CARBON LIMITS

Abatement potential and costs for oil and gas sector methane emissions in the Arctic countries

Final Report



This report was prepared by Carbon Limits AS.

Project title:

Abatement potential and costs for oil and gas sector methane emissions in the Arctic countries

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The purpose of the project is to improve the knowledge of the oil and gas sector methane abatement potentials and costs in Arctic countries. Arctic countries represent about 40% of the global oil and gas production and account for a large part of global methane emission from the sector.

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Carbon Limits is a consulting company with long standing experience in supporting energy efficiency measures in the petroleum industry. Our team works in close collaboration with industries, government, and public bodies to identify and address inefficiencies in the use of natural gas and through this achieve reductions in greenhouse gas emissions and other air pollutants.

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Acronyms and abbreviations

AD	Activity Data
bbl	Barrel
CAPEX	Capital Expenditure
CH_4	Methane
CO_2	Carbon Dioxide
$CO_{2,e}$	Carbon Dioxide Equivalent
EF	Emission Factor
EGBCM	Expert Group on Black Carbon and Methane
GHG	Greenhouse Gas
Gt	Gigaton = 10^9 ton
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LDAR	Leak Detection and Repair
MAC	Marginal Abatement Cost
NPV	Net Present Value
OPEX	Operating Expenditures
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollars
US EPA	US Environmental Protection Agency
VRU	Vapor Recovery Unit

1. Background to the study

Methane is considered a short-lived climate pollutant with an atmospheric lifetime of about 12 years. Its global warming potential, which expresses its ability to trap heat in the atmosphere, is 84 over a 20- year time horizon[1]. Methane emissions have contributed about 1/4 of manmade global warming[2] and are therefore particularly important as near term measures to curb climate change.

According to the IEA, the oil and gas sector operations represent ¼ of global anthropogenic methane emissions[3], and there are several projections indicating that emissions could increase significantly[4]. The IEA also predicts oil and gas methane emissions to increase some 40% by 2040 in the reference scenario.[5] However, the sustainability of oil and gas supplies can be considerably improved through targeted and cost-efficient measures to reduce these methane emissions. For example, the IEA has estimated that 75% of global oil and gas methane emissions are technically feasible to eliminate (at currently expected oil and gas supply levels).[6] Although the awareness and recognition of the problem has improved, major knowledge gaps remain, hindering development and implementation of cost-efficient actions to reduce emissions.

The purpose of the project is to improve the knowledge of the oil and gas sector methane abatement potentials and costs in Arctic countries. Arctic countries represent about 40% of the global oil and gas production[7] and account for a large part of global methane emission from the sector.

The project is linked to the Arctic Council Framework of Action on Enhanced Black Carbon and Methane Emissions Reductions ("Framework"), and the work of the Expert Group on Black Carbon and Methane ("EGBCM") under the Framework. The Framework states that Arctic countries commit to take leadership by "further reducing black carbon and methane emissions from [their] countries". Some 60% of methane emissions of Arctic countries are from the oil and gas sector and therefore central to the aspirations of the Framework and tasks for EGBCM.

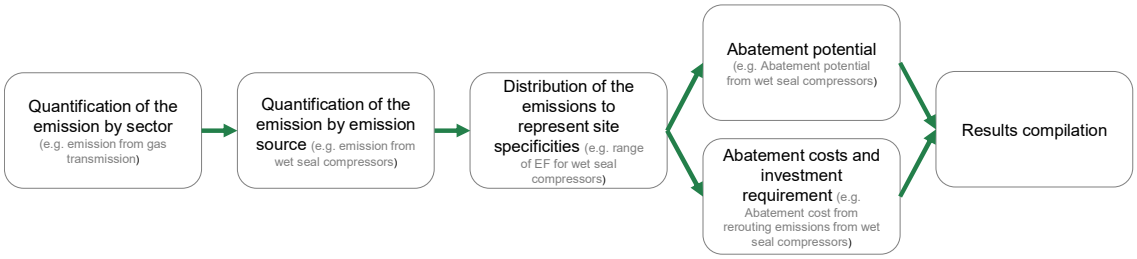
Together with this report, Carbon Limits delivered tableau® dashboards available at the following address: https://public.tableau.com/views/MACC-MethaneintheOilandGasSector-Arctic_ready/Emissions?:embed=y&:display_count=yes&publish=yes

2. Approach and methodology

This study focused on the main oil and gas producing countries in the Arctic: Russia, USA, Canada and Norway. The figure below provides an overview of the methodology applied for this study.

[1] Applying a time horizon of 100 years, which is used in greenhouse as inventories, methane is estimated at a global warming potential 28 times higher than CO_2.
[2] IPCC fifth assessment reports Chapter 8. https://www.ipcc.ch/report/ar5/wg1/mindex.shtml
[3] https://www.earth-syst-sci-data.net/8/697/2016/essd-8-697-2016.pdf, and IEA World Energy Outlook 2017.
[4] https://www.globalmethane.org/documents/gmi-mitigation-factsheet.pdf
[5] See Chapter 10 Figure 10.13 in the IEA World Energy Outlook 2017
[6] See Section 10.4 of the IEA World Energy Outlook 2017
[7] BP statistical review

Figure 1: Overview of the methodology applied



Emissions per sector from UNFCCC reports were used as a starting point for the analysis. Emission were then estimated for each emission source. When relevant an abatement option was defined, and the abatement potential, abatement cost and investment requirement were estimated.

Emission factors and CAPEX distributions are used to reflect the variability of the emissions per site. This approach is different than other abatement cost studies published and aims at reflecting more closely the variable attractiveness of the abatement projects as experienced in the field.

The following paragraphs describes the approach in further details.

2.1 Quantification of the emissions by sector

As per IPCC guidance, magnitude of emissions can be estimated as follows:

$$Emission_i = Activity\ Data_i * Emission\ Factor_i$$

- Activity data (AD) refers to the economic and social activity (e.g. volume of production, number of crude storage tanks or gas volume burned in gas engines)
- Emission factor (EF) refers to coefficients for emissions or removals per unit of activity (e.g.kgCH_4/crude storage tank)

Three Tier approaches can be applied to estimate emissions depending on the amount/quality of data available:

- Tier 1 is a top down approach based on applying default emission factors to very general activity data categories
- Tier 2 is an approach that either requires country specific EFs or relies on a mass balance approach
- Tier 3 is a rigorous bottom up approach, involving identification of involving identification of equipment-specific emission sources, technology-specific emission factors, collection of amounts and types of fuel burnt per type of technology, count of equipment units, measurement of emission at plant level, measurement of emission rates per equipment type, etc.

Norway, Canada and USA report under UNFCCC methane emissions using a Tier 3 approach whereas Russia uses a Tier 1 methodology except for gas transportation (Tier 2 – country specific emission factor).

