased) based on conservative assumptions in particular for combustion efficiency. This is supported by measurements of flares at onshore facilities with DIAL LIDAR and will be in line with the principle of applying a conservative estimate until more detailed information is available on actual levels of these emissions.

7.3.3 Emissions of nmVOC

Emissions of other unburnt hydrocarbons are effected by the same conditions as methane emissions. For nmVOC, measurements undertaken with the DIAL LIDAR technique show higher emissions factors than the default factor. For low-pressure flares at the Snøhvit facility emissions factors were measured at 2.2 g nmVOC, which corresponds to 3.0g $nmVOC/Sm^3$. It should be noted, this gas has a high methane content and correspondingly low levels of heavier components. Therefore, it is not representative of flaring offshore.

As with CH_4, the project team believes that the nmVOC emissions factor used for offshore flaring (0.06g $nmVOC/Sm^3$) and onshore are low and should be revised (increased) based on more conservative assumptions. This is supported by DIAL LIDAR measurements taken at onshore flaring facilities.

7.3.4 Particulate emissions (Black Carbon)

In 2011, the emissions factor for particulate emissions (black carbon (BC)), used in calculating Norwegian emissions was updated to 0.856g PM_{10}/Sm^3. The factor is based on recent research at Carleton University. Most research work on understanding black carbon up until now has been undertaken in controlled

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[71] http://www.klif.no/nyheter/dokumenter/statoilhydro_hammerfestLNG_soknad091208.pdf

laboratory tests. Since BC emissions from flaring are highly variable, there is great uncertainty related to the size of emissions.

Chapter 3.3.6 summarizes information on governing parameters on formation of particulate emissions. At this time, there is considerable uncertainties related to estimates of these emissions and available information on existing emissions levels is very limited.

In spite of a wide literature search, it was only possible to identify two sources that provide quantified emission factors for black carbon particles:

- US EPA AP-42 section 13.5 (2) presents four different factors. These relate to flaring through formation of visible smoke (black carbon). The factors are based on the 1983 CMA study (22) and provided in µg/litre (litre refers to the volume of the flare plume)

No smoke:	0 µg/liter
Light smoke:	40 µg/liter
Medium smoke:	177 µg/liter
Heavy smoke:	274 µg/liter

Due to the measurement approach and the reference to visual smoke observations, it is difficult to form a sufficient basis to derive an emission factor per Sm3 flared.

- Laboratory experiments conducted at Carleton University (Johnson et al) shows that black carbon (soot) formation increases with increased flare tip diameter, gas density and energy content (heating value (HV)) (3). The correlation between emissions of black carbon[72] and heating value (HV) is presented in formula 4, and was derived from the results shown in **Figure 2**.

$$EF_{BC} = 0.0578(HV) - 0.29 \qquad \textbf{(4)}$$

This correlation is the basis for the Norwegian emissions factor[73].

In the TCEQ study carried out by Aerodyne, measurements of particulate emissions were performed, but the result published cannot be used to derive an emission factor (27).

In order to assess the uncertainty associated with utilizing results of flare tests carried out by Carleton University and Aerodyne, test conditions have been compared to Norwegian conditions. The comparison is shown in **Table 19**. The Table shows significant differences between the test conditions and conditions in Norway. It should be noted that no flares in Norway have comparable conditions to those tested by Carleton University.

Table 19: Comparison between test conditions and Norwegian conditions

	Aerodyne	Carleton University	Does it represent Norwegian condition?[74]	Implications for black carbon emissions
Flare tip diameter	Full scale	12,7 to 76,2 mm	For 3 of 71 flares	Uncertain implications

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[72] Due to measurement instruments used the correlation only refers to the BC portion.

[73] The emissions factor for particulates at 0,856 g PM_{10}/Sm^3 is obtained by adding the assumed average heating value of 48 MJ/Sm^3 and dividing the results by 0.8 to get the total particulate quantity.

[74] Based on a comparison of the conditions tested at Carleton University in relation to available data for Norway.

Type of flare	Air and steam assisted flares	Unassisted, sub-sonic pipe flares	For 38 of 86 flares	Large implications (particularly smoke formation)
Gas velocity	Unspecified	0,12 to 8,4 m/s	For 31 of 46 flares	Large implications (particularly smoke formation)
Wind	Up to 7 m/s	No wind	Reported wind is higher than 8 m/s in average	Uncertain implications
Transient regime	Not assessed	Not assessed	>1,000 ignitions per year	Uncertain implications, potentially large
Gas energy content	Only propane and propylene	37 to 48 MJ/m^3	For 37 of 71 flares	Large implications

The project team believes that there is insufficient basis to revise current emissions factors at this time. The existing emission factor is based on the best currently available information on the relationship between operating conditions and particulate emissions. However, there is great uncertainty of the magnitude of these emissions both in Norway and internationally. Published works show significant differences between measured emissions factors. There are several ongoing research projects to reduce this uncertainty, but it is unclear when the results will be available and whether they will be representative of Norwegian conditions.

