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Technical Paper

The uncertainty of a unique Predictive Emissions Monitoring System based on hybrid development

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1 INTRODUCTION

Methane is more potent than carbon dioxide at trapping the Earth's heat, indeed the Global Warming Potential –GWP– allows comparing how much warming a newly emitted gas will cause, relative to the same mass of carbon dioxide, or CO_2, over a set period. The methane GWP20 is equal to 85. This means it is 85 times more potent and enforcement of the emission control thru regulations/standards are coming ready and will be released soon. It is also a key component of the gas emissions and tax penalties to be put in place.

A continuous emission monitoring system —CEMS— is a real-time measurement of gas emissions but it is quite complex to keep running. The system comprises sampling, conditioning, analytical components, and software that provide direct, real-time, continuous measurements of pollution by analysing representative samples. It is an important tool for pollution monitoring, control, and reporting. The system ensures data accuracy, higher monitoring frequency, minimal manual intervention, firm regulatory monitoring, and better transparency to strengthen the pollution control regime.

But today the trend is to use Predictive Emission Monitoring Systems —PEMS— which is an alternative and/or back-up to traditional hardware sensors for measuring a wide number of parameters from an emissions system. Such parameters are various gas concentrations (e.g. NOx, CO_2, H_2S…), flow rates, and particle/dust concentration.
PEMS are compliant and accepted by international environmental regulations and standards (for example PS 16 [4]) which we will introduce. The uptime of the PEMS system is greater than 99.5%. The reduced lifetime cost compared to CEMS hardware is up to 50% lower. Finally, the PEMS is part of the digital transformation happening in the oil and gas industry.

Behind these statements and benefits, a very relevant question stays: What is the uncertainty available/got with such a solution? We have been working over the years in this direction.

2 OVERVIEW OF THE PROBLEM & STANDARDS

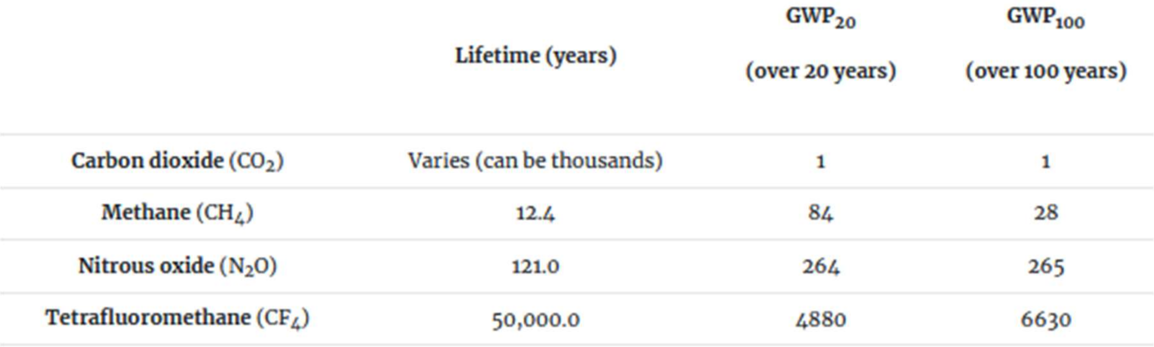
Weel & Sandvig company has developed an innovative hybrid predictive emission monitoring system —PEMS— which is based on the first principle's model and semi-analytical model for the prediction of the NOx, CO, CH_4, and CO_2 components. However, to develop a new product/solution, it is important to establish the process, review the process, and check that the system is complying with the performance specification from "Predictive Emission Monitoring Systems in Stationary Sources" [4] which explains the way to establish the performance of the PEMS against continuous emission monitoring system; and, finally, develop and implement the uncertainty on the CH_4 gas emission to address our main raised question.

Different factors can influence the global warming potential —GWP— value, which compares how much warming a newly emitted gas will cause, relative to the same mass of carbon dioxide, or CO_2, over a set period. These are often used to calculate CO_2 equivalents, and this is including:

1) The gas's inherent ability to warm
Some gases trap heat better than others, and some also produce chemical reactions that can lead to the production of other greenhouse gases, among other effects. Methane, for example, is a better heat trapper than CO_2 and also can increase lower-atmospheric ozone, which indirectly adds to methane's warming ability.

2) The lifetime of the gas
Different gases persist in the atmosphere for different periods. Some, such as methane, break down rather quickly, while others can last hundreds or thousands of years, still contributing to warming.

Methane is more potent than carbon dioxide at trapping the Earth's heat, indeed the GWP allows comparing how much warming a newly emitted gas will cause, relative to the same mass of carbon dioxide, or CO_2, over a set period. The methane GWP20 is equal to 85. This means it is 85 times more potent and enforcement of the emission control thru regulations/standards are coming ready and will be released soon over 20 years. The nitrous oxide N_2O has a GWP20 = 264, and it is also a key component of the gas emissions and tax penalties to be put in place.



	Lifetime (years)	GWP_{20} (over 20 years)	GWP_{100} (over 100 years)
Carbon dioxide (CO_2)	Varies (can be thousands)	1	1
Methane (CH_4)	12.4	84	28
Nitrous oxide (N_2O)	121.0	264	265
Tetrafluoromethane (CF_4)	50,000.0	4880	6630

Table 1: GWP for the main gas emissions

The CEMS is a real-time measurement of gas emissions, but it is quite complex to keep running. The system comprises sampling, conditioning, and analytical components and software that provide direct, real-time, continuous measurements of pollution by analysing representative samples. It is an important tool for pollution monitoring, control, and reporting. The system ensures data accuracy, higher monitoring frequency, minimal manual intervention, firm regulatory monitoring, and better transparency to strengthen the pollution control regime. PEMS are compliant and accepted by international environmental regulations as soon as they comply with standards [4] which we will introduce. The uptime of the PEMS system is greater than 99.5%. The reduced lifetime cost compared to CEMS hardware is up to 50% lower. Finally, the PEMS is part of the digital transformation happening in the oil and gas industry.

3 PREDICTIVE EMISSIONS MONITORING SYSTEM & PERFORMANCE SPECIFICATIONS

For using PEMS, the developer or operators should show compliance with performance specification 16 [4] to determine whether the PEMS is acceptable for demonstrating compliance with applicable requirements. The procedure allows for certifying the PEMS after the initial installation and periodically thereafter to ensure the PEMS is operating properly. The key steps of the analysis are presented here below.

3.1) How to certify the PEMS after installation

After installation, the PEMS must pass a relative accuracy (RA) test and accompanying statistical tests in the initial certification test to be acceptable for demonstrating compliance with applicable requirements. Ongoing quality assurance tests also must be conducted to ensure the PEMS is operating properly. It should be kept in mind that the amount of testing and data validation that is required depends upon the regulatory needs, i.e., whether precise quantification of emissions will be needed or whether a sign of exceedance of some regulatory threshold will suffice.
The standard mentioned that "Performance criteria are more rigorous for PEMS used in determining continual compliance with an emission limit than those used to measure excess emissions. You must perform the initial certification test on your PEMS before reporting any PEMS data as quality-assured". As explained in PS 16 periodic evaluation needs to be made to ensure the long-term quality of data and a procedure is shown. Finally, the owner or user is always responsible for properly maintaining and operating the PEMS.

3.2) Initial PEMS certification

Three types of certifications are introduced and answer a specific need:

1) PEMS is being used to report only excess emissions, a minimum of 3 runs at 3 levels of Relative Accuracy (RA) are recommended.

2) PEMS is being used to report continual compliance standards, a minimum of 9 runs at 3 level RA are required.

3) Periodic Quality Assurance assessment is a quarterly activity (Relative Accuracy Audits RAA) and a yearly relative accuracy test audit (RATA). The frequency could be changed (see note) based on performing the previous year, albeit Weel & Sandvig recommend a yearly basis or if the RAA deviates more than ± 8 %.

