Application of continuous emissions measurement systems (CEMS) for the determination of CO_2 emissions

Experience and assessments by the German Emissions Trading Authority (DEHSt)

Umwelt Bundesamt

DEHSt
Deutsche
Emissionshandelsstelle

Editorial information

Publisher
German Emissions Trading Authority (DEHSt)
at the German Environment Agency
Bismarckplatz 1
D-14193 Berlin
Phone: +49 (0) 30 89 03-50 50
Fax: +49 (0) 30 89 03-50 10
emissionstrading@dehst.de
Internet: www.dehst.de/EN

Authors
Holger Göttel (V 2.1), Burkhard Lenzen (V 3.2) and Christian Schneider (V 3.1)

Status: November 2019

Cover image: Tkemot/Shutterstock.com

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Abbreviations

AMS	Automatic measurement system
AST	Annual surveillance test
BeP	Uniform nationwide practice for monitoring emissions
BImSchG	Federal Immission Control Act
BAT	Best available technology
CO_2	Carbon dioxide
DEHSt	German Emissions Trading Authority
EU ETS	Europen Emissions Trading Scheme
FTIR	Fourier Transformation Infrared Spectrometer
IED	Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions
CEMS	Continuous emission monitoring system
STA	Short-term average
MRR	Monitoring & Reporting Regulation
N_2O	Nitrous oxide
NDIR	Non-dispersive infrared sensor
QAL	Quality Assurance Level
SRM	Standard reference measurement method
TDLS	Diode laser spectroscopy
GHG	Greenhouse Gas

1 Introduction

In this report, we describe various experiences with the use of CEMS to monitor CO_2 emissions from stationary installations in the EU ETS. They are based on monitoring German installations and, apart from applications for CO_2, also consider applications for nitrous oxide (N_2O). In addition, we also rely on several international publications on the subject.

Chapter 3 gives an overview of the legal requirements using CEMS for monitoring GHG emissions under the scope of EU-ETS. In addition, Chapter 4 sets out the basic differences between the registration and calculation of emission data compared to the regulations for monitoring of classic air pollutants.

Chapter 5 summarizes the experience of using CEMS in the EU ETS. It will be both specific problems and solutions as well as fundamental aspects when using CEMS are shown and discussed. Furthermore, the two methods calculation and KEMS are compared. Therefor some international publications on this topic are mentioned.

Finally, we give initial assessments about the advantages and disadvantages of using CEMS and the official verification of emission data about CEMS. These serve as a possible orientation basis for a decision on the correct choice of determination method against a background of special framework conditions and requirements for monitoring and reporting emissions.

2 Brief introduction to the development of continuous emission monitoring

At the European level, the IE Directive [1] is the most important European regulatory basis for the approval and operation of industrial installations. In particular it aims at harmonising environmental standards in Europe and thereby create fairer conditions with regard to competition. One of the major improvements compared to the predecessor directive is the strengthening of the "BAT" BREFs, which contain regulations on "Best Available Techniques" in the fields of industrial installations with particular environmental relevance. The BAT conclusions being the key results of the establishment of the individual BAT reference documents have been adopted at European level in a separate procedure under the IE Directive and published in the Official Journal of the EU. This will enhance the compulsory nature of the authorisation of environmentally friendly and innovative techniques at the European level. In order to ensure implementation into German law, the existing authorisations to issue ordinances and administrative provisions were supplemented and extended (German Environment Agency, 2019). The 13th Ordinance on the Implementation of the Federal Immission Control Act (BImSchG) [2] translates the IE Directive's requirements for large combustion plants (e. g. thermal power plants) into national law. The "Bundeseinheitliche Praxis bei der Überwachung der Emissionen" (BeP, Uniform nationwide practice for monitoring emissions) has been published in Germany for the evaluation of the emission data [3], which is a national administrative provision for the proper application of CEMS. Due to the diverse immission control regulations for the continuous of air pollutants and the associated automatic evaluation of the collected data, the Federal / State Association for Pollution Control (LAI) has assisted to compile these requirements with the title "Continuous emission monitoring – status identification and classification "(SKK) [4].

Continuous emission monitoring has also played a role in European emissions trading (EU ETS) since the beginning of the 3rd trading period in 2013. In addition to the calculation approach, it is one of two methods used to determine greenhouse gas emissions. The EU ETS is the key climate policy instrument in Europe that can cost-effectively reduce greenhouse gas emissions from energy and industrial plants and from aviation within Europe.