The following possibilities exist for obtaining greater knowledge on the relationship between operating conditions and particle emissions for gas flaring operating in Norway:

- **Measurement campaigns** can be implemented using measurement techniques under development by Carleton University and Aerodyne for onshore facilities and/or offshore installations[12]. According to Carleton University and Aerodyne measuring techniques can be used onshore in Norway. Measurements offshore may be difficult to implement and may prove to be very costly (practical challenges and costs will depend on the selected measurement techniques, the design of the installation, weather conditions, etc.). Since there are limited opportunities to control and change the physical parameters of flares in operation (e.g. flare rate and gas composition), these types of measurement campaigns only provide information on a limited number of operating conditions. On the other hand, for Norwegian flares it means access to accurate data for flaring rates (ultrasonic meters) and gas compositions (online GC), which may make it interesting to perform measurement campaigns in Norway.
- **Measurements in large-scale test facilities**. In a test facility, measurements could be conducted for a range of operating parameters and for various flare designs during a limited period of time. However, this will require close cooperation with one or more suppliers of flare technologies and access to a test facility to allow measurements under operating conditions representative of flaring in Norway.
- **Quantitative analysis and verification of CFD models** represents a valuable addition to physical measurements of emissions, and may possibly, facilitate modelling of operating conditions that are not necessarily tested and measured physically. Several experts pointed out that none of the Computational Fluid Dynamics (CFD) models currently used to analyse flaring are validated to quantify emission of black carbon (i.e., they are not currently suitable for estimating this type of emission).

Of the above options, implementing a controlled test program in a large-scale test facility appears to be the most interesting. It can also enable testing of several alternative measurement technologies and improvement/verification of CFD models for wider application.

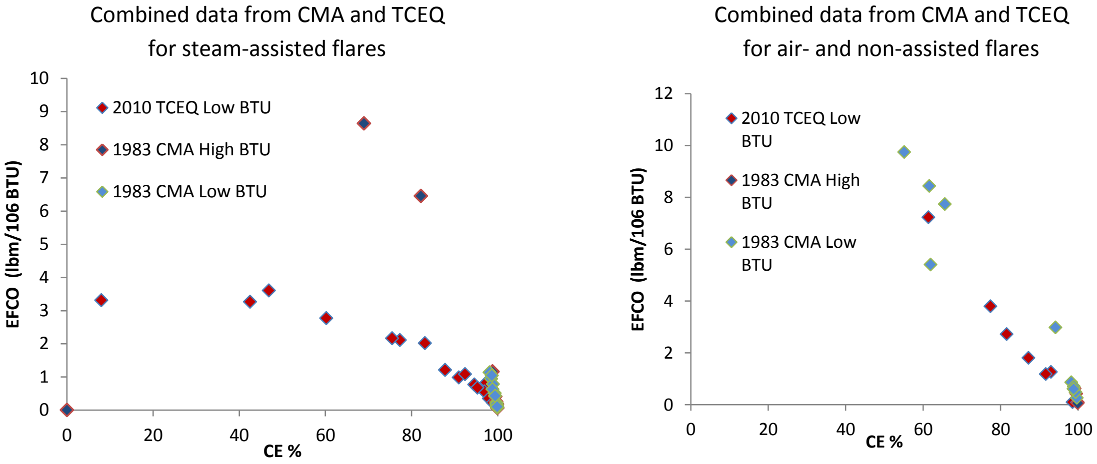
The basis for estimating emissions factors for particulates (including BC and OC) is very thin, and factors used for Norway are associated with great uncertainty. The emissions factors should be revised when additional test results for conditions more representative of flaring in Norway are available. Carbon Limits recommends that an initiative is taken to facilitate and organize future measurement programs in a way that makes them useful and relevant in both the Norwegian and international context.

7.3.5 Emissions of CO

The origin of the default emissions factor of 1.5 g CO/Sm^3 is unknown. Carbon monoxide is one of the main products (and indicators) of incomplete combustion, and is included in the formula for combustion efficiency. To quantify the efficiency of combustion in a flare, the CO must be measured. CO measurement can be done directly (in the smoke plume) or remotely. Although it is currently not possible to continuously measure emissions from flaring it is likely that some of the available technologies (especially PFTIR (36)), can be used in measuring campaigns under normal operating conditions to establish a flare-specific emissions factor.

To assess the recommended emissions factor in Norway, CO data from the CMA study (1983) and the TCEQ study (2010) were used to identify trends related to combustion efficiency. Results are shown in **Figure 15**. The figure shows measured emissions of CO as a function of combustion efficiency for steam-assisted flare and air- or non-assisted flares. Emissions factors for CO increase almost linearly as combustion efficiency decreases, except for steam-assisted flares, when gas with low heating value is burned.

Figure 15: Comparison between emissions factor for CO and combustion efficiency (23) (22)



By removing points in **Figure 15** where combustion efficiency is lower than 98%, we get the data presented in **Table 20**.

Table 20: CO emissions factors from CMA and TCEQ studies (lbm/10^6 BTU)

	CMA-data from 1983					TCEQ-data from 2010		
	Steam-assisted High GCV	Steam-assisted Low GCV	Air-assisted High GCV	Air-assisted Low GCV	All data	Steam-assisted Low GCV	Air-assisted Low GCV	All data
Average	**0,3504**	**0,3465**	**0,2755**	**0,5496**	**0,3715**	**0,280**	**0,090**	**0,185**
Maximum	1,0744	1,0515	0,5766	0,8032	1,0744	0,3412	0,0949	0,3412
Minimum	0,0509	0,0502	0,0497	0,2474	0,0497	0,2180	0,0854	0,0854
Std. deviation	0,3904	0,3308	0,2533	0.1886	0,3226	0,0871	0,0067	0,1205

Information is available in both studies to calculate emissions factors in g CO per unit mass instead of g CO per unit of energy. For steam-assisted flares, emission factor approximates 7.4g CO/kg gas both for flare gas with high- and low-heating values (BTU). For air and non-assisted flares with high BTU the resulting emissions factor is 5.8g CO/kg gas, while low BTU is 11.6g CO/kg gas. These values are higher than the recommended factor in Norway when the values are converted to a volume basis (average gas density is assumed to be slightly higher than 1kg/Sm^3). Based on correlations illustrated in **Figure 15**, the recommended emissions factor for offshore reflects an assumed combustion efficiency of 99.7% to 99.9%. The assessment is based on calculations with a selection of available measurement data (all points with CE>95%, non-assisted flares, high heating values).