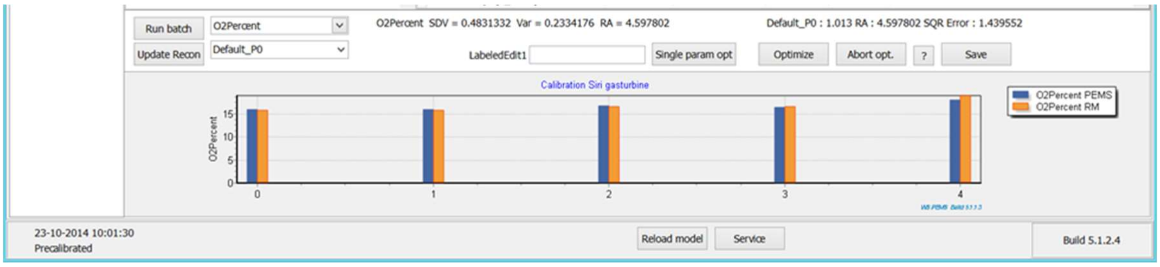
Note: If a PEMS passes all quarterly RAAs in year#1 and also passes the subsequent yearly RATA in the second year (year#1+1), it is possible to perform a single midyear RAA in the second year in place of the quarterly RAAs. This option may be repeated, but only until the PEMS fails either a mid-year RAA or a yearly RATA. When such a failure occurs, quarterly RAAs should be resumed in the quarter following the failure and continue conducting quarterly RAAs until the PEMS successfully passes both a year of quarterly RAAs and a subsequent RATA.

The PS 16 mentions clearly that more tests can be made for each level and then you can reject up to 3 tests maximum as long that the minimum required number is achieved; however, the rejecting data should be recorded, albeit not used. It is also important to mention that the PEMS should be defined for a range or working envelope and show working in this range. It should be also understood that the certification can be established on a smaller range than the working envelope as soon as an explanation or support document is available. Using PEMS outside of the range per se, the extrapolation of the data is not valid. The limitation could be limited by fuel type too.

3.3) Initial PEMS certification

All tests must be done at three operating levels, with the following definition from PS 16 and some specific recommendations based on experience in operation. Tests shall be performed at a low-loading (or production) level between the minimum safe, stable loading and not over 50 % of the maximum level of loading. An intermediary level between the low and high levels of loading. A high-load level means a range between 80 % and 100 % of the maximum level of loading.
It is important to have the different critical parameters following the type of turbine constant during the test, which should be longer than 21 minutes (3 x 7 minutes). If the initial range of the PEMS for the emissions unit is for example operating at 80 % - 100 % of its range (initial test and validation under these conditions) but later, the emission unit is working at 50 % - 100 % of its range, another RA test, and statistical tests, as applicable, should be conducted to verify that the new conditions of 50 % - 100 % of the range are functional. These tests must show that the PEMS provides acceptable data when operating in the new range or with the new critical PEMS parameter(s). This should be completed at the earlier 60-unit operating days or 180 calendar days after the failed RATA or after the change that caused a significant change in emission rate.
If the PEMS cannot pass a quarterly RAA or yearly RATA, or if changes occur or are made, that could cause a significant change in the emission rate (e.g., turbine aging, process modification, new process operating modes, or changes to emission controls), the PEMS must be recertified using one of the three types of certifications above.

A typical calibration result with WP PEMS is presented in figure 1, where the PEMS is in blue and the CEMS is in orange.


O2Percent SDV = 0.4831332 Var = 0.2334176 RA = 4.597802

Default_P0 : 1.013 RA : 4.597802 SQR Error : 1.439552

23-10-2014 10:01:30
Precalibrated

Build 5.1.2.4

Figure 1: 5 Different runs presented during a calibration (PEMS in blue, CEMS in Orange)

3.4) Initial PEMS certification

The development of the WS PEMS is a hybrid solution based on known physical principles based on physical and mathematical assumptions supporting the processing which will be explained at a high level to keep the Weel & Sandvig company proprietary information confidential and some non-linear regressions analysis necessary to identify the effect of the variation of one parameter on the entire system. A graphical example is presented in figure 2, which is PS 16 preferred option; however, for uncertainty analyses, a quantification of the effect thru the derivative is the best option and has been implemented in the latest WS PEMS.

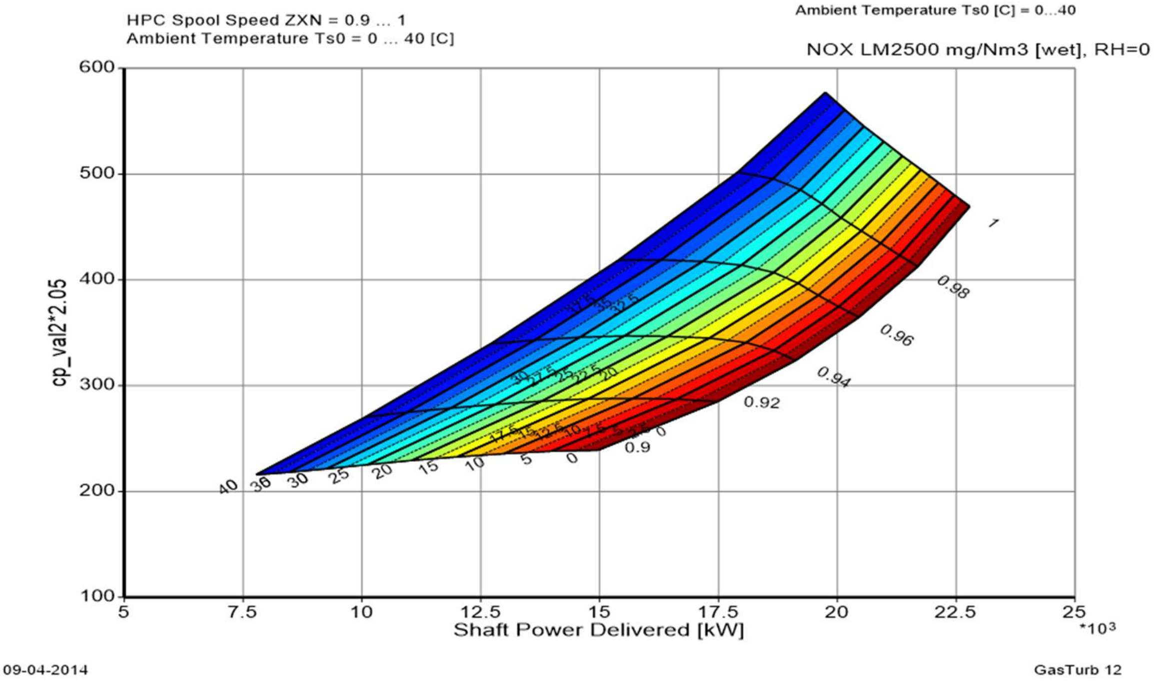


Figure 2: Typical NOx emission factor "cp" vs. a gas turbine loading

3.5) Relative Accuracy Test Audit Frequency – RATA

The RATA should be done on the yearly basis (4 times a quarter to be precise) however if a new sensor is installed, or a replacement sensor is installed then a new RATA after replacement should be made if the output parameter supplies a critical PEMS parameter. This includes if the new sensor provides a different output or scaling or changes the historical training dataset of the PEMS. Replacement of a non-critical sensor that does not cause an impact on the accuracy of the PEMS does not trigger a RATA.

All sensors must be calibrated as often as needed, but at least as often as recommended by the manufacturers. This is important to establish properly the uncertainty of the gas emissions measured by the PEMS.

4 WS PREDICTIVE EMISSIONS MONITORING SYSTEM

4.1 Failure of a sensor & Robustness of the WS PEMS model

WS PEMS development is complying with the sensor evaluation inside the PS16, which shows to detect failures and report them on the daily basis. The current WS PEMS development is based on the use in parallel of multiple physical models (on average 4 to 6) that should converge based on the assumptions of the same results. The deviation of one of them will lead to spotting the malfunctioning equipment and allow the production of relevant PEMS data by disregarding this identified process. This has been shown working over several sets of data during desk auditing.