The methane emissions estimates reported to UNFCCC have been used as a basis for the analysis[8]. Emission estimates for 2016 are available for all the Arctic states (as Annex-I countries). Similarly, the

[8] Since 2015 and as of March 2019, there has not been any new updated national reports on methane emissions published on the website of the Expert Group on Black Carbon and Methane under the Arctic Council (https://oaarchive.arctic-

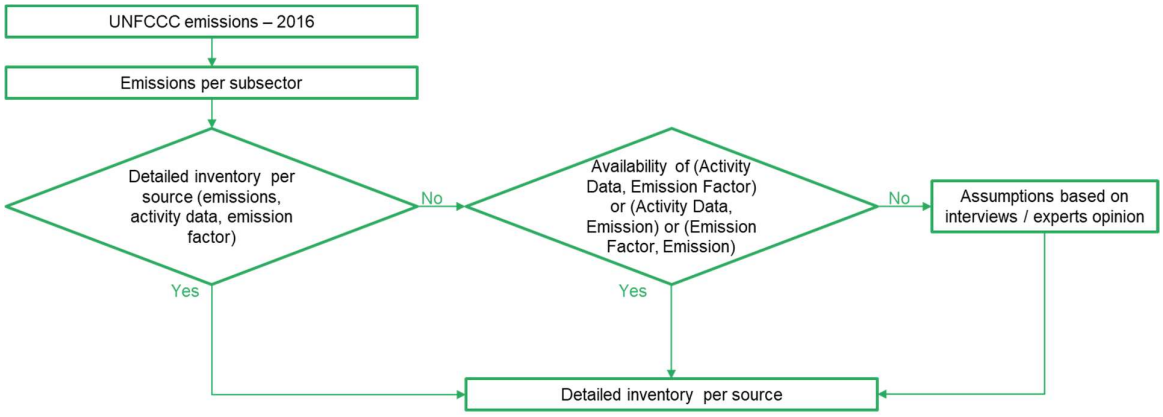
split of emission by sub-sector is derived from the emissions reported to UNFCCC. It should be noted that methane emissions from oil and gas activities are reported under different emission categories (see Appendix 1). Experts currently consider that these estimates are uncertain even when estimated with a Tier 3 methodology.

2.2 Quantification of the emissions by emission sources

In order to identify proper mitigation options, emissions have to be further broken down by emission source. The approach for this step has been significantly different depending on the country. In USA and Norway, estimates by emission source were directly available. However, even though Canada reports its emissions using a Tier 3 methodology, the detailed inventory is not available to the public at a level of details that allows the division of emissions by categories to be deduced. The same goes for Russia as, as mentioned above, the country is using a Tier 1 / Tier 2 methodology for reporting under UNFCCC.

Therefore, for both countries, public/case analyses were used and interviews with operators and technology providers were carried out to estimate the emission by emission source, the activity data and the average emission factor. The interviews made it possible to adapt existing data and verify key assumptions regarding local practices and equipment used.

Figure 2: Workflow for defining the detailed inventory per source per country



The following table provides more detail on the specific approach for each country to construct the emissions by emission source category.

Table 1 - Sources of information for detailed methane emission inventory from the oil and gas sector

	Illustrative example	**USA**	**Russia**	**Norway**	**Canada**
Aggregate emission data	Total methane emissions from the oil and gas value chain	UNFCCC report for 2016 published in 2018			
Emission data per sub sector	Methane emissions from oil production (upstream)	UNFCCC report for 2016 published in 2018			
Relevant emission sources		US EPA Inventory of Greenhouse Gas	International emissions sources list have been modified to reflect current practice in Russia.	Cold venting and fugitive emissions from Norwegian	The same emission sources as the ones displayed in US EPA Inventory were used

council.org/handle/11374/1168). The analysis focuses on the emissions as of 2016 and does not perform any projection in the future (Given the current uncertainty regarding future oil and gas markets, emission levels in the future were not projected.)

	Illustrative example	USA	Russia	Norway	Canada
		Emissions and Sinks[9]		offshore oil and gas activities – 2016[10]	tuned to Canadian practices.
Current practice	Share of tanks with a VRU		Based on literature review and interviews with local experts. Distribution of activity data between different practices has been tuned for Russian specific conditions for all the major sources of emissions		Based on literature review and interviews with local experts
Split of emission by emission source within a subsector	Emissions from storage tanks without a VRU in the oil production subsector		Deducted from the Emission factors and activity Data (see below)		Derived from the UNFCCC reporting including Canadian specific activity data and emission factors.
Emission factor by emission source within a subsector	EFs of storage tanks without VRU in the oil production subsector		Emission factors from measurements in the region has been used when possible. International emission factors have been used for the remaining categories	Field specific annual report – Cold venting and fugitive emissions from Norwegian offshore oil and gas activities – 2016	Clearstone / Carleton University, 2018. Update of Equipment, Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas.[11] EFs from US inventory Statistical Analysis of leak detection and repair in Canada[12]
Activity Data by emission source within a subsector	Number of storage tanks without VRU in the oil production subsector		Many activity data were based on Russian specific information (for example the number of distribution meter, the length of distribution pipeline, …). However in some cases it has been necessary to reconciliate the emissions calculated with the emissions reported. In those cases, the activity data were modified	Cold venting and fugitive emissions from Norwegian offshore oil and gas activities – 2016	CAPP[13], Natural Resources Canada[14], Government of Canada[15] statistics and open data Interview – field experts Deduced from US data

2.3 Distribution of the emissions to represent site specificities

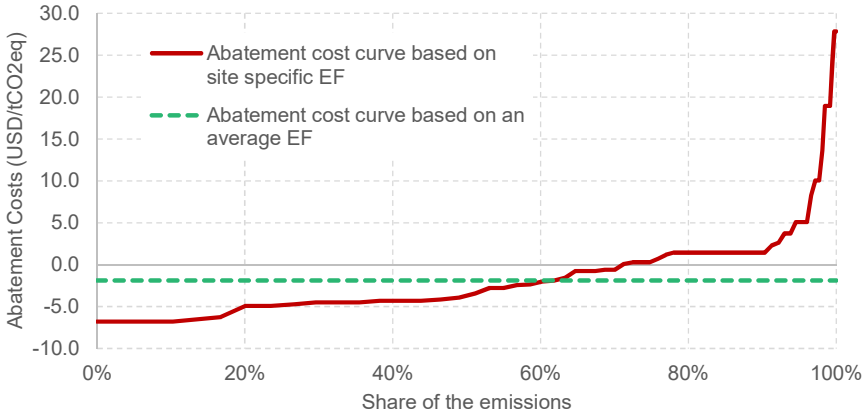
Field data shows that emission rates from similar equipment are highly variable and can vary by a factor of 1000[16]. Emission factors depend on many factors including the type and the age of the equipment, the season, maintenance practice and the operating conditions[17]. This variability impacts heavily the abatement costs experienced by operator.

The following figure[18] illustrates the variability of the abatement costs for 62 pumps in US and Canada. The abatement cost estimated based on the average EF misrepresents the site-specific

[9] https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2016-ghg
[10] http://www.miljodirektoratet.no/no/Publikasjoner/2016/Juni-2016/Cold-venting-and-fugitive-emissions-from-Norwegian-offshore-oil-and-gas-activities--summary-report/
[11] https://www.aer.ca/documents/UpdateofEquipmentComponentandFugitiveEmissionFactorsforAlber-1.pdf
[12] https://www.carbonlimits.no/project/statistical-analysis-leak-detection-and-repair-canada/
[13] https://www.capp.ca/publications-and-statistics/statistics/statistical-handbook
[14] https://www.nrcan.gc.ca/energy/infrastructure/18856
[15] https://open.canada.ca/en
[16] «Quantifying cost effectiveness of systematic Leak Detection and Repair Programs using Infrared cameras", Carbon Limits report CL-13-27 (2014).
[17] «Quantifying cost effectiveness of systematic Leak Detection and Repair Programs using Infrared cameras", Carbon Limits report CL-13-27 (2014).
[18] Analysis extracted from : https://www.carbonlimits.no/project/methane-abatement-potential-from-oil-and-gas-systems-in-kazakhstan/

abatement costs for a large share of the facilities. In this example, the abatement costs is positive for almost 60% of the pumps evaluated, while the abatement costs based on the average EF is negative.