The project team recommends revising the emissions factor for CO. In revising the emissions factor, measurement data for actual emissions from representative high pressure flares should be included.

7.3.6 Emissions of N_2O

The background for the default emissions factor for N_2O of 0.002g N_2O/Sm^3 is unknown. Generally, the emissions factor for N_2O from flaring has been subject to much less attention than for other gases. Although N_2O is not described in the US EPA's AP-42, it is an important greenhouse gas that is routinely measured by waste gas measurements, both in the US (45) and in the rest of the world (46). Research literature providing emissions data on N_2O for open flares was not found. The 1994 PFTIR study (38)) included measurements of N_2O during flare testing but no data was reported. The project team considers it necessary for further research to establish an N_2O emissions factor from flaring.

7.3.7 Emissions of SO_X

A flare specific emissions factor for SO_X can be determined measuring SO_X in the waste gas.

There is no recommended emissions factor for SO_X. Since emissions of SO_X are directly related to H_2S content in the flare gas, it is determined by SO_2 emissions from flaring through measured and/or estimated H_2S content, and on the assumption that SO_X mainly consists of SO_2 (39). This is also the practice in Norway. Measurements of H_2S content in the flare gas is performed in oil refineries. The project team considers this a reasonable approach until alternative methods are in place (39).

7.4 Conclusions and recommendations

Comparison of methods and emissions factors used in Norway against methods and factors used in other comparable countries show that for some components, there are relatively large differences in the expected levels of emissions. Based on the review of data collected from companies, it is not obvious that the level of recommended emissions factors can be explained by technological or operational differences. For several emissions components, it is currently not possible to determine emissions factors without significant uncertainty in the resulting emissions estimates. This is because there is little access to representative measurement data for full-scale flares that are representative of Norwegian conditions. The project team, therefore, has the following recommendations:

- When estimating emissions factors for CH_4, nmVOC, CO and particulates from flaring, a consistent set of assumptions for gas composition and combustion efficiency should be used.
- To verify that the level of estimated emissions factors for CH_4, nmVOC, CO and particulates are reasonable, measurements for full-scale flares or controlled tests of flares under conditions representative of Norway should be undertaken. These measurements can be combined with results from calculations from models.
- The emissions factor for NO_X of 1.4 gNO_X/Sm^3, recommended for use offshore, is in the lower end of the range presented in the SINTEF report (40). The value of 1.4g NO_X/Sm^3 was calculated on the basis of a factor from the US EPA AP-42, which is heavily based on measurements for steam-assisted flaring. The emissions factor for NOx should be revised (increased) to better reflect flaring conditions existing offshore. Revisions should be based on updated measurement results and calculations performed using SINTEF's “d-scaling law”.
- The emissions factor recommended for CH_4, nmVOC and CO seem low and should be revised (increased) based on conservative assumptions for combustion efficiency. This is supported by measurements done for flaring at onshore facilities with DIAL LIDAR and in in line with the principle of applying a conservative estimate until more detail information is available on actual levels of these emissions.
- The basis for estimating emissions factors for particulates (BC and OC) is very thin, and the factors presented for Norway are associated with great uncertainty. When additional test results for conditions more representative of flaring in Norway are available, they should be revised. An initiative to facilitate and organize future measurement programs should be undertaken in a way that makes them useful and relevant in both the Norwegian and international context.

8. Potential Measures

The Norwegian Environment Agency's "2012 Flare Project" included a survey of potential measures to reduce flaring and its associated emissions. The purpose of the survey was to obtain information on companies' action plans and their assessment of potential measures, including cost-benefit analysis and any perceived barriers. This chapter contains a summary of data and analysis of measures obtained from companies as well as analyses by the project team of the potential.

8.1 Analysis and assessment of potential measures

Companies provided descriptions of more than 150 potential measures to reduce gas flaring or emissions from gas flaring. The information made available, however, is of varying quality, and rarely quantitative.
For many of the identified potential measures, companies reported challenges related to quantifying the cost/benefit and reduction potential. This was particularly true for measures to improve production regularity and measure to improve procedures and field/installation specific flare strategies. These types of measures constitute half of the reported potential measures. Only six of the 150 potential measures provided quantified information on costs, flaring/emissions reduction potential and net present value. Missing data hampered analysis of potential measures and emission reductions.
The reported measures were divided into two main categories, depending on how they affect emissions from flaring:

(i) Measures to reduce the amount of gas flared, and
(ii) Measures to modify the combustion conditions in the flare and reduce specific emissions.