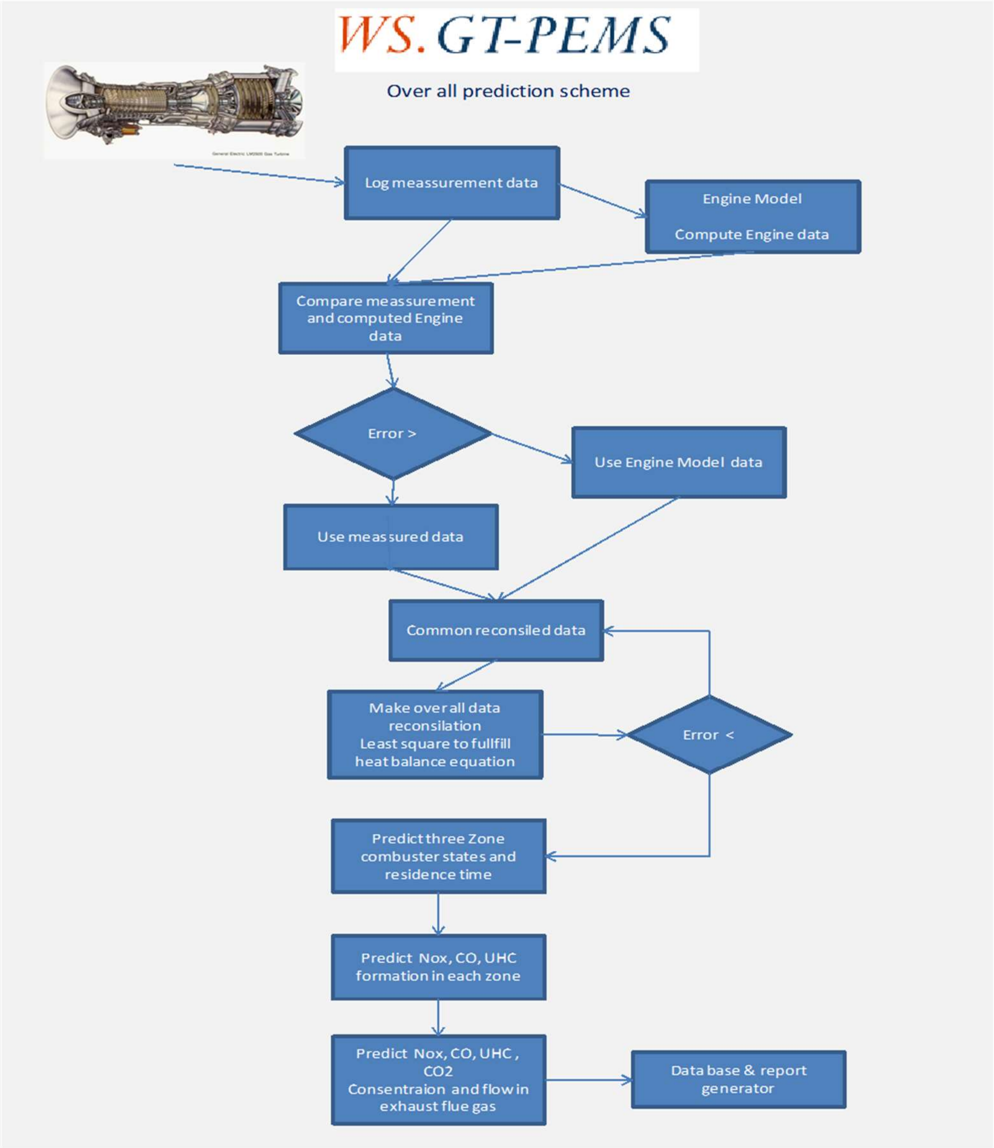


Figure 3: PEMS Calculation scheme including data reconciliation

A simple description of the specific process is that the WS PEMS is developed with a two-level data validation scheme to assure that measurement errors will not affect the emission result significantly: The first level assures that sensor measurement values are within the expected range for the actual operation point (gross error detection). Next critical engine parameters are then predicted by a rigoristic first principal engine components model. The "engine models" will typically use the following input (Pressure, Temperature, ambient temperature, ambient pressure, Bleed valve position…). Data predicted by the engine models are compared with the actual measurements. Measurements are then good (accepted) or bad (rejected) if they are within or outside the range of validity (example of the range definition in Figure 2). The second level of data reconciliation uses the root square method to adjust engine global parameters to fulfil the heat balance and engine model parameters based on weighted errors. The overall method is shown schematically in figure 3. The key in this test is to estimate the sensor signal error for each user signal in a way that the basic energy and mass balances are fulfilled. For example, assuming that the real process value Xi is then defined by Xi=Xm,i+ΔXi where Xm,i is the measured value and ΔXi is the correction/error value. This online data reconciliation minimises the direct effect of incorrect sensors.

4.2 Validation of the PEMS Measurements

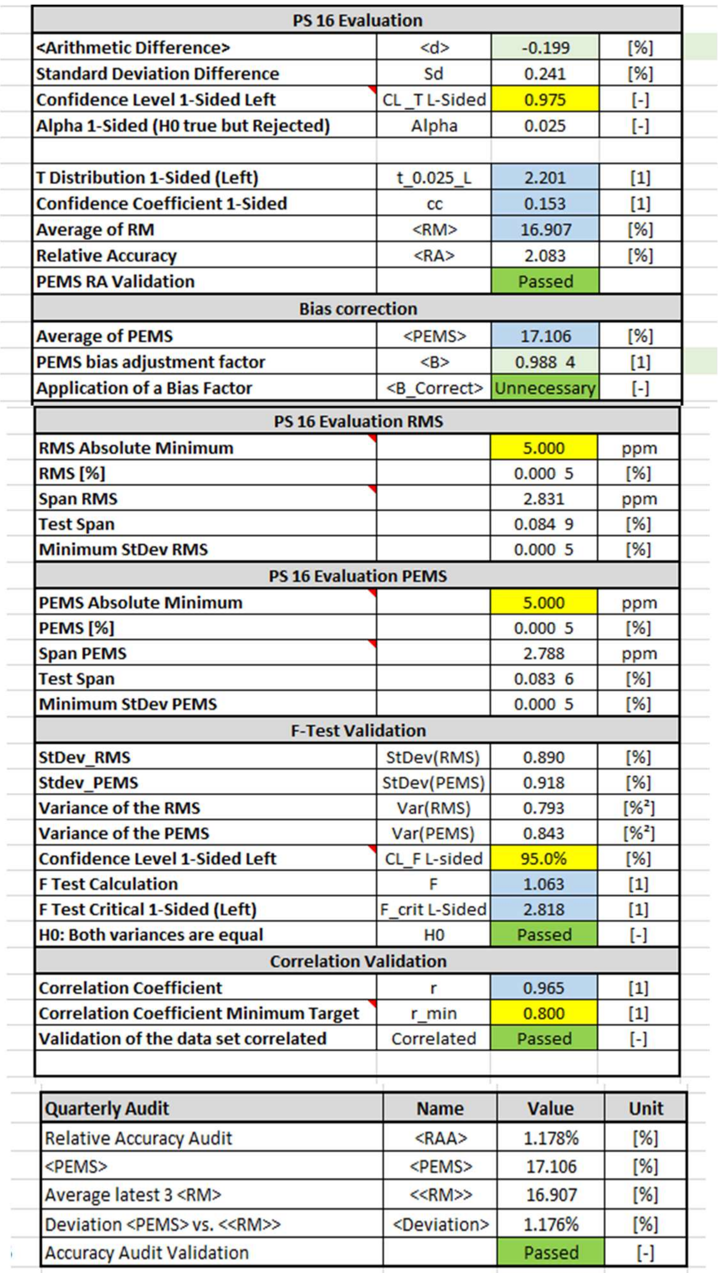
Data are collected simultaneously from the PEMS and the RM, and the validation can follow the PS 16 recommendations. The purpose of this section is not to rewrite the equations presented in the PS16 document, but to highlight the key steps. The implementation was made using Excel and was audited against some specific standard (statistics) when possible.
As shown earlier, the sensor evaluation system must check the integrity of each PEMS input at least daily and WP PEMS is complying with this standard as soon as it is running and has a permanent check continuously available to spot any as early as possible any issues. The other parameters to monitor for acceptability of the test comparison are summarised in the following table:

Test Parameter	Acceptability
RAA	3-test ≤ 10 % of RM
RATA	≤ 10 % with 100 ppm ≤ PEMS ≤ 20 % with 10 ppm ≤ PEMS ≤ 100 ppm $-2\ \text{ppm} \leq \overline{\text{PEMS-RM}} \leq +2\ \text{ppm}$ with PEMS ≤ 10 ppm
Bias Correction	No correction if $-cc \leq d_{avg} \leq cc$
PEMS Training	Fcritical ≥ F r ≥ 0.8 with SNR ≥ 4 r is not used as a criterion of acceptability if SNR < 4

Table 2: QA and QC

4.3 Example of validation

The implementation and guidelines were developed in Excel for the final incorporation inside the software to make the immediate outcome statement about the PASS/FAIL test. This section highlights the development of the solution and the major steps in the calculation. The T-test, F-test, and correlation validation were calculated (table 3), this leads to validation or not the test comparison by looking at the variance of both systems and then calculating the correlation between both sets of data.