Figure 3: Abatement costs for a sample of injection pumps- North America – Illustrative



To reflect this site specific variability, three different emissions factors have been used for the analysis for each emission source. The weight of the three different EFs (i.e. the share of activity data associated to the EF) has been estimated based on typical EF distribution.

Over the past few years, Carbon Limits has performed statistical analysis of emission rates of various types of equipment and equipment components based on the data from North America and Europe. In addition, the company has performed a number of measurement campaigns in Kazakhstan, Ukraine and Azerbaijan. This knowledge, in addition to country and equipment specific studies, was used to define a distribution of emission factors, as opposed to an average emission factor per emission source.

2.4 Quantification of the abatement potential

For each emission source *i*, the abatement was estimated based on the following equation:

$$Abatement\ Potential_i = Emission_i * Applicability\ of\ the\ technology_i * Reduction\ efficiency\ _i,$$

where

The applicability of the technology (in %) represents the share of the total emissions from a particular emissions emission source to which the abatement technology can be applied.

Reduction efficiency (in %) represents the percentage of technically achievable emissions reduction for an abatement technology, after it has been implemented.

The following table presents the data source for each of these assumptions.

Table 2 - Sources of information for applicability and efficiency of mitigation technologies

Parameter	Illustrative example	
Applicability of the mitigation technology per emission source within a subsector	Share of the storage tanks that can be	Expert's opinion based on interviews / field trips - case analyses

Parameter	Illustrative example	
	fitted with a VRU	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.[19] Carbon Limits, 2016. Zero emission technologies for pneumatic controllers in the USA - Applicability and cost effectiveness.[20]
Emission reduction of the mitigation technology per emission source within a subsector	Emission reduction achieved with a VRU	EDF/ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.[21] ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results.[22] EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. EDF/Pembina/ICF, 2015. Economic Analysis of Methane Emission Reduction opportunities in the Canadian Oil and Natural Gas Industries [23] Expert's opinion based on interviews / field trips - case analyses

Appendix 2 summarizes the mitigation options considered in the analysis, along with the applicability, efficiency, lifetime and costs assumed.

2.5 Quantification of the abatement costs and investment requirement

The abatement cost measures the cost of reducing one ton of CO_2 equivalent. Abatement costs were calculated as follows:

$$Abatement\ cost = \frac{-\ NPV\ of\ the\ cashflow\ over\ the\ lifetime\ of\ the\ project}{Sum\ of\ the\ discounted\ emission\ reduction\ over\ the\ lifetime\ of\ the\ project}$$

Where the cash flow includes

- the upfront investment to install the new technology
- the change in OPEX (compared to the reference technology – in our study the baseline is continue to emit and not implement any abatement measure) and
- the value of the gas saved through the project, when relevant.

An interest rate of 10% was used.

It is important to highlight that the abatement costs are sensitive to gas price depending on the location of the emissions along the value chain, sol local information were collected for the Arctic states. Gas price assumption varies between 0.5 and 6 USD/MMBtu (or 18 to 200 USD/ thousand cubic meter) depending on the country and the part of the chain (see Appendix 2).

CAPEX/OPEX, labour costs and equipment lifetime were taken from existing North American literature when relevant[24]. To reflect site specific circumstances, the variability of the CAPEX has also been modelled, with two levels of CAPEX (low and high), which are assumed to be equally probable.

[19] https://www.epa.gov/sites/production/files/2016-06/documents/mac_report_2013.pdf
[20] https://www.carbonlimits.no/wp-content/uploads/2017/01/Report_FINAL.pdf
[21] https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf
[22] http://onefuture.us/wp-content/uploads/2018/05/ONE-Future-MAC-Final-6-1.pdf
[23] https://www.edf.org/sites/default/files/content/canada_methane_cost_curve_report.pdf
[24] A few techno-economic analyses of projects carried out by Carbon Limits earlier suggest that the site to site variability was quite high, and likely higher than the country-to-country variability.

Table 3: Sources of information for costs of mitigation technologies

	Illustrative example	
Costs of the mitigation technology per emission source within a subsector	CAPEX and OPEX of a VRU	International markets – labor costs adapted to the country based on data from www.averagesalarysurvey.com In 2016 USD Natural gas STAR Program, Recommended Technologies to reduce methane emissions[25] EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results. Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator[26] Carbon Limits, 2016. Zero emission technologies for pneumatic controllers in the USA - Applicability and cost effectiveness. EDF/ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries. EDF/Pembina/ICF, 2015. Economic Analysis of Methane Emission Reduction opportunities in the Canadian Oil and Natural Gas Industries MJB&A, 2016. Pipeline Blowdown Emissions and Mitigation Options.[27] Expert's opinion based on interviews / field trips - case analyses

2.6 Result compilation

The abatement potential and costs were then calculated for all the emission sources and for each country (in total 1100 abatement potential and costs were estimated). The abatement options are then ranked by abatement costs (the first being the one with the lowest cost). The cumulative abatement potential possible at lowest cost compared to today's emissions is calculated. The cumulative investment required to reach this level of abatement is also available.

All the results are presented in tableau® dashboards publicly available. The results are presented per categories, countries and part of the oil and gas value chain.

Presentations of the results – emission categories and definition of sector along the oil and gas value chain.

Methane emissions sources are defined very differently in the different Arctic Nations. For example, there are as many as 210 emission source in the US oil and gas methane emission inventory while Norway has 35[28] categories reflecting the specific (offshore) emissions sources. To simplify the presentation of results, the team defined 9 emission categories:

1. Hydraulic fracturing & well completion, exploration and drilling
2. Natural gas driven pneumatic controllers and pumps
3. Compressors
4. Venting of associated gas at upstream oil production facilities (which includes the emissions reported under 1.B.2.c.1.i in UNFCCC if relevant)
5. Hydrocarbon liquid storage tank. Hydrocarbon loading and transportation
6. Equipment depressurization and blowdowns from pipelines and facilities
7. Component and equipment leaks
8. Incomplete combustion (including associated petroleum gas (APG), engines, turbines, fired heaters) (which includes the emissions reported under 1.B.2.c.2 and 1.A.1.c.ii in UNFCCC if relevant)

[25] https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions
[26] https://www.aer.ca/documents/DelphiAlbertaMethaneAbatementCostStudy.pdf
[27] http://blogs.edf.org/energyexchange/files/2016/07/PHMSA-Blowdown-Analysis-FINAL.pdf
[28] Add Novatech AS - M-511 -Delrapport 2 - Utslippsmengder og kvantifiseringsmetodikk Utarbeidet for Miljødirektoratet

9. Other sources (including casinghead venting from oil wells, liquids unloading from gas wells, glycol dehydrators and others)

These emissions can happen at one or different level(s) of the oil and gas value chain. The value chain was divided in 5 parts:

1. Exploration and production
2. Natural gas processing
3. Oil refining
4. Natural gas transmission and storage
5. Natural gas distribution

The table presented in the Annex 1 illustrates how the sectors presented in this report relates to the UNFCCC emission categories.