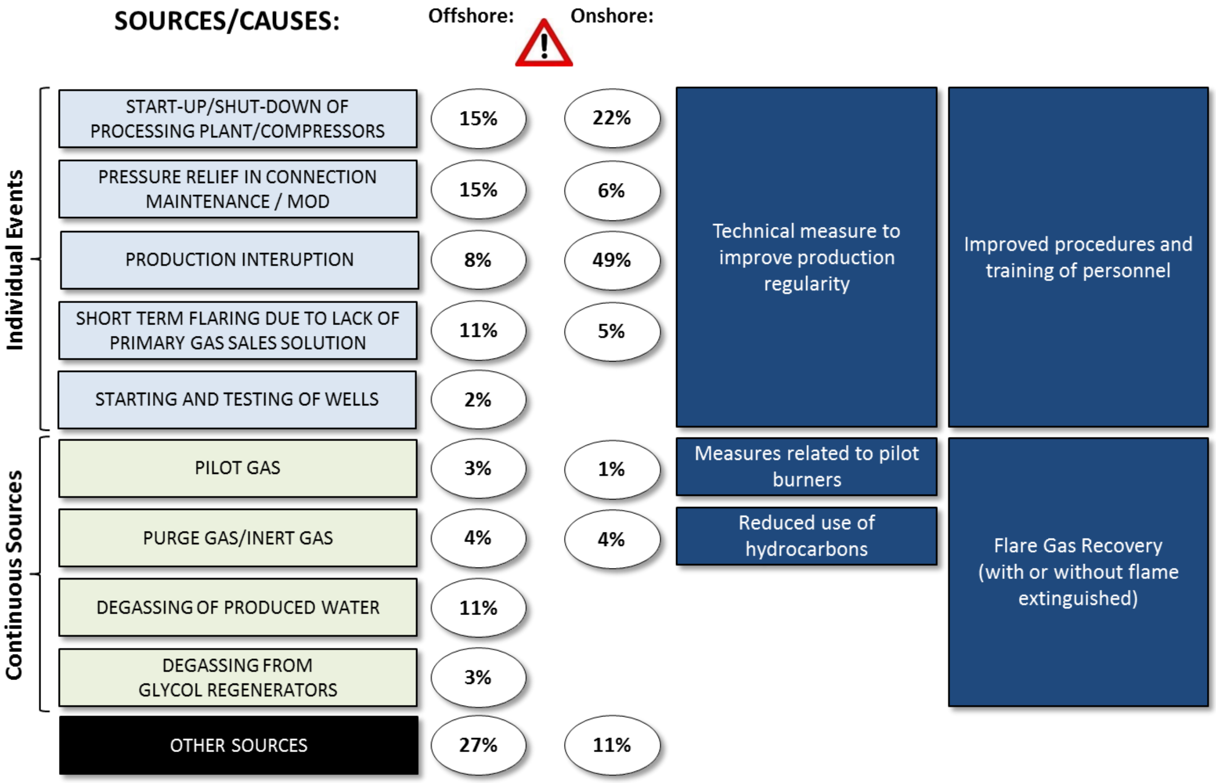
The two main categories were further divided into subcategories (see overview in Table 21).

Table 21: Categorized overview of reported potential measures

Type of measure		Subcategory	# of reported measures
i.	**Technical measures**	Technical measures to improve regularity	14
		(Increased) flare gas recovery	29
		Various measures to reduce the amount of gas sent to flare	2
	Operational measures	Improvements in procedures and flare strategies	62
		Training of personnel	1
	Modification of flare design	Measures related to the pilot burner	1
		Reduced use of hydrocarbon as purge gas	4
		Other measures related to flare design	2
ii.	**Technical measures**	Choice of flare system to optimize combustion	1
	Operational measures	Control use of assistance medium	3

Figure 16 shows a simple overview over sources/causes of flaring and potential measures in the main categories. The figure also shows the estimated distribution of the sources of flaring (see **Chapter 5.2**). The distribution of gas flaring depending on the sources contains large uncertainties and might vary from year to year.

Figure 16: Simple Overview of potential measures, sources of flaring and share of total flaring sources in 2011



For potential measures aimed at limiting non-continuous flaring, including during start up and shut down of the installation, maintenance, modifications and operational disruptions (which together accounted for 80% of flaring in 2011, primarily qualitative assessments of the reduction potential were conducted. Only a few quantitative assessments were carried out.

For potential measures directly targeting flare systems, the following approach was used in assessing the reduction potential (illustrated in **Figure 17**):

Based on information obtained from companies, an assessment was made for each source of flaring that may be affected by the measure ("Relevant portion of flaring"). This flaring volume is again divided into four subcategories (shown in **Figure 17**):

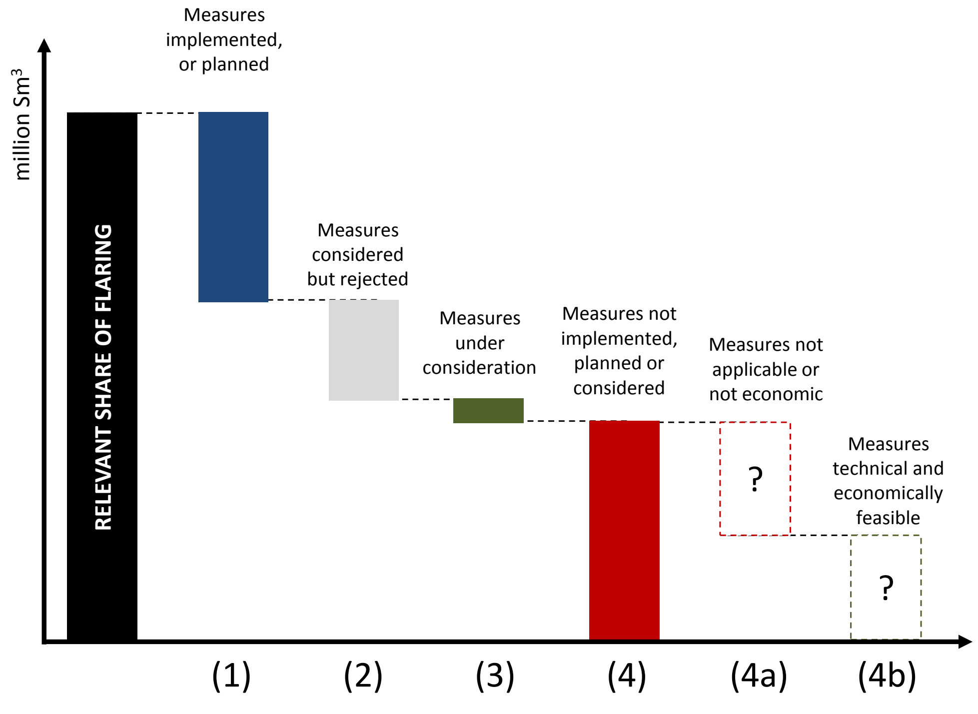
(1) Measures implemented or planned (i.e. where an investment decision is taken)
(2) Measures considered but rejected (based on information from companies)
(3) Measures under consideration (based on information from companies)