PS 16 Evaluation			
<Arithmetic Difference>	<d>	-0.199	[%]
Standard Deviation Difference	Sd	0.241	[%]
Confidence Level 1-Sided Left	CL_T L-Sided	0.975	[-]
Alpha 1-Sided (H0 true but Rejected)	Alpha	0.025	[-]
T Distribution 1-Sided (Left)	t_0.025_L	2.201	[1]
Confidence Coefficient 1-Sided	cc	0.153	[1]
Average of RM	<RM>	16.907	[%]
Relative Accuracy	<RA>	2.083	[%]
PEMS RA Validation		Passed	
Bias correction			
Average of PEMS	<PEMS>	17.106	[%]
PEMS bias adjustment factor	<B>	0.988 4	[1]
Application of a Bias Factor	<B_Correct>	Unnecessary	[-]
PS 16 Evaluation RMS			
RMS Absolute Minimum		5.000	ppm
RMS [%]		0.000 5	[%]
Span RMS		2.831	ppm
Test Span		0.084 9	[%]
Minimum StDev RMS		0.000 5	[%]
PS 16 Evaluation PEMS			
PEMS Absolute Minimum		5.000	ppm
PEMS [%]		0.000 5	[%]
Span PEMS		2.788	ppm
Test Span		0.083 6	[%]
Minimum StDev PEMS		0.000 5	[%]
F-Test Validation			
StDev_RMS	StDev(RMS)	0.890	[%]
Stdev_PEMS	StDev(PEMS)	0.918	[%]
Variance of the RMS	Var(RMS)	0.793	[%²]
Variance of the PEMS	Var(PEMS)	0.843	[%²]
Confidence Level 1-Sided Left	CL_F L-sided	95.0%	[%]
F Test Calculation	F	1.063	[1]
F Test Critical 1-Sided (Left)	F_crit L-Sided	2.818	[1]
H0: Both variances are equal	H0	Passed	[-]
Correlation Validation			
Correlation Coefficient	r	0.965	[1]
Correlation Coefficient Minimum Target	r_min	0.800	[1]
Validation of the data set correlated	Correlated	Passed	[-]

Quarterly Audit	Name	Value	Unit
Relative Accuracy Audit	<RAA>	1.178%	[%]
<PEMS>	<PEMS>	17.106	[%]
Average latest 3 <RM>	<<RM>>	16.907	[%]
Deviation <PEMS> vs. <<RM>>	<Deviation>	1.176%	[%]
Accuracy Audit Validation		Passed	[-]

Table 3: T-Test, F-test validation (variance) and correlation validation

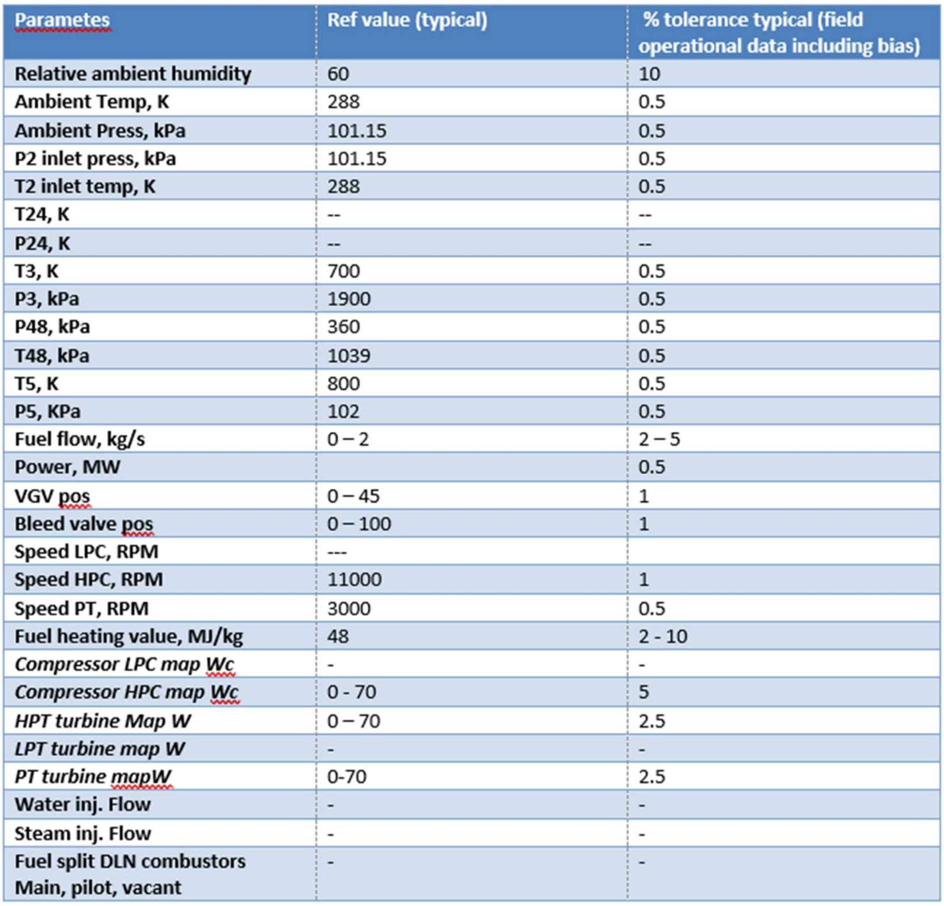
5 EVALUATION OF THE UNCERTAINTY OF THE PEMS MEASUREMENT

5.1 Overview of the problematic

If the PS 16 document allows testing the PEMS versus the real-time measurement, the major limitation is that no information can be given about the uncertainty of the PEMS. It could be understood that this is a process that is specific and related to the development of each PEMS model, but this is an essential outcome from a regulation point of view.

The primary objective here is: what is the uncertainty of the WS PEMS measurement? To express it, we need to have access to the uncertainty of each parameter used inside the WS PEMS model and then the respective sensitivity coefficients. Having in mind that on average there are 20 parameters (aka sensors or measurements for one PEMS output), and the equations are not explicit then the first step of the analysis was to develop a software solution capable of providing the relevant sensitivity information associated with a parameter reading. This will be combined with the other parameters and sensitivity coefficient to establish the overall uncertainty for the CH4 gas emission (either concentration or mass flow rate). The sensitivity evaluation was based on an automatic derivation around the current functioning point, which was set by allowing the model to establish the dependency versus small variation and looking at the first-order magnitude or the tangential to the described curve for a parameter. It is then over 20 x 3 data generated for each measurement and the model calculates the methane emission in concentration and mass flow rate. This was then over 120 data for each recording. Finally, this was generating a file of several ten thousand data to do the overall uncertainty statement. A specific analysis was necessary and developed ad hoc.

In this example, the models are based on the 20 parameters listed below. These parameters could be different on the type of turbines or compressors.