Emissions trading only works if all parties involved trust it. This requires a complete, consistent, error-free and transparent monitoring, reporting and verification system. Both parties, the company and the state, must be sure that one tonne of CO_2 is reported for the emission of one tonne of CO_2 – "A tonne must be a tonne!". The calculation approach uses the principle of mass conservation. The CO_2 emissions are determined based on the material/fuel input used, its carbon content and the stoichiometric conversion factor of 3.664 t CO_2/t C. In contrast to the calculation approach, direct continuous emission measurement (CEMS) continuously determines the CO_2 concentration and the flue gas volume flow rate in the chimney or flue gas duct using an automatic measurement system (AMS). The CO_2 mass flow rate can be obtained by multiplying the two quantities measured. Further multiplication by time (e. g. operating time) yields the absolute CO_2 emissions in the respective baseline period.

The German Emissions Trading Authority at the German Environment Agency (DEHSt) is the national authority in Germany for monitoring European emissions trading and installations participating in emissions trading.

3 Use of CEMS to monitor greenhouse gas emissions in EU ETS

3.1 Requirements for CEMS according to the Monitoring & Reporting Regulation

The legal basis for monitoring greenhouse gases within the framework of European emissions trading is the European Monitoring & Reporting Regulation (MRR, EU No. 601/2012) [5]. According to Article 40(2) MRR, operators of stationary installations are entitled to monitor all CO_2 emissions for all emission sources of an installation using CEMS if certain requirements are met.

The MRR specifies various tiers for all determination methods in order to provide operators with emission-dependent accuracy specifications, i. e. the higher the emissions from an installation, the higher the accuracy requirements for the emission determination of the installation. The tier concept is intended to enable cost-efficient CO_2 monitoring where the operator has competent authority approved in a plant-specific monitoring plan.

Operators using CEMS must meet the highest tier (uncertainty for the determination of the CO_2 mass flow rate: tier 4 < 2.5%) for emission sources with emissions of

- more than 5,000 t CO_2 or
- more than 10% (maximum 100,000 t CO_2) of the total emissions of the installation.

Deviation from this requirement is possible provided that the operator can demonstrate that both the fulfilment of the tier requirement and the highest tier calculation result in disproportionate costs or are technically impossible. As a minimum, however, tier 1 shall be complied with.

Table 1: Accuracy requirements and uncertainty thresholds for CEMS in the EU ETS

	Tier 1	Tier 2	Tier 3	Tier 4
CO_2 emissions sources	10%	7.5%	5%	2.5%
N_2O emissions sources	10%	7.5%	5%	–

3.2 Requirements for quality assurance of CEMS

In accordance with the Article 43 MRR stipulations, various options are available for recording CO_2 emissions using CEMS. The CO_2 concentration in the flue gas flow can be determined by direct measurement using calibrated AMS and by indirect measurement in cases of high concentration[1]. The flue gas volume flow rate can also be determined by direct volume flow rate measurement using calibrated AMS or by indirect measurement based on a suitable mass balance approach[2]. Direct measurements of both CO_2 concentration and flue gas volume flow rate are clearly preferred in the applications installed to date.

The emission measurement systems for determining the annual emission quantities of greenhouse gases (GHG) shall be operated under continuous application of the EN 14181 quality assurance measures (Stationary source emissions – Quality assurance of automated measuring systems) [6] and EN 15259 (Air quality – Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report) [7]. The calibration according to EN 14181 and the selection of the measurement point (or the measurement cross-section) according to EN 15259 shall be performed according to the requirements of Article 42(2) MRR by testing and calibration laboratories that are accredited according to EN ISO/IEC 17025 [8] for the relevant testing and calibration procedures or are to be regarded as equivalent within the meaning of Article 34(2 and 3) MRR.

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[1] The CO_2 concentration results from the difference of all other measured concentrations to 100%.

[2] The mass balance approach usually determines the flue gas volume by the combustion air supplied and the gas composition in the flue gas flow.