2.7 Limitations and uncertainties

It is important to highlight the important uncertainties associated with the inputs which impact the uncertainty of the outputs of the calculations. In the following paragraph, the main uncertainties and limitations of the analysis are pointed out.

Total emission levels: the emissions considered in this analysis are based on UNFCCC reporting. Russia is reporting its methane emissions using a Tier 1 approach (except for natural gas transportation where Russia uses a Tier 2 approach). These emissions are highly uncertain. Even for tier 3 estimates, experts are currently highlighting the remaining uncertainties associated with existing estimates.

Excluded emission sources: for each country, already mitigated emission sources and the ones with really low emission levels were not considered in the analysis. In addition, in the USA, only onshore emissions were taken into account in the analysis whereas in Norway, the analysis focused only on offshore emissions. All in all, more than 90% of the methane emissions are included in the analysis.

Split in by emission sources: the split in emission sources for Russia and Canada were performed through targeted interviews and through public data collection. For some of the emission sources, the values obtained are highly uncertain due to data gaps.

Distribution of emission factors: These distributions are based on measurement campaigns and statistical analyses performed by Carbon Limits, in addition to a literature review performed as of 2018/2019. These are to Carbon Limits knowledge the most reliable values available as of today. These distributions should be reviewed when more data become available.

Cost uncertainties: the costs are taken from the literature and are generic costs. Even though Carbon Limits took a range of costs to represent the site specificities. These costs are highly uncertain but are linked to the level at which the study is performed. The uncertainties around the costs are -50%/+100% as can be expected for this type of studies.

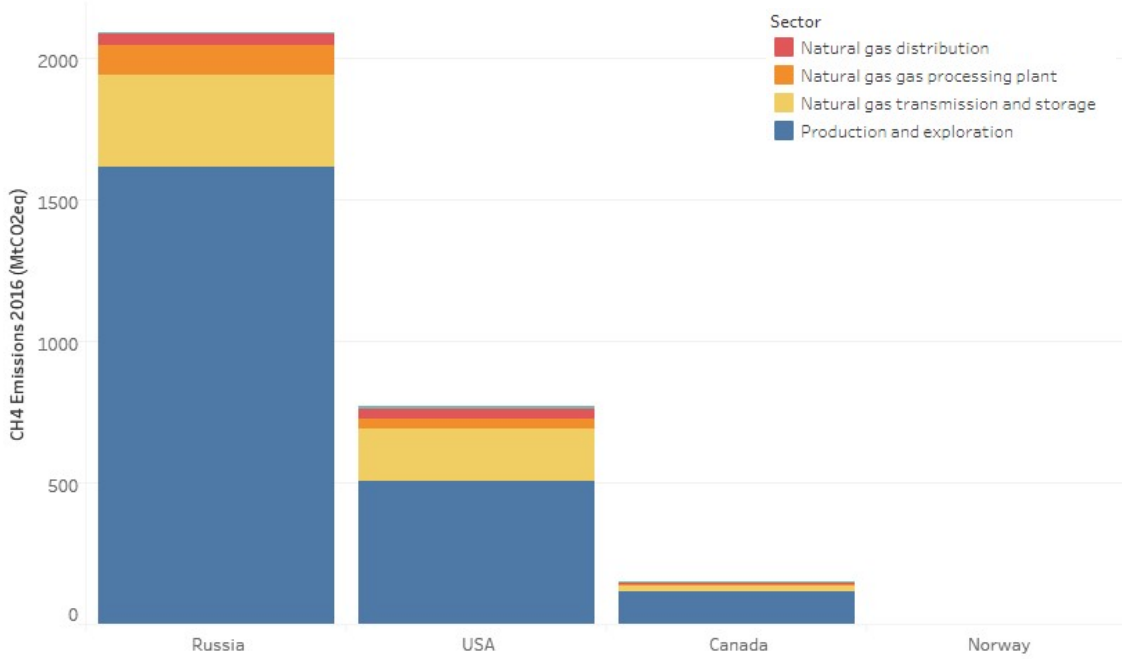
3. Results

This paragraph focuses on the main results obtained in this analysis. Further analysis of the results is possible using the compiled dashboards on tableau® available at the following address: https://public.tableau.com/views/MACC-MethaneintheOilandGasSector-Arctic_ready/Emissions?:embed=y&:display_count=yes&publish=yes .

3.1 Emissions

Russia, the USA, Canada and Norway have been reporting methane emissions from the oil and gas sector of around 3 $GtCO_{2,e}$[29] (36 $MtCH_4$ - $GWP(CH_4,20years)=84\ tCO_{2,e}/tCH_4$), Russia reporting 69% of the total and USA 25%. Figure 4 shows the methane emissions per emission sectors and per countries.

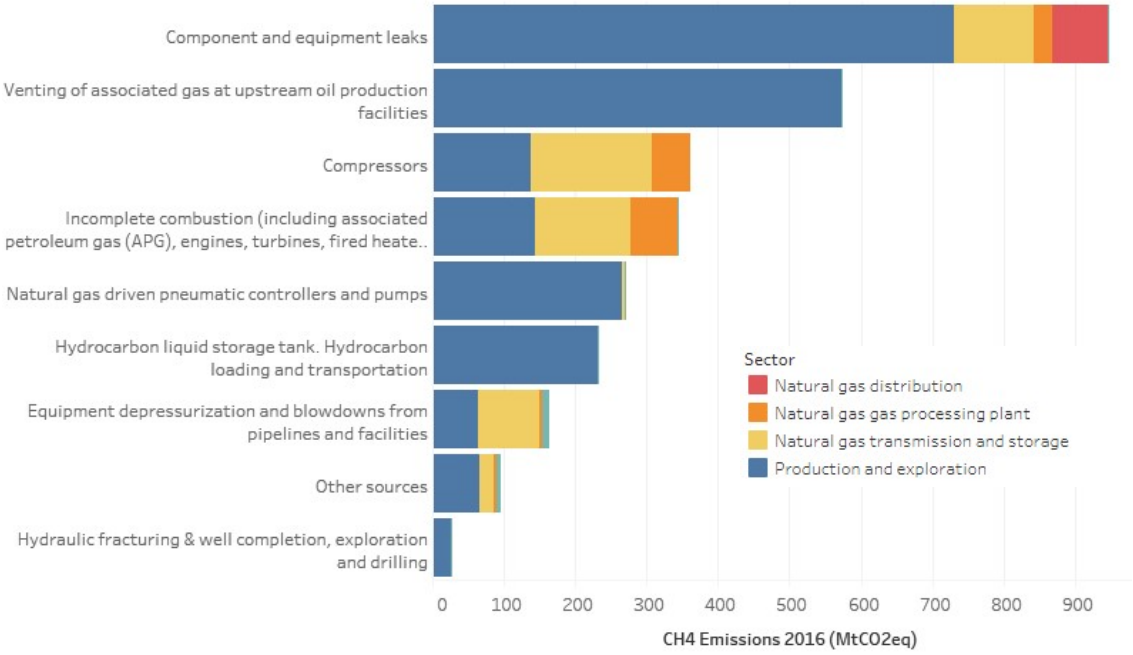
Figure 4: CH_4 emissions in the main oil and gas producing Arctic countries per sector



The oil and gas exploration and production sector represents the vast majority of the emissions (more than 75%). Components and equipment leaks, venting of associated gas at upstream oil production facilities, incomplete combustion and compressors are the main emission categories when considering the methane emissions for the Arctic countries in total.