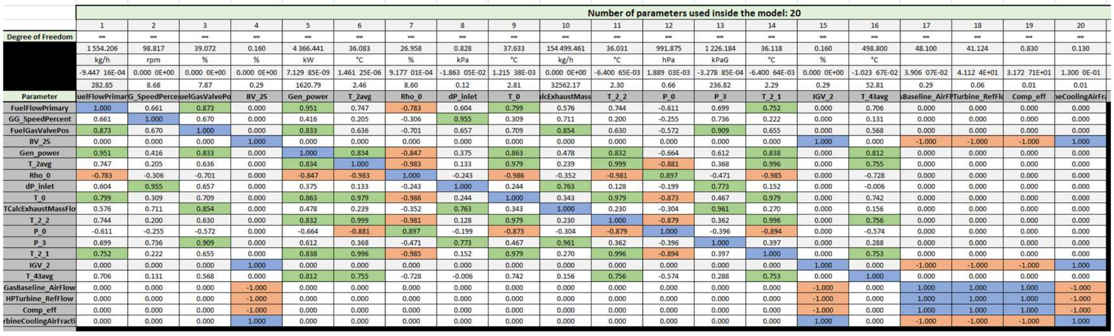


Parametes	Ref value (typical)	% tolerance typical (field operational data including bias)
Relative ambient humidity	60	10
Ambient Temp, K	288	0.5
Ambient Press, kPa	101.15	0.5
P2 inlet press, kPa	101.15	0.5
T2 inlet temp, K	288	0.5
T24, K	--	--
P24, K	--	--
T3, K	700	0.5
P3, kPa	1900	0.5
P48, kPa	360	0.5
T48, kPa	1039	0.5
T5, K	800	0.5
P5, KPa	102	0.5
Fuel flow, kg/s	0 – 2	2 – 5
Power, MW		0.5
VGV pos	0 – 45	1
Bleed valve pos	0 – 100	1
Speed LPC, RPM	---	
Speed HPC, RPM	11000	1
Speed PT, RPM	3000	0.5
Fuel heating value, MJ/kg	48	2 - 10
Compressor LPC map Wc	-	-
Compressor HPC map Wc	0 - 70	5
HPT turbine Map W	0 – 70	2.5
LPT turbine map W	-	-
PT turbine mapW	0-70	2.5
Water inj. Flow	-	-
Steam inj. Flow	-	-
Fuel split DLN combustors Main, pilot, vacant	-	-

Table 4: Example of the parameters used inside the explicit model for a turbine

5.2 Correlation evaluation among the parameters

It is expected that some parameters should be correlated, like multiple temperature and pressure sensors. This example leads to defining 190 correlation factors (20 x (20-1))/2). This produces, after analysis, a table of correlation factors (table 5). The blue cells represent a strict positive correlation between two parameters (aka sensors) (i.e. + 1); the green shows a highly correlated dependency (> + 0.75), the orange shows a high anti-correlation or negative correlation (< - 0.75).



	Number of parameters used inside the model: 20																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Degree of Freedom	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
[redacted]	1 554.206	98.817	39.072	0.160	4 366.441	36.083	26.958	0.828	37.633	154 499.461	36.031	991.875	1 226.184	36.118	0.160	498.800	48.100	41.124	0.830	0.130
[redacted]	kg/h	rpm	%	%	kW	°C	%	kPa	°C	kg/h	°C	hPa	kPaG	°C	%	°C				
[redacted]	-9.447 16E-04	0.000 0E+00	0.000 0E+00	0.000 0E+00	7.129 85E-09	1.461 25E-06	9.177 01E-04	-1.863 05E-02	1.215 38E-03	0.000 0E+00	-6.400 65E-03	1.889 03E-03	-3.278 85E-04	-6.400 64E-03	0.000 0E+00	-1.023 67E-02	3.906 07E-02	4.112 4E+01	3.172 71E+01	1.300 0E-01
[redacted]	282.85	8.68	7.87	0.29	1620.79	2.46	8.60	0.12	2.81	32562.17	2.30	0.66	236.82	2.29	0.29	52.81	0.29	0.06	0.01	0.01
Parameter	uelFlowPrimar	G_SpeedPerce	uelGasValvePo	BV_25	Gen_power	T_2avg	Rho_0	dP_inlet	T_0	lcExhaustMass	T_2_2	P_0	P_3	T_2_1	IGV_2	T_43avg	sBaseline_AirFl	Turbine_RefFl	Comp_eff	eCoolingAirFra
FuelFlowPrimary	1.000	0.661	0.873	0.000	0.951	0.747	-0.783	0.604	0.799	0.576	0.744	-0.611	0.699	0.752	0.000	0.706	0.000	0.000	0.000	0.000
GG_SpeedPercent	0.661	1.000	0.670	0.000	0.416	0.205	-0.306	0.955	0.309	0.711	0.200	-0.255	0.736	0.222	0.000	0.131	0.000	0.000	0.000	0.000
FuelGasValvePos	0.873	0.670	1.000	0.000	0.833	0.636	-0.701	0.657	0.709	0.854	0.630	-0.572	0.909	0.655	0.000	0.568	0.000	0.000	0.000	0.000
BV_25	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	-1.000	-1.000	-1.000	1.000
Gen_power	0.951	0.416	0.833	0.000	1.000	0.834	-0.847	0.375	0.863	0.478	0.832	-0.664	0.612	0.838	0.000	0.812	0.000	0.000	0.000	0.000
T_2avg	0.747	0.205	0.636	0.000	0.834	1.000	-0.983	0.133	0.979	0.239	0.999	-0.881	0.368	0.996	0.000	0.755	0.000	0.000	0.000	0.000
Rho_0	-0.783	-0.306	-0.701	0.000	-0.847	-0.983	1.000	-0.243	-0.986	-0.352	-0.981	0.897	-0.471	-0.985	0.000	-0.728	0.000	0.000	0.000	0.000
dP_inlet	0.604	0.955	0.657	0.000	0.375	0.133	-0.243	1.000	0.244	0.763	0.128	-0.199	0.773	0.152	0.000	-0.006	0.000	0.000	0.000	0.000
T_0	0.799	0.309	0.709	0.000	0.863	0.979	-0.986	0.244	1.000	0.343	0.979	-0.873	0.467	0.979	0.000	0.742	0.000	0.000	0.000	0.000
TCalcExhaustMassFlo	0.576	0.711	0.854	0.000	0.478	0.239	-0.352	0.763	0.343	1.000	0.230	-0.304	0.961	0.270	0.000	0.156	0.000	0.000	0.000	0.000
T_2_2	0.744	0.200	0.630	0.000	0.832	0.999	-0.981	0.128	0.979	0.230	1.000	-0.879	0.362	0.996	0.000	0.756	0.000	0.000	0.000	0.000
P_0	-0.611	-0.255	-0.572	0.000	-0.664	-0.881	0.897	-0.199	-0.873	-0.304	-0.879	1.000	-0.396	-0.894	0.000	-0.574	0.000	0.000	0.000	0.000
P_3	0.699	0.736	0.909	0.000	0.612	0.368	-0.471	0.773	0.467	0.961	0.362	-0.396	1.000	0.397	0.000	0.288	0.000	0.000	0.000	0.000
T_2_1	0.752	0.222	0.655	0.000	0.838	0.996	-0.985	0.152	0.979	0.270	0.996	-0.894	0.397	1.000	0.000	0.753	0.000	0.000	0.000	0.000
IGV_2	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	-1.000	-1.000	-1.000	1.000
T_43avg	0.706	0.131	0.568	0.000	0.812	0.755	-0.728	-0.006	0.742	0.156	0.756	-0.574	0.288	0.753	0.000	1.000	0.000	0.000	0.000	0.000
GasBaseline_AirFlow	0.000	0.000	0.000	-1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-1.000	0.000	1.000	1.000	1.000	-1.000
HPTurbine_RefFlow	0.000	0.000	0.000	-1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-1.000	0.000	1.000	1.000	1.000	-1.000
Comp_eff	0.000	0.000	0.000	-1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-1.000	0.000	1.000	1.000	1.000	-1.000
rbineCoolingAirFracti	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.000	-1.000	-1.000	-1.000	1.000

Table 5: Example of the parameters used inside the explicit model for a turbine

5.3 Evaluation of the additional uncertainties for each parameter

This standard deviation is not the only value to consider in the uncertainty calculation for a parameter; we need to consider the following elements:

1) **Repeatability** is the measurement precision under a set of repeatable conditions.