Test methods according to ISO 12039 (Emissions from stationary sources – Determination of carbon monoxide, carbon dioxide and oxygen – Process parameters and calibration of automatic measurement systems) [9] shall preferably be used for the calibration of the CO_2 concentration measurand. The standards EN ISO 16911-1 (Stationary source emissions – Manual and automatic determination of velocity and volume flow rate in flue gas ducts, Part 1 "Manual reference method") [10] and 16911-2 (Part 2 "Continuous measurement methods") [11] shall be applied to the calibration of the flue gas volume flow rate parameter. The water vapour content in the flue gas shall be determined in accordance with the requirements of EN 14790 [12].

In order to ensure that the measuring instruments determine emission quantities sufficiently accurately, they must be suitable for the respective application, correctly installed, regularly calibrated and checked for their function on a regular basis.

Table 2: Quality assurance for CEMS

	Certification of automatic measuring systems (AMS)	Installation, calibration and validation of AMS	Continuous quality assurance of AMS in operation
Quality assurance level (QAL) according to EN 14181	Suitability testing and certification (QAL1)	Installation, calibration (QAL2) and annual surveillance test (AST)	Drift and precision controls (QAL3)
Test interval	One-off (suitability test) and after major changes (supplementary test)	Installation: one-off (or after major changes to the installation or the AMS) QAL2: every 3 years (or after major modifications to the facility or the AMS or in the event of failed validation test under AST) AST: annually	4 hours – 12 months (depending on the length of the field tests and the results on drift behaviour within the QAL1)
Relevant standards	EN 14181 EN ISO 14956 EN 15267-1, -2, -3	EN 14181 EN ISO 16911-1, -2 EN 15259 ISO 12039 EN 14790	EN 14181 EN ISO 16911-1, -2 EN 15259 ISO 12039 EN 14790
Responsibility	Testing institutes accredited for suitability testing	Accredited testing and calibration laboratories	Operators

3.2.1 Suitability testing (QAL1)

The suitability testing of continuous measurement and evaluation equipment is carried out in Germany by accredited verifiers and announced by the German Environment Agency. If relevant changes are made to the notified measurement equipment (e. g. software changes), these shall be accepted within the framework of a (simplified) supplementary test. Notices of changes to measurement and evaluation equipment already announced shall be published accordingly.

The certificates of the measurement equipment currently QAL1-approved can be downloaded from the website https://qal1.de/en/index.htm.

The expanded measurement uncertainty determined in the course of the suitability test must be shown for each certified measurand in the QAL1 certificate. According to EN 15267-3 [13], the requirement for the expanded uncertainty of a measurand is 75% of the permissible expanded uncertainty as specified in Directive 2010/75/EU (confidence interval of 95%), related to the target certification range (permissible measurement range). Directive 2010/75/EU does not specify any confidence interval for flue gas volume flow rate and CO_2 concentration, as these are regarded as baseline values in the monitoring of air pollutants. For the CO_2 measurand, the stipulation for the measurand carbon monoxide (CO) is generally used for the assessment of basic suitability.

In addition to EN 15267, EN ISO 14956 [14] must also be taken into account when determining the measurement uncertainty within the scope of QAL1. Among other things, EN ISO 14956 specifies procedures for determining the uncertainty of measurement results using relevant process parameters of the measurement procedure.

3.2.2 Installation, calibration (QAL2) and annual surveillance test (AST)

Suitability-tested measuring and evaluation equipment may be used exclusively to monitor emissions from installations subject to emissions trading. After the initial installation of an AMS or after major modifications to an AMS or to the measuring location, the existence of a corresponding product conformity (QAL1) with the requirements of EN 15267-1, -2, -3 and EN 14181 must be checked against the framework of inspection of the correct installation from a testing and calibration laboratory notified in accordance with § 29b BImSchG [15]. The stipulations of EN 15259 must also be observed when installing the measuring equipment and reference measurement points. The on-site conditions and compliance with the requirements for the installation of the AMS and the reference measurement points for the calibration of the AMS shall be documented in the form of a standardized sample report by testing and calibration laboratories notified in accordance with § 29b BImSchG. As a result, the proper installation can be confirmed using this report if all requirements are met.

Deviations from the requirements shall be described and their influence explained in the installation report. If necessary, the certificate of proper installation shall be restricted or refused so that the measuring instruments or measuring location must be upgraded.