(4) Measures not implemented, planned or considered (based on the information received). In the absence of any information, measure may fall into one of two subcategories:
    (4a) Measures not applicable technically or economically
    (4b) Measures technically and economically feasible (representing a reduction potential)

The distribution of flare gas volumes are based on information obtained on causes of flaring, flare technology, the implemented and potential measures.

For the subcategories under (4) an attempt was made to highlight reduction potentials, given installation specific conditions and experiences from similarly implemented measures. Concerning subcategory (4a) some installations there were technical limitations (e.g. low pressure, small and fluctuating volumes of gas, which can make flare gas recovery technically challenging), while for others implementing the measures could affect safety (such as increased risk of flaring or reduced combustion of H_2S). Yet other installations had low profitability in implementing measures under the current framework represented determining factors. Measures that are both technically and economically feasible, i.e., with actual reduction potential, belong to (4b). There is no robust data, however, to quantify the reduction potential for potential measures in this subcategory.

Figure 17: Methodological approach for analysis of potential measures for reducing continuous flaring



In the next section, potential measures contained in

Table 21 are presented. Reviews and recommendations are also included.

8.2 Overview of measures for reducing the amount of gas flared

Given the current flaring situation, an assessment of reduction potential of measures related to reducing the amount of flare gas was made.

8.2.1 Measures for reducing non-continuous flaring

Technical measures – Improvements in regularity of production:

As described in **Chapter 5.1.1**, implementing technical measures to improve production regularity provides significant win-win opportunities, i.e., avoiding unplanned shutdowns and production. Examples of reported measures in this category are[75]:

- Upgrading of control systems
- General upgrading of equipment (to reduce unforeseen equipment failures)
- Establishment of double security of lift in the well area
- Replacement of compressors
- Installing drainage on compressor packing to reduce the number of unplanned stoppages

Table 22 contains an overview of the technical and economic aspects for this category of measures.

Table 22: Technical and economic aspects related to technical measures to improve production regularity

Effect on flare rate:	Barrier:	CAPEX:	OPEX:	Benefit:
Measure Specific (and difficult to estimate) 0.05 to 25 million Sm^3/year	Measure specific	Measure specific 2 to 200 million NOK	Measure specific 0 to 8 million NOK/year	Increased production Reduced costs related to emissions

As shown in **Table 22**, this category includes very different measures. The effect of these measures are facility specific. Quantification of mitigation potential of this category has therefore not been possible. The majority of the reported measures are planned to occur over the next three years. Given the current market situation, businesses have strong incentives to maintain regularity in production, and a continuous focus on identifying and implementing measures directly or indirectly to avoid downtime and associated flaring.

Operational measures - Improvement of procedures and flare strategy:

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[75] The companies themselves pointed out that measures to improve regularity of production have not been captured appropriately within the survey. This is because measures to increase production regularity are not primarily driven by the purpose of reducing flaring, and therefore, the surveys have not been consistent filled in (the type of measures reported have to some extent been dependent on the recipient and those involved in describing the measures are reflected survey).

Companies, through the survey, reported on 62 different measures related to this category. Examples of relevant measures are described in Chapter 5.1. As with the measures implemented over the past decade (**Chapter 5.1.1**), the effect of implementing additional measures of this type were not quantified by companies. Companies reported on challenges associated with estimating costs, since measures of this category are implemented as part of the company's continuous and broader efficiency improvement, including larger energy efficiency programs.

An overview of the technical and economic aspects related to this category of measures is described in **Table 23**.

Table 23: Technical and economic aspects related to measures to improve procedures and flare strategy

Effect on flare rate:	Barrier:	CAPEX:	OPEX:	Benefit:
Difficult to quantify 0,1 to 4,4 million Sm^3/year	Possible loss of production Complexity with operational impact on other installations	0 to 1 million NOK	0 to 1 million NOK/year	Value of gas not flared and reduced costs related to emissions

As shown in **Figure 16**, a significant proportion of flaring in 2011 related to temporary unavailability of the primary gas utilisation option. The amount of gas flared at such events is largely influenced by current procedures and strategy related to when and how production should be reduced or shut down. Several respondents to the survey pointed out that attempting to reduce this cause of flaring may not have the desired effect. Alternatively, by selecting to shut down for a limited period, the shutdown and start-up of the plant could result in a non-negligible flaring. In some cases, this will also require increased use of energy sources and lead to other types of emissions. An example is the need to use pumps/gas lift to start production again after a shutdown.