2) **Reproducibility** is different from repeatability because you need to change something (a variable) in your measurement process.

3) **Stability** over the years (usually looking at the last 3 yearly calibration reports). It is a random error do not confuse it with drift.

4) **Bias** Analysis is a systematic error rather than uncertainty. It informs about how accurately your measurements are compared to the target value.

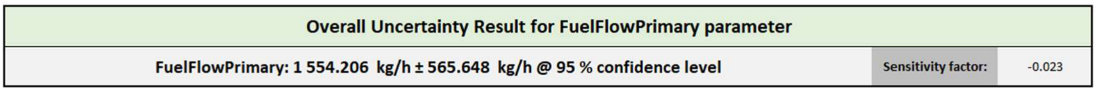
5) **Drift** over the years (usually over the last 3 years) determines how the error in the measurement process changes over time (variation per day between calibrations). It is not a random error but a systematically increasing error.

6) **Resolution** is the smallest change in a quantity being measured, that causes a perceptible change in the corresponding indication.

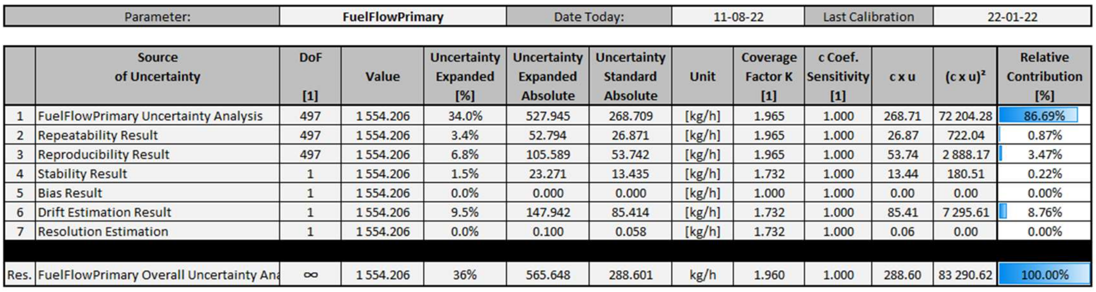
An example is given in table 6. The parameter review is the fuel flow primary over a recording period. The value given above has been introduced and then the variance has been estimated for each source of uncertainty and then the overall uncertainty is in line with the ISO 5168 [1] and GUM [3].

Note: The set of data used is a dummy file and then the absolute value is not the most important one. For confidentiality reasons, we show the process, and briefly, some real data are presented later.

The process, as explained in [1] and [3], should follow a matrix analysis. The input data have been introduced (left column in table 6), and the standard uncertainty was evaluated based on the distribution (such as Z distribution, uniform distribution) aka coverage factor in table 6. The coefficient of sensitivity is defined as explained in the previous sections then the impact can be established for each source of uncertainty. The variance for each parameter and the overall variance can be estimated based on the sum of the square standard uncertainty. The next step is the evaluation of the standard and expanded uncertainty for the studied parameter, which is obtained by doing the reverse process with a coverage factor of 1.960 and a coefficient sensitivity equal to 1. A relative contribution from each identified source of error highlights the major contributor (last column on the right in table 6), and this is quite important in the maintenance program to have in place for the entire system to spot quickly what are the major contributors. Finally, the statement on the overall uncertainty can be made for this given parameter. This will be repeated for the 20 identified parameters in this example.



Overall Uncertainty Result for FuelFlowPrimary parameter		
FuelFlowPrimary: 1 554.206 kg/h ± 565.648 kg/h @ 95 % confidence level	Sensitivity factor:	-0.023



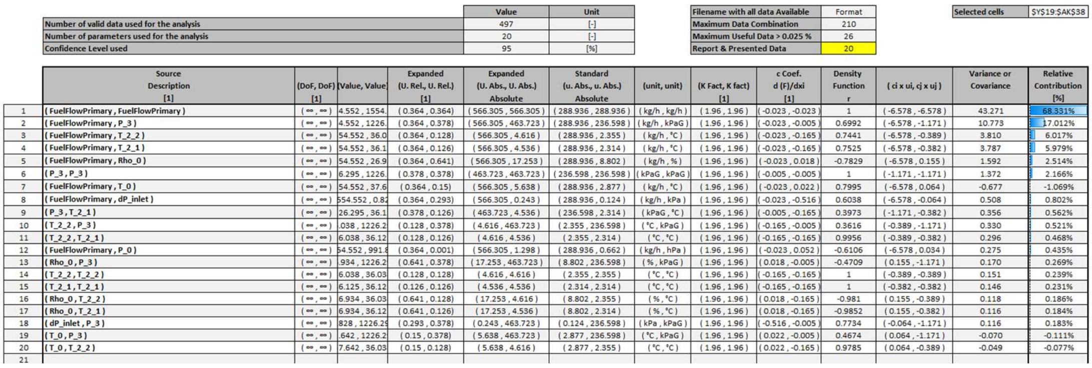
Parameter:	FuelFlowPrimary	Date Today:	11-08-22	Last Calibration	22-01-22

	Source of Uncertainty	DoF [1]	Value	Uncertainty Expanded [%]	Uncertainty Expanded Absolute	Uncertainty Standard Absolute	Unit	Coverage Factor K [1]	c Coef. Sensitivity [1]	c x u	(c x u)²	Relative Contribution [%]
1	FuelFlowPrimary Uncertainty Analysis	497	1 554.206	34.0%	527.945	268.709	[kg/h]	1.965	1.000	268.71	72 204.28	86.69%
2	Repeatability Result	497	1 554.206	3.4%	52.794	26.871	[kg/h]	1.965	1.000	26.87	722.04	0.87%
3	Reproducibility Result	497	1 554.206	6.8%	105.589	53.742	[kg/h]	1.965	1.000	53.74	2 888.17	3.47%
4	Stability Result	1	1 554.206	1.5%	23.271	13.435	[kg/h]	1.732	1.000	13.44	180.51	0.22%
5	Bias Result	1	1 554.206	0.0%	0.000	0.000	[kg/h]	1.000	1.000	0.00	0.00	0.00%
6	Drift Estimation Result	1	1 554.206	9.5%	147.942	85.414	[kg/h]	1.732	1.000	85.41	7 295.61	8.76%
7	Resolution Estimation	1	1 554.206	0.0%	0.100	0.058	[kg/h]	1.732	1.000	0.06	0.00	0.00%
Res.	FuelFlowPrimary Overall Uncertainty Ana	∞	1 554.206	36%	565.648	288.601	kg/h	1.960	1.000	288.60	83 290.62	100.00%

Table 6: Presentation of the result for a parameter

5.4 Typical outcome of the entire analysis

Table 7 shows that there is sometimes no correlation between the measurement and then the problem can be reduced from over 190 correlation factors to something much more reasonable in size with 20 to 30 correlation factors to consider. In this dummy example, only 25 had an impact higher than ± 0.025 % of the overall uncertainty. Table 7 presents only the 20 first of them (arbitrarily selected). What is important to review from this table is the contribution of the multiple combinations as presented on the right side and ranked from the highest contributor (top) to the lowest selected (i.e. 20 lines here). The main contributor (first line) is the FuelFlowPrimary variance, which is representing over 68 % of the overall uncertainty (right column). The second major contributor is the FuelFlowPrimary associated with the Pressure P_3, this set represents over 17 % of the overall uncertainty. The last one (20th contributor) presented is the temperature T_0 associated with T_2_2 and the set is contributing to – 0.077 %. This effort to make a ranking allows focusing on the most important parameters in the development of a maintenance plan to reduce the overall uncertainty.