The calibration (QAL2) of the properly installed AMS shall be regularly performed by accredited test laboratories according to EN ISO 17025 or equivalent. At least 15 comparative measurements shall be performed between the AMS permanently installed at the emission source and the (mobile) standard reference measurement methods (SRM) of the test laboratories. A calibration function (regression line) is calculated for each measurand from the comparative measurements between AMS and SRM in accordance with Chapter 6 of DIN EN 14181. They will be used to convert the AMS raw values to be determined in the future [in the unit of mA] into physical measured values [e. g. % by vol. CO_2] (see Figure 3 and Figure 4). The measuring signal of the AMS is thus corrected by the calibration factors from the measured values of the SRM recorded at the same time and traced back to a uniform international standard. A calibration of baseline quantities (e. g. flue gas temperature) is not required but is recommended to minimise the uncertainties of the standardised measured values of the measurands.

In addition to a functional check of the AMS and within the scope of the annual surveillance test (AST), the continued validity of the previous QAL2 performed is also checked by at least 5 comparative measurements with the SRM.

3.2.3 Ongoing quality control (QAL3)

The operator is responsible for the ongoing quality control during the operation of the calibrated AMS. Drift and precision checks are carried out at the zero point and at the reference point of all AMSs involved. Drift and precision according to Chapter 7.2 of EN 14181 can either be tested combined or separately. Both procedures are designed in such a way that adjustment, maintenance or repair and, if necessary, recalibration of the AMS must be carried out if there is a deviation from the AMS process parameters determined in the suitability test or from the maximum permissible uncertainty from corresponding EU directives.

3.3 Measuring methods and equipment to determine CO_2 emissions in the EU ETS from guided sources

Most CEMS applications used in stationary installations include the following basic components:

- a CO_2 analyser,
- a flue gas velocity measurement to determine the flue gas volume flow rate,
- a flue gas temperature measurement, an absolute pressure measurement and optionally a measurement for determining the water vapour content in the flue gas, positioned at the same location as the sampling for determining the CO_2 concentration and the flue gas volume flow rate in the same reference state (dry or moist under normal conditions (1,013.25 bar and 273.15 K),
- and an automatic data acquisition and processing system for the evaluation of emission data.

The flue gas volume flow rate is typically calculated by multiplying the average flue gas velocity by the measurement cross-sectional area. The achievable measurement accuracy of permanently installed velocity measurements depends on how they are positioned and aligned in the measurement cross-section. The measurements should be positioned to provide a representative average flue gas velocity across the measurement cross section (i. e. arrangement of measurement sections with sufficient undisturbed inlet and outlet sections, positioning outside areas of laminar flow or turbulence and air leaks).

The measurement of CO_2 concentration and flue gas velocity for calculating the flue gas volume flow rate usually takes place at different reference conditions. The data must therefore be converted to the same reference states in order to be able to calculate the CO_2 quantity from an emission source. Figure 1 shows various arrangements regarding the required corrections of the flue gas volume flow rate based on the existing reference state of the GHG concentration.