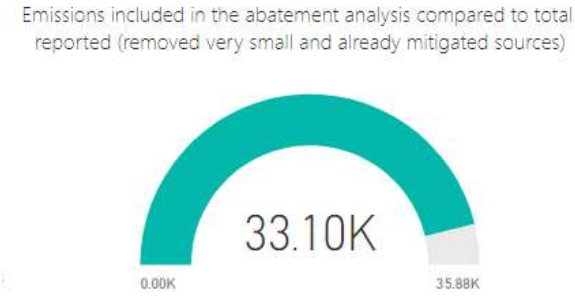
[29] This is equivalent to the CO_2 emissions from the iron and steel sector worldwide.

Figure 5: Share of the CH_4 emissions per oil and gas per emission category



As mentioned in the limitations chapter (2.7), the project team did not evaluate the abatement option for some minor sources of emissions. The abatement analysis still covered more than 90% of the emissions as depicted on the figure below.

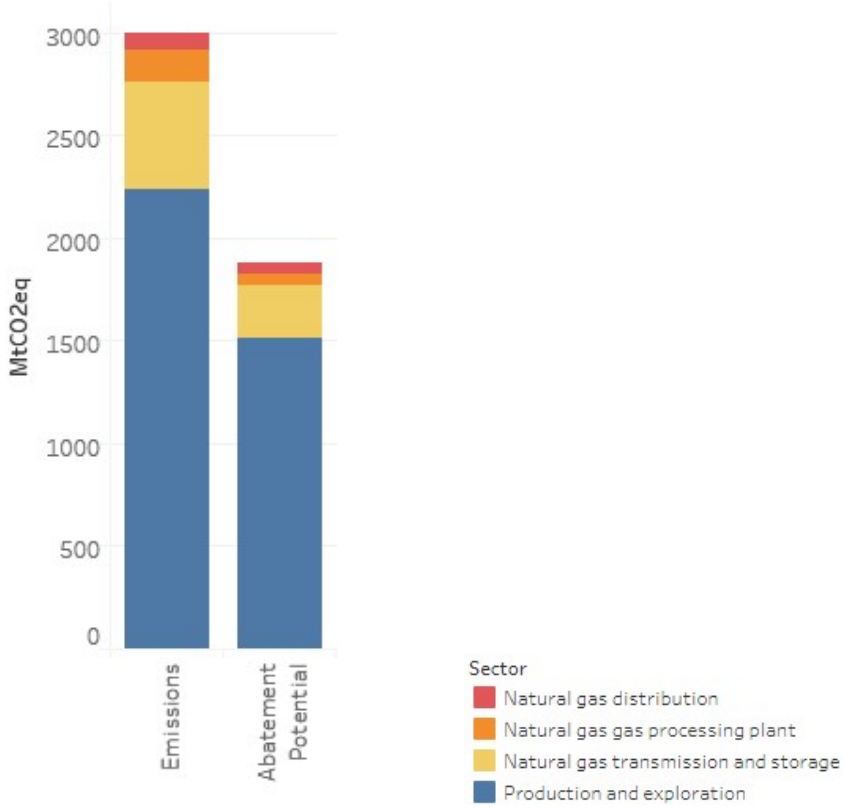
Figure 6: Methane emissions taken into account in the abatement analysis



3.2 Abatement potential

The results from the analysis show that it is possible, from a technical point of view, to reduce the emissions by at least 60% compared to 2016 total methane emissions, representing around 1.9Gt$CO_{2,e}$ of reduction.

Figure 7: Abatement potential vs methane emissions in million tonnes of CO_2 equivalent



The production and exploration sector represents the largest abatement potential (more than 80% of the total abatement potential). 69% of the abatement potential can be achieved in Russia, 25% in the USA. The abatement potential in Norway is fairly limited.

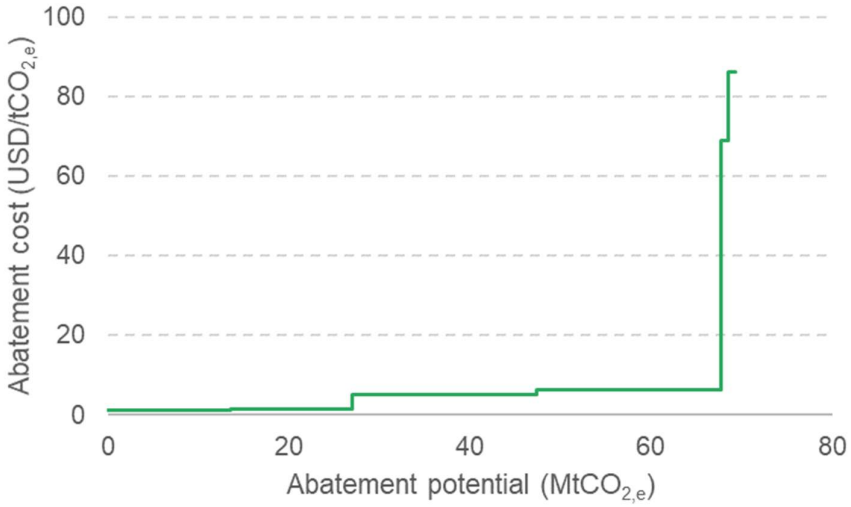
Figure 8: Share of methane abatement potential between the main oil and gas producing Arctic countries



3.3 Abatement cost and investment required

As explained in the methodology described above, for each emission source, an abatement cost curve was constructed representing the emission factor and CAPEX variability. Figure 9 shows an example of the cost curves used in the analysis for one specific emission source.

Figure 9: Cost curve example for pneumatic device vents (Intermittent Bleed) used in natural gas production in the USA



Given the large number of data points and to allow prioritizations, the abatement costs are presented by categories:

- Negative abatement costs
- Costs between 0 and 10 USD/$tCO_{2,e}$
- Costs above 10 USD/$tCO_{2,e}$.

The results per country and per emission category are presented on the next figures. These visuals are available on the tableau® dashboards.