	Value	Unit
Number of valid data used for the analysis	497	[-]
Number of parameters used for the analysis	20	[-]
Confidence Level used	95	[%]

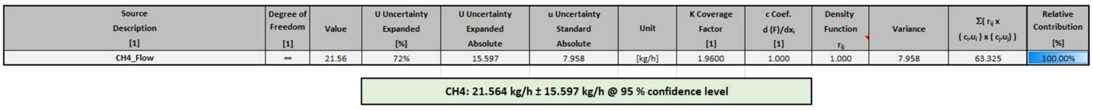
Filename with all data Available	Format
Maximum Data Combination	210
Maximum Useful Data > 0.025 %	26
Report & Presented Data	20

Selected cells	$Y$19:$AK$38

	Source Description [1]	(DoF, DoF) [1]	(Value, Value)	Expanded (U. Rel., U. Rel.) [1]	Expanded (U. Abs., U. Abs.) Absolute	Standard (u. Abs., u. Abs.) Absolute	(unit, unit)	(K Fact, K fact) [1]	c Coef. d (F)/dxi [1]	Density Function r	(ci x ui, cj x uj)	Variance or Covariance	Relative Contribution [%]
1	(FuelFlowPrimary , FuelFlowPrimary)	(∞ , ∞)	4.552 , 1554.	(0.364 , 0.364)	(566.305 , 566.305)	(288.936 , 288.936)	(kg/h , kg/h)	(1.96 , 1.96)	(-0.023 , -0.023)	1	(-6.578 , -6.578)	43.271	68.331%
2	(FuelFlowPrimary , P_3)	(∞ , ∞)	4.552 , 1226.	(0.364 , 0.378)	(566.305 , 463.723)	(288.936 , 236.598)	(kg/h , kPaG)	(1.96 , 1.96)	(-0.023 , -0.005)	0.6992	(-6.578 , -1.171)	10.773	17.012%
3	(FuelFlowPrimary , T_2_2)	(∞ , ∞)	54.552 , 36.0	(0.364 , 0.128)	(566.305 , 4.616)	(288.936 , 2.355)	(kg/h , °C)	(1.96 , 1.96)	(-0.023 , -0.165)	0.7441	(-6.578 , -0.389)	3.810	6.017%
4	(FuelFlowPrimary , T_2_1)	(∞ , ∞)	54.552 , 36.1	(0.364 , 0.126)	(566.305 , 4.536)	(288.936 , 2.314)	(kg/h , °C)	(1.96 , 1.96)	(-0.023 , -0.165)	0.7525	(-6.578 , -0.382)	3.787	5.979%
5	(FuelFlowPrimary , Rho_0)	(∞ , ∞)	54.552 , 26.9	(0.364 , 0.641)	(566.305 , 17.253)	(288.936 , 8.802)	(kg/h , %)	(1.96 , 1.96)	(-0.023 , 0.018)	-0.7829	(-6.578 , 0.155)	1.592	2.514%
6	(P_3 , P_3)	(∞ , ∞)	6.295 , 1226.	(0.378 , 0.378)	(463.723 , 463.723)	(236.598 , 236.598)	(kPaG , kPaG)	(1.96 , 1.96)	(-0.005 , -0.005)	1	(-1.171 , -1.171)	1.372	2.166%
7	(FuelFlowPrimary , T_0)	(∞ , ∞)	54.552 , 37.6	(0.364 , 0.15)	(566.305 , 5.638)	(288.936 , 2.877)	(kg/h , °C)	(1.96 , 1.96)	(-0.023 , 0.022)	0.7995	(-6.578 , 0.064)	-0.677	-1.069%
8	(FuelFlowPrimary , dP_inlet)	(∞ , ∞)	554.552 , 0.82	(0.364 , 0.293)	(566.305 , 0.243)	(288.936 , 0.124)	(kg/h , kPa)	(1.96 , 1.96)	(-0.023 , -0.516)	0.6038	(-6.578 , -0.064)	0.508	0.802%
9	(P_3 , T_2_1)	(∞ , ∞)	26.295 , 36.1	(0.378 , 0.126)	(463.723 , 4.536)	(236.598 , 2.314)	(kPaG , °C)	(1.96 , 1.96)	(-0.005 , -0.165)	0.3973	(-1.171 , -0.382)	0.356	0.562%
10	(T_2_2 , P_3)	(∞ , ∞)	.038 , 1226.2	(0.128 , 0.378)	(4.616 , 463.723)	(2.355 , 236.598)	(°C , kPaG)	(1.96 , 1.96)	(-0.165 , -0.005)	0.3616	(-0.389 , -1.171)	0.330	0.521%
11	(T_2_2 , T_2_1)	(∞ , ∞)	6.038 , 36.12	(0.128 , 0.126)	(4.616 , 4.536)	(2.355 , 2.314)	(°C , °C)	(1.96 , 1.96)	(-0.165 , -0.165)	0.9956	(-0.389 , -0.382)	0.296	0.468%
12	(FuelFlowPrimary , P_0)	(∞ , ∞)	54.552 , 991.8	(0.364 , 0.001)	(566.305 , 1.298)	(288.936 , 0.662)	(kg/h , hPa)	(1.96 , 1.96)	(-0.023 , 0.052)	-0.6106	(-6.578 , 0.034)	0.275	0.435%
13	(Rho_0 , P_3)	(∞ , ∞)	.934 , 1226.2	(0.641 , 0.378)	(17.253 , 463.723)	(8.802 , 236.598)	(% , kPaG)	(1.96 , 1.96)	(0.018 , -0.005)	-0.4709	(0.155 , -1.171)	0.170	0.269%
14	(T_2_2 , T_2_2)	(∞ , ∞)	6.038 , 36.03	(0.128 , 0.128)	(4.616 , 4.616)	(2.355 , 2.355)	(°C , °C)	(1.96 , 1.96)	(-0.165 , -0.165)	1	(-0.389 , -0.389)	0.151	0.239%
15	(T_2_1 , T_2_1)	(∞ , ∞)	6.125 , 36.12	(0.126 , 0.126)	(4.536 , 4.536)	(2.314 , 2.314)	(°C , °C)	(1.96 , 1.96)	(-0.165 , -0.165)	1	(-0.382 , -0.382)	0.146	0.231%
16	(Rho_0 , T_2_2)	(∞ , ∞)	6.934 , 36.03	(0.641 , 0.128)	(17.253 , 4.616)	(8.802 , 2.355)	(% , °C)	(1.96 , 1.96)	(0.018 , -0.165)	-0.981	(0.155 , -0.389)	0.118	0.186%
17	(Rho_0 , T_2_1)	(∞ , ∞)	6.934 , 36.12	(0.641 , 0.126)	(17.253 , 4.536)	(8.802 , 2.314)	(% , °C)	(1.96 , 1.96)	(0.018 , -0.165)	-0.9852	(0.155 , -0.382)	0.116	0.184%
18	(dP_inlet , P_3)	(∞ , ∞)	828 , 1226.29	(0.293 , 0.378)	(0.243 , 463.723)	(0.124 , 236.598)	(kPa , kPaG)	(1.96 , 1.96)	(-0.516 , -0.005)	0.7734	(-0.064 , -1.171)	0.116	0.183%
19	(T_0 , P_3)	(∞ , ∞)	.642 , 1226.2	(0.15 , 0.378)	(5.638 , 463.723)	(2.877 , 236.598)	(°C , kPaG)	(1.96 , 1.96)	(0.022 , -0.005)	0.4674	(0.064 , -1.171)	-0.070	-0.111%
20	(T_0 , T_2_2)	(∞ , ∞)	7.642 , 36.03	(0.15 , 0.128)	(5.638 , 4.616)	(2.877 , 2.355)	(°C , °C)	(1.96 , 1.96)	(0.022 , -0.165)	0.9785	(0.064 , -0.389)	-0.049	-0.077%
21													

Table 7: Calculation of the standard and overall uncertainty for the parameter

Combining all information described previously leads to the final statement about the uncertainty either on the mass flow or in concentration (ppm) of methane, as presented in table 8.



Source Description [1]	Degree of Freedom [1]	Value	U Uncertainty Expanded [%]	U Uncertainty Expanded Absolute	u Uncertainty Standard Absolute	Unit	K Coverage Factor [1]	c Coef. d (F)/dx$_i$ [1]	Density Function r$_{ij}$	Variance	Σ(r$_{ij}$ x (c$_i$.u$_i$) x (c$_j$.u$_j$))	Relative Contribution [%]
CH4_Flow	∞	21.56	72%	15.597	7.958	[kg/h]	1.9600	1.000	1.000	7.958	63.325	100.00%

CH4: 21.564 kg/h ± 15.597 kg/h @ 95 % confidence level

Table 8: Statement about the uncertainty on the CH_4 emissions either in mass flow rate or concentration following the analysis.