Shutdown of plants have major economic consequences associated with the loss of production. What is considered acceptable in relation to flaring by unplanned events or operating disturbances are included in the businesses' flare strategies. Installation specific conditions will also have an impact on what is an optimal strategy in such cases. There is a need for more detailed analysis to gain an understanding of whether considerations and principles for handling this type of events are reasonably consistent between different installations and companies.

The potential of improving procedures and strategies has long been considered significant. NPD noted in 2002, *"further reduction in flaring can largely be achieved by focusing on operational procedures."* In the 2005 NOROG report "Reducing Flaring on the Norwegian Shelf", the maximum theoretical reduction potential on the Norwegian continental shelf is estimated to be around 30 percent of the total flaring level for 2001-2003. The reduction potential primarily relates to operational measures and planning, and preparation of work/procedures on installations. The report KONKRAFT No. 5 (2009) (30) highlight the same conclusions.

It is the project team's impression that business has implemented a number of measures to improve procedures and strategies. Sustained focus and the large number of reported measures under consideration and implemented shows that there is still potential in terms of reducing flaring related to maintenance and modifications, start-up/shut-down of process plant and wells, and handling unplanned events/malfunctions. The information made available from the different facilities, does not provide a sufficient basis to quantify the reduction potential.

Operational measures - Training of personnel:

Only one concrete measure was reported to improve training of operating personnel. The planned measure covers training of operating personnel to provide a better understanding of production optimization. It was not been possible to quantify the reduction potential from this measure.

A significant proportion of the flaring caused by process disruptions, were considered by respondents to be due to human errors. It is, therefore, important that business have a continuous focus on good training. Examples of measures include greater use of simulator training, which makes operating personnel better able to handle normal and abnormal operating situations (e.g. unplanned shutdowns, start-up/shutdown of process plants and replacement of compressors). However, there is limited information to assess the reduction potential and cost-benefit aspects related to improved training of personnel.

8.2.2 Measures to reduce continuous flaring

Technical measure – Flare gas recovery:

This category covers two types of measures (see **Chapter 6.2** for more details):

- Installation of systems for flare gas recovery
- Installation of systems for flare gas recovery and installation of ignition system (resulting in unlit flare)

These solutions have been used in Norway since the 1990s and could in theory be used for high- and low-pressure flares, both offshore and onshore. In practice, it has proved to be technically challenging to operate systems for the recovery of small and variable amounts of gas with very low pressure.

Many older installations have implemented measures to recover flare gas, and many have chosen unlit flares. Over the last ten years, flare gas recovery and unlit flares were implemented at most new installations and this technology has been considered as BAT. Business reported 29 assessments related to this category of measures. 22 of them are not considered technically or economically feasible for various reasons. Limited profitability and minimal environmental benefits were highlighted by multiple businesses as barriers for further action on older installations. **Table 24** shows an overview of the technical and economic conditions for this category measures.

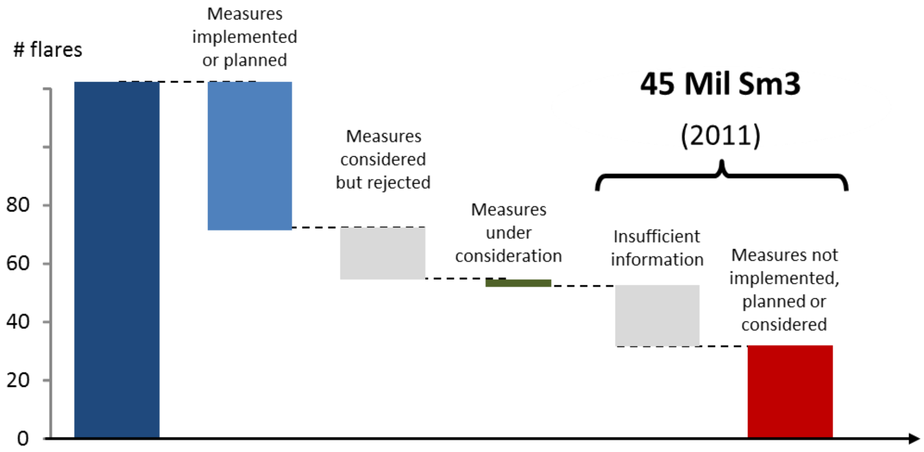
Table 24: Technical and economic aspects related to flare gas recovery and unlit flares

Effect on flare rate:	Barrier:	CAPEX:	OPEX:	Benefit:
0,1 to 6 million Sm^3/year per flare	Security Cost-benefit (lifetime) Operational challenges	20 to 300 million NOK	1 to 1,5 million NOK/year Operation of equipment (and eventual	Value of gas (which is not flared) Reduced costs of emissions

	(small and variable amounts)		consumption of pellets for ignition)	

The reduction potential (**Figure 18**) is estimated from information on flare systems and from information on implemented and potential measures. A flaring volume of approximately 45 million SM^3 in 2011 was related to installation where the project team is unaware of whether assessment of this measure had been undertaken.

Figure 18: Assessment of residual potential reduction in flaring due to increased flare gas recovery



Continuous flaring from degassing of produced water and degassing of the glycol regeneration at six installations constituted a large proportion of the estimated 45 million Sm^3. It would be useful to investigate whether updated assessments were conducted on implementing flare gas recovery at these installations.