Figure 10: Abatement cost and potential per Arctic countries

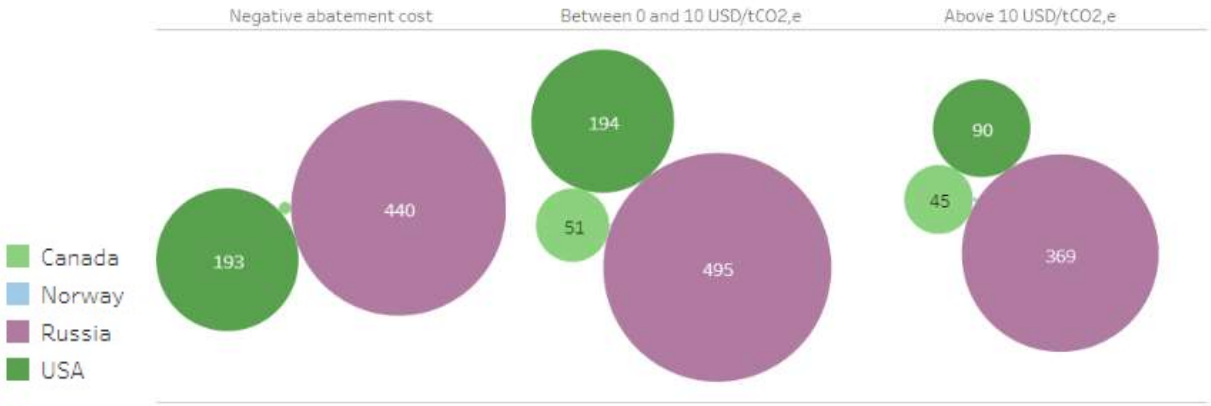


Figure 11: Abatement cost and potential per emission category and country (same color coding as Figure 12)



Around 1/3 of the abatement potential can be done at a negative abatement cost, or no net cost. Most of the abatement potential lying in the “components and equipment leaks” emission category. Mitigation options in this emission category are mostly annual or quarterly LDAR.

70% are achievable at a cost of below 10 USD/$tCO_{2,e}$. The tableau® dashboards allow for further analyses. By clicking on the filters, it is possible to see the distribution of the abatement potential and cost per country and per sector.

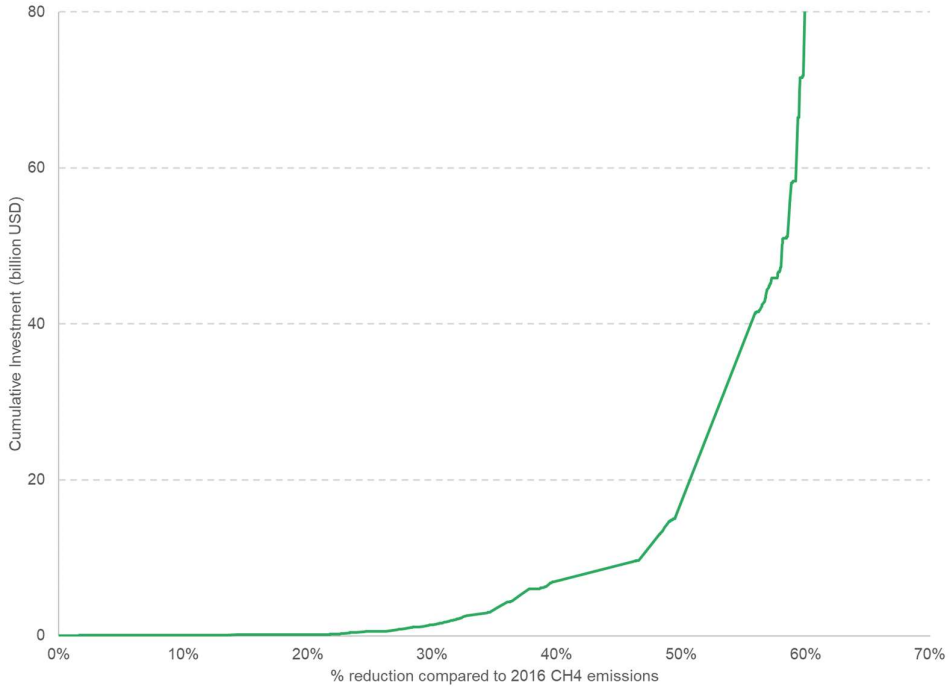
Table 4 indicates that 33% of the abatement potential (corresponding to around 20% reduction compared to 2016 methane emissions) could be achieved at a negative abatement cost with a limited investment of 0.15 billion USD. Reaching 70% would require an investment of 9.5 billion USD. A massive investment is required to achieve the full abatement potential.

Table 4:Investment required in each cost category

Cost category	**Abatement potential - $MtCO_{2,e}$**	**Total Investment – billion USD**
Negative abatement cost	630	0.15
Between 0 and 10 USD/$tCO_{2,e}$	760	9.5
Above 10 USD/$tCO_{2,e}$	500	>3000

Figure 12 shows the cumulative investment required to reach an emission reduction target. There are some low hanging fruits in terms of mitigation option however a target above 50% reduction (compared to 2016 reported methane emission) would require a substantial investment.

Figure 12: Cumulative investment required to reach a set target of % emission reduction



The tool developed under tableau® allows the user to set an abatement target and to see in which country, sector, category and at which cost it is possible to reach this target. In Appendix 4, an example of how to use this function is given.

4. Conclusions

Carbon Limits has developed a model which calculates the abatement potential and costs of methane emission mitigation technologies in the main oil and gas producing Arctic countries: Russia, USA, Canada and Norway. In 2016, these countries were reporting to UNFCCC close to 3 $GtCO_{2,e}$ of methane emissions from the oil and gas sector.

Carbon Limits by investigating more than 90% of the methane emissions has shown that it was technically feasible to reduce at least 60% of the methane emissions. For each emission source, a simplified distribution of emission factors and costs were considered to represent in the best way possible the emission source specificities. Around 1/3 of the abatement potential can be realized at a negative cost while 70% of the abatement can be reached at a cost of below 10 USD/$tCO_{2,e}$. The “components and equipment leaks”, compressors and liquid storage tanks represents the largest abatement potential at no cost.

Carbon Limits created tableau® dashboards to further analyse the results produced by the model. With these dashboards it is possible for the user to visualize all the results from the analysis with application of different filters (country, sector, emission category). In addition, the user can set an abatement target to see in which country, sector, category and at which cost it is possible to reach this target.

Appendix 1 – Oil and Gas sector emissions categories according to IPCC 2006 guidelines and emissions reported by Arctic countries

GHG emissions from the oil and gas operations are reported under the following emission categories within UNFCCC reporting framework (see 2006 IPCC Guidelines for National Greenhouse Gas Inventories[30] for more information). The correspondence with the sectors used in this report are presented in the last column.

Table 5: Oil and Gas sector emissions categories according to IPCC 2006 guidelines and correspondence with the sectors used in this report

IPCC code	Source name	Explanation	Sector
1.A.1.b	Petroleum refining	All combustion activities supporting the refining of petroleum products including on-site combustion for the generation of electricity and heat for own use.	Oil Transport and refining
1.A.1.c.ii	Manufacturing of solid fuels and other energy industries: Other energy industries	Combustion emissions arising from own (on-site) energy use by the energy-producing industries other than coke, brown coal briquettes and patent fuel production. This includes the emissions from own-energy use for oil and gas extraction and the processing and upgrading of natural gas.	Production and exploration Natural gas processing
1.A.3.e.i	Other transportation: Pipeline transport	Combustion related emissions from the operation of pump stations and maintenance of pipelines. Transport via pipelines includes transport of gases, liquids, slurry and other commodities via pipelines. Distribution of natural or manufactured gas, water or steam from the distributor to final users is excluded and should be reported in 1.A.1.c.ii or 1.A.4.a.	Natural gas transmission and storage
1.A.4.a	Other sectors: Commercial/Institutional	Emissions from fuel combustion in commercial and institutional buildings (including distribution of natural or manufactured gas, water or steam from the distributor to final users)	Natural gas distribution
1.B.2	Fugitive emissions from fuels: Oil and natural gas and other emissions from energy production	Comprises fugitive emissions from all oil and natural gas activities. The primary sources of these emissions may include fugitive equipment leaks, evaporation losses, venting, flaring and accidental releases.	*See table below*