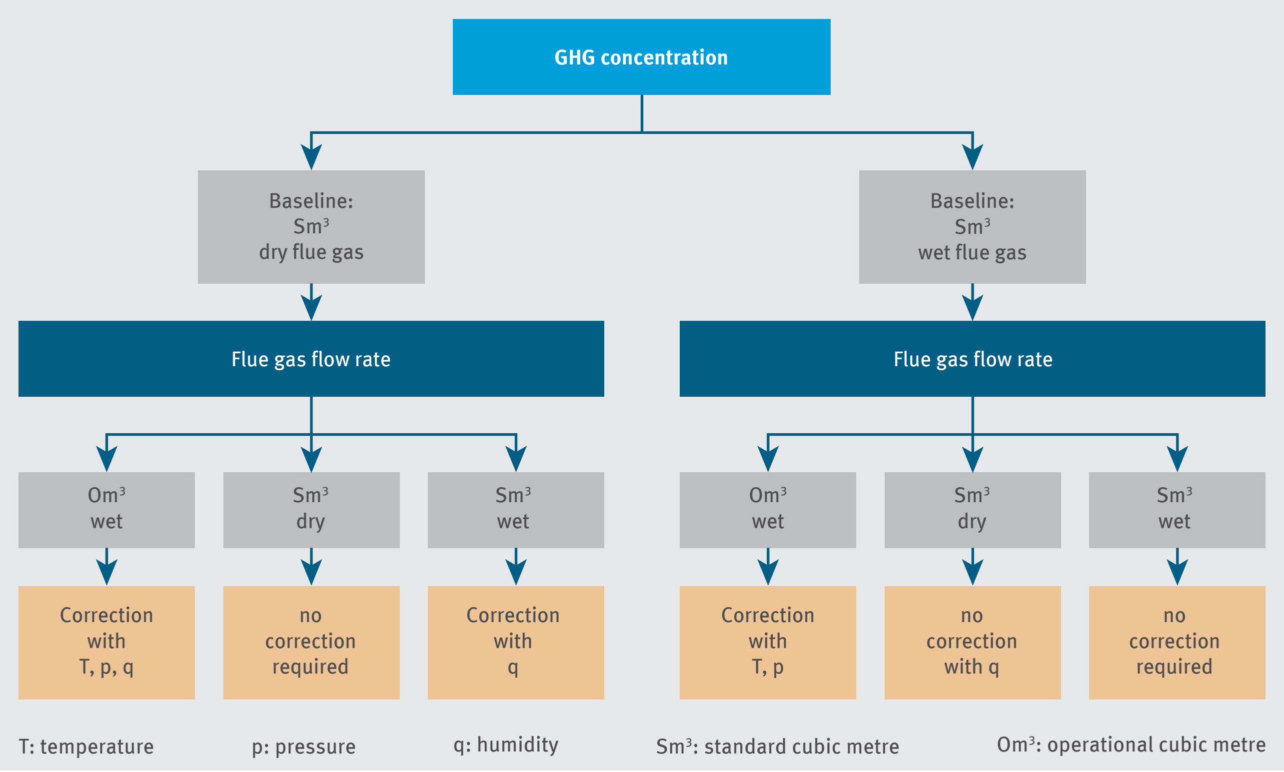

Figure 1: Evaluation scheme for the continuously recorded emission data

3.3.1 Status of measurement technology used in combustion plants (gaseous air pollutants and flue gas boundary parameters)

When solid fuels are used in large combustion plants, as a minimum the mass concentrations of the gaseous air pollutants NO_X, SO_2 and CO in the flue gas shall be continuously determined in accordance with 13th BImSchV. In addition to the pollutant components to be monitored, the volume fraction of O_2 required for the reference value calculation shall be determined in parallel. Also, at least the reference values (flue gas boundary parameters), flue gas temperature, flue gas volume flow rate and absolute pressure shall be determined in order to assess the proper operation. The continuous determination of water vapour concentration in the flue gas may be omitted under certain conditions (e. g. if the water vapour concentration in the flue gas is to be regarded as "constant" after a flue gas desulphurisation unit).

In large combustion plants, individual component analysers are frequently used to monitor emissions in clean gas. This is presumably due to the limited number of flue gas components to be continuously monitored which usually leads to the use of the more economical "cold measurement technique"[3]. Measurement of water vapour content was and is not absolutely necessary in the flue gas of thermal power plants. In order to determine the sulphur separation efficiency of the flue gas desulphurisation process in power plants, the SO_2 concentrations in the raw gas must also be determined. "Hot gas measurements" or in-situ measuring instruments are often used here due to the flue gas composition and measuring conditions.

In contrast, hot gas multi-component analysers have been used in waste incineration plants to monitor emissions for many years. This is connected to the requirement for continuous monitoring of additional air pollutants e. g. HCl, which can only be determined using "hot gas" or in-situ measuring instruments.

3.3.2 Suitability and scopes of various measurement methods at stationary sources

The CO_2 emissions in flue gases from stationary installations are determined by infrared spectrometry. Analysers using a non-dispersive infrared sensor (NDIR) are widely used. A distinction has to be made between simple designs with a two-cuvette arrangement and devices that operate according to the gas filter correlation principle. The gas filter correlation method is particularly suitable for minimising any cross sensitivities (due to water vapour in the sample). Newer multi-component analysers use a Fourier transform infrared spectrometer (FTIR). Diode laser spectroscopy (TDLS) is used in in-situ measuring instruments. From our point of view, the aforementioned measuring principles and designs are equally suitable to determine CO_2 concentration sufficiently accurately. The choice of the analyser depends largely on the field of application (i. e. specifically in flue gas conditions) and the installation location.

The flue gas velocity can be determined using for instance

- ultrasonic travel time difference measurement,
- dynamic pressure measurement or
- an impeller anemometer.

The first two measurement methods are most commonly used in incineration plants.

The following table gives an overview of the advantages and disadvantages of the aforementioned measuring principles.