Modifications to the flare design - Measures related to the pilot:

Pilot burner are traditionally used to ignite gas flares. Where pilot burners are used, the pilot must have sufficient size and stability to keep the flare lit, even under extreme conditions (i.e. sufficient heat dissipation to ignite the flare gas). Companies reported only one concrete measure on pilot burners, reducing the number of pilot burners operating on an onshore facility. Generally, there are three different types of measures related to pilot burners, which can provide reduced flaring and emissions:

- Replacement with new type pilot burner (s), i.e., more fuel-efficient design
- Reduced number of pilot burners in operation
- (Re)installation of pilot burner(s)

New types of pilot design make it is possible to reduce amounts of fuel necessary to sustain the flare by up to 85%[76]. The main barrier for this type of measure is reduced security and limited profitability. Replacement of pilot burners presupposes a shutdown of the plant[77]. Pilot burners typically have a lifespan of about seven years, but can be up to 30 years. Transition to more fuel efficient pilot designs, should be considered when replacing pilot burners. This type of measure is in most cases, only relevant when replacing whole flare system. Reduction potentials associated with this type of measure is limited compared with other types of measures.

A third type of measure is (re)installing pilot burner(s). As described in **Chapter 5.1.2**, pilot burners were installed at three offshore installations in the last few years. The measure was implemented to ensure a steadier flare flame thereby reducing the amount of gas used to keep the flare lit especially in bad weather. With use of a pilot burner, the amount of purge gas (natural gas) necessary to sustain the flare reduces significantly. The effect of installing a pilot burner is reported at over 2 million SM^3/year per flare. The reduction potential for this kind of measure is considered limited.

Modifications of the flare design - Reduced use of natural gas as purge gas:

For most new installations and onshore facilities, nitrogen (N_2) is used as purge gas. Several older operating plants without systems for flare gas recovery and unlit flares use hydrocarbon gas (HC gas) as purge gas. HC gas is also used as shielding gas in tanks, but this is less relevant for flaring. For installations using HC gas as purge gas, two measures can lead to a reduction of the volume of gas flared:

- Installation of equipment for reduced use of purge gas (see **Chapter 6.2** for details)
- Transition to use of nitrogen (N_2) as the purge gas

Table 25 and **Table 26** provides an overview of technical and economic aspects related to these measures.

Table 25: Technical and economic aspects related to installation of equipment for reduced use of purge gas

Effect on flare rate:	Barrier:	CAPEX:	OPEX:	Benefit:
Reduction of 50 to 90% of the purge gas volume	Security (danger to extinguish the torch) Low profitability	Measure specific (unknown)	Measure specific (unknown)	Value of gas (not flared) and reduction of emissions

Table 26: Technical and economic aspects related to transition to use of N_2 as purge gas

Effect on flare rate:	Barrier:	CAPEX:	OPEX:	Benefit:
Reduction corresponding to	Security (danger to unlit flares)	Equipment for the production of N_2 (+	Costs related to production of N_2	Value of gas (not flared) and

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[76] There is a continuous development in the pilot design, based primarily on a desire of extended lifetime and improved stability under difficult weather conditions. Pilot burners from the mid-80s were designed to burn about 10 Sm^3/hour, while new pilot burners fuel consumption is down to 1.4 Sm^3/hour, according to supplier John Zink.

[77] Business highlighted that there are unquantifiable costs associated with re-prioritizing work within a short shutdown period.

100% of the purge gas volume	N_2 can reduce combustion efficiency Low profitability	back-up) 20 to 50 million NOK		reduction of emissions Reduced maintenance of flare tip

As for other types of measures entailing changes to the flare system, these measures require that the facility is shut down. Despite a significant number of installations offshore and the majority of onshore facilities using hydrocarbon gas as purge gas, the reduction potential for this category is considered limited. The reduction potential (approximately 95 percent) is linked to a limited number of installations. Based on experience, transition to N_2 as the purge gas, is often considered as a reasonable measure with major modifications and implementation of flare gas recovery with unlit flares.

8.3 Overview of measures to change combustion conditions in the flare

This project focused on increasing knowledge on emissions of NO_x, CO, SO_2, VOC (methane and nmVOC) and particulates from flaring. Measures that contribute to reducing the amount of flared gas are generally expected to contribute to reductions in emissions of the above components. In some cases, emissions of individual components increase due to changing combustion conditions, as described in **Chapter 3.3**. There are also specific potential measures related to the flare system, which in theory have a positive impact on emissions of individual components. These are briefly presented below.

8.3.1.1.1 Technical measures – Choice of flare system for optimizing combustion conditions:

As described in **Chapter 6.1**, many factors determine the optimal design of the flare system of a given installation. Efficient combustion and smoke free operations are achievable if the flare system is installed, maintained and used according to design specifications.

It is possible to affect emissions from flaring by utilizing alternative flare designs, when developing new installations or replacing flare systems on older facilities (see **Chapter 3.3)**. However, limited quantitative information is available on emissions effects of such measures.

Flare technologies described in **Chapter 6.2** are mature and have, in many cases, broad application. It has not been customary to include and emphasize quantitative assessments of emissions of various components associated with a specific flare technology. Suppliers do not seem, at present, to have sufficient documentation/knowledge related to emissions of NO_x, CO, VOC (methane and nmVOC) and particulates under varying operating conditions. This makes it difficult to carry out a comparison of different technologies in the selection of flare design. Therefore it has not been possible to quantify the emission reduction of selecting flare designs with more attractive features.

The project team (Combustion Resources) undertook a very detailed expert assessment of current combustion conditions of flare in operation in Norway. The assessment was carried out for each flare based on information on type of flare tip, flare tip diameter, characteristics of the gas flared and the type of purge gas used. The experts' assessment is that most flares have limited risk of poor combustion efficiency. However, individual flares were considered to be at risk of poor combustion conditions, which can cause major emissions, including, particulates, methane, nmVOC and CO. This applies to flares with large flare tip diameter, low flaring rates and high liquid level in the flare gas.