[30] http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Table 6: 1.B.2 – detailed emission categories and correspondence with the sectors used in this report

UNFCCC category	UNFCCC name	Sector
1.B.2.a	Oil	*General category*
1.B.2.a.1	Exploration	Production and exploration
1.B.2.a.2	Production	Production and exploration
1.B.2.a.3	Transport	Oil Transport and refining
1.B.2.a.4	Refining/Storage	Oil Transport and refining
1.B.2.a.5	Distribution of oil products	Oil Transport and refining
1.B.2.b	Natural gas	*General category*
1.B.2.b.1	Exploration	Production and exploration
1.B.2.b.2	Production / Processing	Production and exploration Natural gas processing
1.B.2.b.3	Transmission	Natural gas transmission and storage
1.B.2.b.4	Distribution	Natural gas distribution
1.B.2.b.5	Other leakage	Natural gas processing Natural gas transmission and storage Natural gas distribution
1.B.2.c	Venting and flaring	*General category*
1.B.2.c.1	Venting	*General category*
1.B.2.c.1.i	Oil	Production and exploration
1.B.2.c.1.ii	Gas	Production and exploration
1.B.2.c.2	Flaring	*General category*
1.B.2.c.2.i	Oil	Production and exploration
1.B.2.c.2.ii	Gas	Production and exploration

The following methane emissions from oil and gas operations were reported by the Arctic countries to UNFCCC in 2018 for 2016.

Table 7: Methane emissions from the oil and gas sector in the Arctic countries based on UNFCCC reporting[31]

Country	Methane emissions from the oil and gas sector ($ktCH_4$) - 2016
Russia	24904
USA	8375
Canada	1767
Norway	35
Denmark	4
Sweden	2.5
Finland	1.3
Iceland	0.02

[31] https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018

Appendix 2 – Mitigation options: applicability, efficiency and costs – basis 2016

Emission category	Mitigation option	Mitigation applicability	Mitigation efficiency	Activity Data (AD) unit	CAPEX range (USD/AD-unit)	OPEX range (USD/AD-unit/y)	Lifetime (year)	Information Source
Hydraulic fracturing & well completion, exploration and drilling	Reduced Emission Completion	90%	80%	events		40,000 - 55,000	1	Natural gas STAR Program, Recommended Technologies to reduce methane emissions[32] EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.[33]
Liquids unloading from gas wells	Plunger lift	80%	50%	venting wells	3,000-20,000	1,500 - 1,750	5	ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results.[34] EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.
Glycol dehydrators	Optimize glycol circulation rate and install flash tank separators	90%	67%	plant	10,000-40,000	350-420	5	Natural gas STAR Program, Recommended Technologies to reduce methane emissions Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator[35] EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.
Natural gas driven pneumatic controllers and pumps	Chemical Pumps - Replacement with electric pumps	90%	100%	pump	5,000 – 10,500	80 - 150	10	Carbon Limits, 2016. Zero emission technologies for pneumatic controllers in the USA - Applicability and cost effectiveness.[36] ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results. Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator

[32] https://www.epa.gov/natural-gas-star-program/recommended-technologies-reduce-methane-emissions
[33] https://www.epa.gov/sites/production/files/2016-06/documents/mac_report_2013.pdf
[34] http://onefuture.us/wp-content/uploads/2018/05/ONE-Future-MAC-Final-6-1.pdf
[35] https://www.aer.ca/documents/DelphiAlbertaMethaneAbatementCostStudy.pdf
[36] https://www.carbonlimits.no/wp-content/uploads/2017/01/Report_FINAL.pdf

Emission category	Mitigation option	Mitigation applicability	Mitigation efficiency	Activity Data (AD) unit	CAPEX range (USD/AD-unit)	OPEX range (USD/AD-unit/y)	Lifetime (year)	Information Source
Natural gas driven pneumatic controllers and pumps	Kimray Pumps - Replacement with electric pumps	90%	100%	pump	10,000 – 13,000	1,500 – 2,500	10	Carbon Limits, 2016. Zero emission technologies for pneumatic controllers in the USA - Applicability and cost effectiveness. ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results. Expert's opinion based on interviews / field trips - case analyses
Natural gas driven pneumatic controllers and pumps	Zero Emission Controllers - retrofit	90%	100%	controller	4,000 – 5,000		10	Carbon Limits, 2016. Zero emission technologies for pneumatic controllers in the USA - Applicability and cost effectiveness.
Compressors	Early replacement of rod packing systems	100%	31%	compressor	5,000 - 8,000		3	ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results. Expert's opinion based on interviews / field trips – case analyses EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.
Compressors	Wet seal degassing recovery	80%	70%	compressor	20,000 – 100,000		10	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. Expert's opinion based on interviews / field trips - case analyses
Venting of associated gas at upstream oil production facilities	Install a flare	90%	98%	bbl	3.3 – 33.4	1.5-1.7	15	ICF, 2015. Economic Analysis of Methane Emission Reduction Opportunities in the Canadian Oil and Natural Gas Industries.
Hydrocarbon liquid storage tank. Hydrocarbon loading and transportation	Install VRU	80%	75%	bbl	7.2E-2 – 6.7E-1	-	15	Expert's opinion based on interviews / field trips - case analyses ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results. Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator
Equipment depressurization and blowdowns from pipelines and facilities	Redesign Blowdown Systems and ESD	70%	95%	station	15,000 – 50,000		10	ICF, 2016. One Future - Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems - Analytical Results.

Emission category	Mitigation option	Mitigation applicability	Mitigation efficiency	Activity Data (AD) unit	CAPEX range (USD/AD-unit)	OPEX range (USD/AD-unit/y)	Lifetime (year)	Information Source
								Expert's opinion based on interviews / field trips - case analyses
Equipment depressurization and blowdowns from pipelines and facilities	Use Mobile compressor stations	100%	80%	mile	2,400 – 2,800		1	MJB&A, 2016. Pipeline Blowdown Emissions and Mitigation Options.[37]
Equipment depressurization and blowdowns from pipelines and facilities	Install surge vessels for capturing blowdown vents	90%	50%	plant	140,000 – 210,000	20,000 - 40,000	15	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030.
Component and equipment leaks	Replace pipeline	95%	100%	Mile	165,000 – 840,000	165 - 840	20	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. Expert's opinion based on interviews / field trips - case analyses
Component and equipment leaks	Quarterly LDAR - Gathering Systems	100%	80%	Station		10,000 - 22,000	1	Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator. EDF, ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.
Component and equipment leaks	Quarterly LDAR - GPP	100%	80%	Station		17,000 – 30,000	1	Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator. EDF, ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.
Component and equipment leaks	Annual LDAR - Wells	100%	60%	Well		1,500 – 2,000	1	Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator EDF, ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.