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[3] A sampling probe enables a partial flow of the flue gas to be sampled, cooled down for drying and analysed.

Table 3: Advantages and disadvantages of various measuring methods for determining the flue gas velocity in ducts and smokestacks

	Advantages	Disadvantages
Ultrasound run time difference measurements	▸ Measurement possible below condensation point and at high dust loads ▸ High measuring accuracy even at low velocities	▸ No available external traceable test standard
Dynamic pressure measurement	▸ Low investment costs ▸ Measurement possible at high flue gas temperatures ▸ Simple execution of grid measurements ▸ Transducer's reference point check (QAL3) possible with traceable test standard	▸ Susceptible to deposition/contamination (frequent cleaning of the dynamic pressure probe might be necessary) ▸ High limit of quantitation (about 5 m/s)
Impeller anemometer	▸ High measuring accuracy at low velocities (‹5 m/s)	▸ Execution as grid or line measurement is rarely possible ▸ Sensitive to mechanical stress (e. g. due to particles, droplets)

3.4 Evaluation of the emissions data from CEMS in the EU ETS

The evaluation of the emissions data is based on the “Uniform nationwide practice for monitoring emissions” (BeP) in Germany, which is a national administrative provision for the correct application of CEMS and was originally written for air pollution control. The new Annex J in the revised 2017 BeP describes the evaluation of emissions data for emissions trading. This evaluation first establishes so-called short-term mean values (STMVs) in accordance with Annex B 1.3 of the 2017 BeP. For STMVs, only the valid raw values are used during the installation’s operation subject to monitoring. According to 4.7.3 2017 BeP, the competent authority specifies the start and end of the operation subject to monitoring and the individual operating modes of the installation in consultation with the operator. The respective criteria shall be determined by means of clear parameters to be determined by the evaluation system. DEHSt has published the “Working aid for CEMS emission data evaluation” [16] for the definition of criteria for the start and end of an operation subject to monitoring.

Figure 2 shows schematically the emissions data evaluation process according to Annex J of the 2017 BeP. The available raw values are categorised in the evaluation calculator based on the installation’s operating condition indicated by measurement and operation signals such as the instantaneous value for the flue gas volume flow rate. After one hour of operation subject to monitoring, the hourly value is checked for validity in accordance with Annex J 1.3 of the 2017 BeP and a corresponding status is assigned to each hourly value. If it is necessary to create a substitute value for an invalid hourly value according to Annex J 1.3, then the calculation is usually performed automatically by the evaluation calculator in accordance with the requirements of Annex J 2. Annex J 2.2 a) (Installations with constant parameters in waste gas) applies to combustion plants. It should be noted that the final substitute value for the measurand in accordance with Annex J 2.2 a) is only available after the end of the reporting year. Missing values for baseline parameters such as temperature, pressure and water vapour content in the waste gas shall be replaced by values from individually specified substitute value methods. The methods used shall be approved by DEHSt together with the monitoring plan. With reference to Annex J 2.3, manual entries for substitute values are also possible (e. g. if mass or energy balances are used outside the evaluation calculator to close data gaps for the waste gas volume flow rate).