Operational measures - Control use of assistance medium:

As described in **Chapter 7.3.2,** heavy use of assistance medium in assisted flares may reduce combustion efficiency, thereby increasing CH_4 emissions. Two types of measures can reduce this risk (47):

i. Training of operational personnel and knowledge sharing
ii. Monitoring and automatic control of assistance medium

Improved training of operating personnel leads to increased attentiveness to controlling combustion conditions in the flare, especially to avoid low combustion efficiency. Knowledge in this area has increased in recent years and new techniques recently adopted. These include techniques that control the use of assistance based on medium heat value in the combustion zone.

However, there is still debate among researchers with regard to detailed understanding of the parameters that govern emissions formation. Companies with assisted flares should therefore pay attention to new findings in this area and ensure operational personnel adopt latest findings.

When using assistance medium, there are trade-offs between, light, noise and emissions. These trade-offs, when control systems are fully/partially manual, are made by operational personnel. The alternative to manual systems are automatic control systems, where operating parameters are controlled automatically and performance (combustion efficiency) is optimized based on available measurement data (including, but not limited to, flare gas rate, pressure, temperature, the pilot, and fuel consumption).

There is very limited access to cost figures for automatic control systems. Automatic monitoring of the flare and control of assistance medium has an estimated cost of approximately 2 million USD per flare in the USA, based on conversations with experts there. This cost estimate includes measurement systems that in many cases might already be installed on existing Norwegian installation (e.g. accurate gas flow measurements and on-line GCs).

There are only eight flares in Norway using air or steam assistance medium (one offshore and seven onshore). Many of these installations specified that some form of optimization of the injection rate of steam or air were available[78], or that there are more blowers where some start as needed (for air-assisted flares). It is unclear whether these optimizations are manual or fully/partially automatic, and details related to the designs of these control systems are not known. At one of the onshore facilities, with three flares, they are evaluating implementation of the "Management Process Control" on their steam system.

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[78] Including that the amount of air or steam injected was dependent on the gas flaring amount (in some cases also the temperature)

Based on available data, the potential for improving combustion conditions in assisted flares in Norway is considered limited.

8.4 Recommendations

It has not been possible to develop a prioritized list of concrete potential measures within the framework of this project. This is due to the limited availability of information on barriers, investment costs, operational costs and impact on emissions. Without this information, it is difficult to carry out a cost-benefit analysis and assessment of technical feasibility of specific measures. An important result of the project, however, is that the knowledge base for the emissions of particulate matter (particularly BC), CH_4, nmVOC, CO and NO_x from flaring is inadequate, hence making it impossible to undertake an analysis of measures.

The project team therefore recommends closing this knowledge gap. Measuring campaigns or measurements in large-scale testing facilities, as described in **Chapter 7.3.4**, should be organized such that they simultaneously include several pollutants associated with flaring.

A large share of flaring in Norway is due to individual events (start-up and shutdown of installations, maintenance and modifications) and operational disruptions. The greatest potential for reducing flaring and associated emissions relate to measures that:

- Improve production regularity,
- Improve operational and maintenance procedures,
- Improve strategies for handling unplanned events, and
- Training operational personnel.

Measures to improve production regularity:

With strong economic incentives related to maximizing oil and gas production, there is reason to believe that there is a keen awareness on this cause of flaring.

Operating and maintenance procedures and strategies for dealing with unplanned events:

It is the project team’s assessment that there are reduction potentials related to improved procedures and strategies and how they are implemented. Quantification of this potential is not possible, nor reasonable assessments of costs of measures based on available data. To clarify the size of potential reductions, the project team recommends conducting a more detailed review of current procedures and strategies for individual installations than has been possible within the framework of this project. The Norwegian Environment Agency, as an integral part the follow-up of a company’s plans for Energy Management and implementation of strategies related to flaring, could implement this. A more thorough follow-up will clarify where opportunities exist to implement improvements and help identify best practices under various operating conditions.

Measures to reduce continuous flaring:

Continuous flaring comprises a relatively limited share of total flaring. The bulk of continuous flaring is associated with a few installations and sources. The project team recommends investigating whether recent assessments of measures for recovery of flare gas have been undertaken at these facilities. This applies particularly to installations where degassing of produced water and degassing of glycol regeneration constitutes a substantial portion of continuous flaring. The same recommendation applies for those installations where the use of hydrocarbon gas as a purging gas constitutes a large share of the total amount flared. Measures relating to use of equipment for reduced use of purge gas and possible (re)installation of pilot burners (where this is not used) would be relevant to further consider for these installations.

It is the project team's assessment that some measures, in many instances, are not viable for older installations due to technical limitations or low profitability. Major changes on key assumptions (for example extended field life) affect decisions related to potential measures. A reassessment of potential measures related to the design of flare systems should occur when planning major modifications, based on BAT requirements.

Systematic identification, analysis and prioritization of potential measures related to flaring:

Companies, both onshore facilitates and offshore installations, rarely systematize and categorize data on flaring events. This poses, as previously mentioned, a potential barrier to effectively identify, analyze and prioritize potential measure related to flare reduction. The project team recommends that installations and facilities map out the pressure relief system and possible sources of flaring. The information should then be used to identify detailed reasons for each flaring event. Preparation of a systematic overview over time, over the causes of flaring, will contribute to increased knowledge and awareness for personnel responsible for preparation of energy management plans. This may facilitate efforts to quantify reduction potentials. When reduction potential is quantified, it becomes possible to prioritize flaring measures in relation other types of measures.

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