[37] http://blogs.edf.org/energyexchange/files/2016/07/PHMSA-Blowdown-Analysis-FINAL.pdf

Emission category	Mitigation option	Mitigation applicability	Mitigation efficiency	Activity Data (AD) unit	CAPEX range (USD/AD-unit)	OPEX range (USD/AD-unit/y)	Lifetime (year)	Information Source
Component and equipment leaks	Quarterly LDAR Compressor Station	100%	80%	Station		11,000 – 19,000	1	Delphi Group. 2017. Methane Abatement Costs: Alberta. Alberta Energy Regulator EDF, ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.
Component and equipment leaks	Annual LDAR - M & R station	100%	60%	Station		1,500 – 2,000	1	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. EDF, ICF, 2014. Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries.
Incomplete combustion (including associated petroleum gas (APG), engines, turbines, fired heaters)	Install Catalytic converter on gas fuelled engines and turbines	10%	56%	MMHPhr	80-100	40-50	10	EPA, 2013. Global Mitigation of non-CO_2 Greenhouse Gases: 2010-2030. SINTEF, 2017. GHG and NOx emissions from gas fueled engines - Mapping, verification, reduction technologies[38]. Lehtoranta et al, 2016. Natural Gas Engine Emission Reduction by Catalysts[39].
Other sources (oil refining vents, natural gas processing plants vents)	Reroute to the flare	70%	90%	MMbbl Associated Gas Recovery unit	250-300 10,000		15	Expert's opinion based on interviews / field trips - case analyses

[38] https://www.nho.no/siteassets/nox-fondet/rapporter/2018/methane-slip-from-gas-engines-mainreport-1492296.pdf

[39] http://www.transsmart.fi/files/400/Natural_Gas_Engine_Emission_Reduction_by_Catalysts.pdf

Appendix 3 – Gas prices used in the study

Gas prices used in the study in USD/MMBtu.

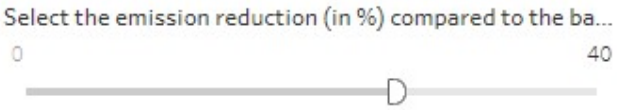
Country	upstream[40]	transmission[41]	distribution[42]
Russia	0.6	1.3	1.8
USA	0.8	1.8	2.6
Canada	0.5	1.2	1.7
Norway	1.8	4.2	6

[40] Deduced from the distribution gas price
[41] Deduced from the distribution gas price
[42] 2017 wholesale gas price - https://www.igu.org/sites/default/files/node-document-field_file/IGU_Wholesale%20Gas%20Price%20Survey%202018%20Final.pdf

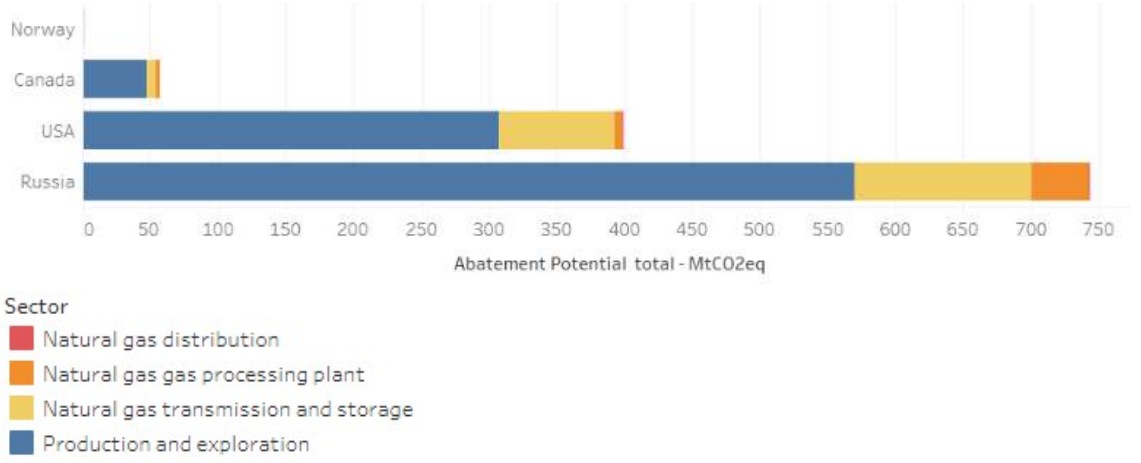
Appendix 4 – Example of use of the tableau® dashboards

In the “Prioritized abatement” dashboard, the user can set its targeted methane emission reduction and see which categories should be prioritized to reach this target at the lowest cost.

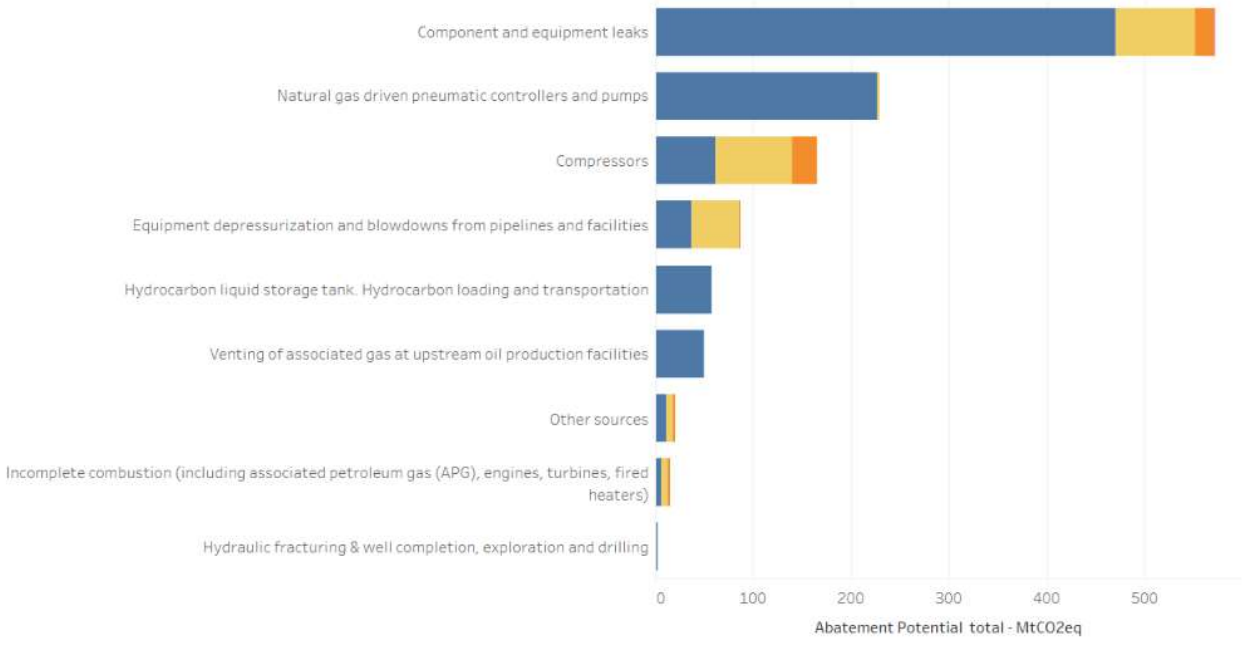
In this example, we set the methane emission reduction to 40% compared to 2016 methane emissions (an absolute number can also be used to set the target).



The dashboard shows in which countries and sectors the abatement potential at the lowest cost is achievable:



In addition, the users can see in which categories and sectors, this abatement potential is achievable



Finally, the share of the abatement costs is given on the dashboard.