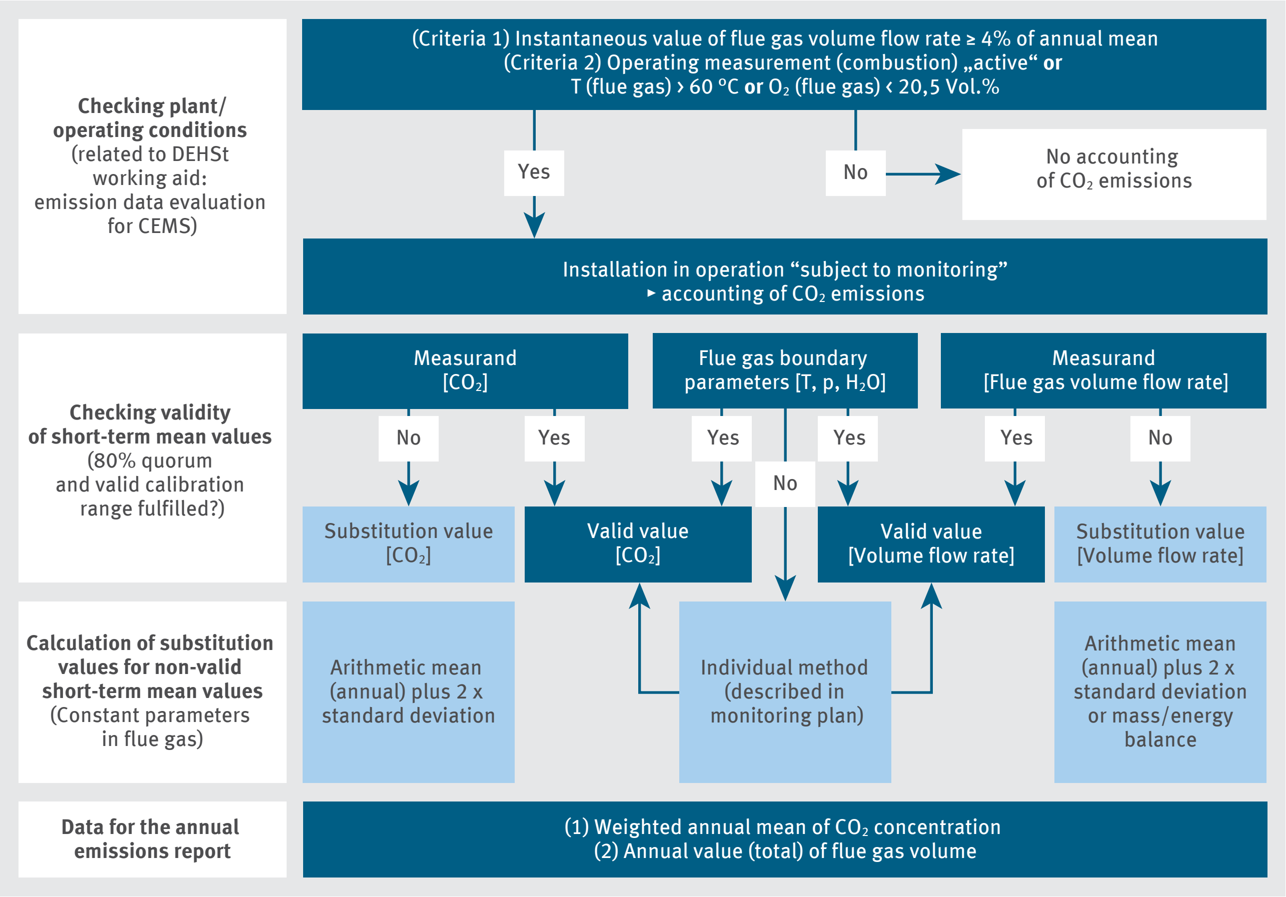

Figure 2: Recording and evaluation of CO_2 emissions according to Annex J of the 2017 BeP in conjunction with the DEHSt working aid for CEMS emission data evaluation using a combustion plant as an example

4 Differences in the monitoring of air pollutant emissions according to IE Directive and of GHG emissions in the EU ETS in Germany

Early experience from emissions report reviews between 2014 and 2018 has shown that the emissions data evaluations for CEMS in accordance with the requirements of the MRR sometimes show considerable deficiencies. The inclusion of the necessary requirements in the BeP has created a legally secure implementation of emissions data evaluation within the scope of the national Greenhouse Gas Emissions Trading Act [TEHG] [17]. This in particular includes a corresponding certification (QAL1) of the evaluation computer.

Table 4 shows the main differences in emissions data evaluation and reporting in the context of monitoring air pollutants under immission control law and in determining GHG emissions in the EU ETS.

Table 4: Differences in the evaluation of emissions data according to BImSchG and MRR[4]