6 FIELD RESULTS

6.1 Overview of the problematic

A recording versus time is presented for the methane flow rate (figure 4) and the concentration (figure 5) with different loadings of the turbine.

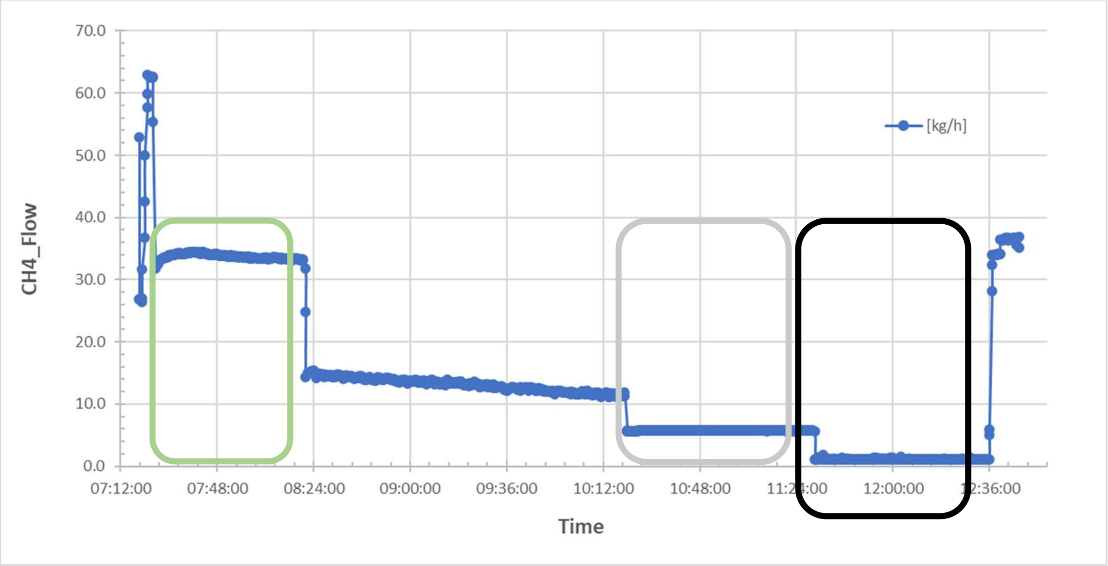


Figure 4: CH4 flow rate emission estimation from the WS PEMS versus time.

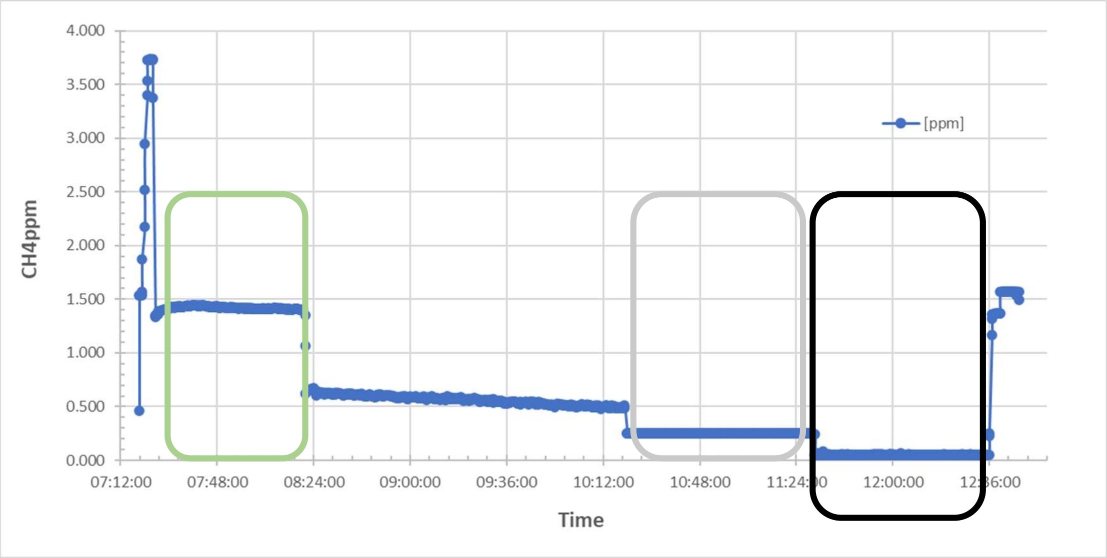


Figure 5: CH4 concentration emission estimation from the WS PEMS versus time.

The full analysis, as explained in the previous chapter was made for the CH_4 concentration and mass flow rates. The data are summarised below first in terms of concentration (ppm gas emission) in table 9, and then in terms of flow rates in table 10. The expanded uncertainties are given at a 95 % confidence level.

CH_4 Concentration	**Average Value**	**Expanded Uncertainty Absolute**	**Expanded Uncertainty Relative**	**Standard Deviation Absolute**
-	**[ppm]**	**[ppm]**	**[%]**	**[ppm]**
Low Load 2.7 MW	1.422	± 0.013	± 0.86	± 0.006(2)
Medium Load 8.2 MW	0.251	± 0.003	± 0.83	± 0.001(1)
High Load 11.0 MW	0.051	± 0.005	± 8.60	± 0.002(2)

Table 9: Statement about the methane emission concentration and uncertainty for 3 cases analysed.

CH_4 Flow Rate	**Average Value**	**Expanded Uncertainty Absolute**	**Expanded Uncertainty Relative**	**Standard Deviation Absolute**
-	**[kg/h]**	**[kg/h]**	**[%]**	**[kg/h]**
Low Load 2.7 MW	33.788	± 0.566	± 1.67	± 0.288(7)
Medium Load 8.2 MW	5.705	± 0.045	± 0.78	± 0.022(7)
High Load 11.0 MW	1.142	± 0.099	± 8.62	± 0.050(2)

Table 10: Statement about the methane mass flow rate emission and uncertainty for 3 cases analysed

7 CONCLUSIONS

To provide relevant uncertainty for a PEMS model, a significant effort needs to be spent on the review of performing each parameter involved in the methane's calculation of gas emissions. The models used in PEMS are in general highly nonlinear and implicit, this leads to a hybrid analysis of the uncertainty (i.e. Type A and B together). A specific development was made inside the WS PEMS model to address this point.

The analysis was made based on the theoretical information available and some practical measurements to quantify some of these effects. The WS PEMS can reach an uncertainty on the CH_4 mass flow rate measurement within ± 1.65 % – ± 8.62 % following the loading; and an overall CH_4 concentration uncertainty below ± 0.86 % to ± 8.60 % with value, in terms of absolute CH_4 emission, within 0.05 ppm to 1.142 ppm, which is exceptionally low. All uncertainties are given with a 95 % confidence level.

Weel and Sandvig's modelling is in line with the performance specification — PS16—. The analysis made showed that the WS PEMS was in line with the REMS. The WS PEMS uses multiple combinations of models that allow for the identification of the faulty sensors and then avoid using this info, associated with a weighing analysis for the final estimation of the gas emissions. This is the cornerstone of the WS PEMS development.

Last but not the least, there is a tendency to shortcut the analysis of the overall uncertainties given by a complex system (multiple measurement devices). The covariance factors can have a significant impact and should not be disregarded in such a process. This report is based on a complete analysis as per the GUM recommendations. This states what the PEMS uncertainty is achievable based on physical models and the pitfalls to avoid for relevant claims for the oil and gas industry.

8 REFERENCE

[1] ISO 5168:2005 Measurement of fluid flow – Procedures for the evaluation of uncertainties

[2] MPMS Chap. 14.10 Natural Gas Fluids Measurement – measurement of Flow to Flares.

[3] Guide to the Expression of uncertainty measurement 2020 – BIPM –

[4] Performance Specification 16 – Specification and test procedures for predictive emission monitoring systems in stationary sources

9 ACKNOWLEDGMENT

This works and the extended study associated with this analysis has been possible thanks to the financial support and data availability from bp.