Monitoring and reporting emissions according to the Federal Immission Control Act (BImSchG)	Monitoring and reporting emissions according to the European Monitoring and Reporting Regulation (MRR)
Measurands to be monitored	
Mass concentration of air pollutants (usually standardised to baseline oxygen content)	GHG mass concentration and waste gas volume flow rate (from which the determination of GHG emissions amounts)
Flue gas volume flow rate “only” represents a baseline value (e. g. Section 20(1) of the 13th BImSchV)	Flue gas volume flow rate is to be determined as a measurand
Accuracy requirements (uncertainties)	
Accuracy requirements for confidence intervals according to 2010/75/EU Annex V, Part 3(9) Requirement applies to the **mass concentration** related to the daily limiting value e. g. ▸ CO: 10% ▸ SO_2 and NO_X: 20%	Tier concept and uncertainty thresholds of the MRR Requirement applies to the **mass flow rate** related to the annual mean value[4]) ▸ CO_2: 2.5 – 10% (level 4 – 1) ▸ N_2O: 5 – 10% (level 4 not applicable, level 3 – 1)
Deduction of measurement uncertainty for **continuous** monitoring (validation) before comparison with emission limiting values	No deduction of measurement uncertainties permitted (Article 5 MRR – Completeness of emission determination)
Registration and evaluation of emissions data	
▸ Validity criterion: 2/3 rule (based on the specified averaging period) ▸ Classification of short-term (STMV), daily (DMV) and annual mean values (AMV): frequency distribution ▸ Substitute value creation only for baseline parameters (usually fixed values for p, T, H_2O component and flue gas volume flow rate) ▸ Individual definition of emission limits for different **operating conditions subject to monitoring** (e. g. start-up operation)	▸ Validity criterion: 80% quorum (based on the length the installation is in operation subject to monitoring within the averaging period; Article 7 MRR – Accuracy) ▸ No classification required ▸ Substitute value creation for parameters (Article 45(2) MRR, Annex J 2 of 2017 BeP) and baseline parameters ▸ Only two installation conditions can be distinguished: installation out of order (no emission determination) or installation in **operation subject to monitoring** (emissions determination); Article 5 MRR – Completeness of emission determination

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[4] The results from QAL2 are used when the AMS is calibrated for the first time (see example calculation in Table 7).

5 Experience and estimates on the use of GHG CEMS in the EU ETS

In “classic” energy installations, the use of CEMS as a monitoring method hardly plays any role at present, apart from a few exceptions. When monitoring CO_2 emissions in combustion plants, CEMS is usually only considered or implemented as a monitoring method if several diverse fuels (e. g. substitute fuels) are used to generate power and/or heat.

The current applications of CEMS for the determination of GHG emissions are focused on:

- Combustion of diverse fuels in power plants and thermal recycling installations,
- Chemical installations (e. g. production of sulphuric acid or bulk organic chemicals),
- Regeneration of catalysts,
- and thermal afterburning (RTO).

There are some positive examples of using CEMS in the EU ETS. It was found that CEMS, as a method for monitoring and reporting CO_2 emissions, achieved high-quality results by consistently implementing the following requirements:

- Design of measuring locationand measuring sections according to the specifications of DIN EN 15259,
- Choice of suitable measuring equipment and measuring principles,
- Exact determination of the cross-section of the flue gas duct,
- Consistent implementation of all stipulated quality assurance measures and
- Regular plausibility checks of the results obtained by comparison with an emission calculation

However, the emission report reviews in 2013–2018 also identified some shortcomings in the collection, quality assurance and calibration as well as in the emissions data evaluation and the calculation of GHG emissions amounts.

5.1 Identified defects and problems

The CO_2 concentration in the flue gas of a combustion plant is comparatively easy to determine. Accordingly, only isolated problems have occurred in this area so far. As a rule, the gaseous components in the flue gasses are evenly distributed even if the measuring cross-section is selected adversely. Thus, in only a few cases does the spatial distribution of the parameter to be determined play a relevant role ("strand formation", e. g. due to the combination of several flue gas flows with different flue gas boundary parameters in a collecting chimney). Due to the broad absorption spectrum of CO_2 within the IR range, cross sensitivities, except for water vapour, are not significant. In addition, CO_2 is present at a comparatively high concentration compared to the other flue gas components. Furthermore, the standards used to adjust the AMS are not subject to any relevant influences (high stability of the test gases). In summary, it can therefore be stated that an exact recording of the CO_2 concentration in flue gases of stationary installations can be achieved in practice with comparatively little effort, provided that regular inspection, maintenance and adjustment of the measuring instruments is carried out by expert personnel.

In contrast, many defects and problems have been identified during the measurement of the flue gas velocity and the flue gas volume flow rate in ducts. For example, many general and specific influencing parameters have to be taken into account when measuring the volume flow rate in order to achieve a small measurement uncertainty. This is shown by the process parameters for measuring methods used in the manual determination of point velocity in the measuring cross-section of flue gas ducts presented in Chapter 8 of ISO 16911-1 and the process parameters for use in the field listed in Chapter 9. In addition, there are the specific influences on site such as the design of the measuring stations (traversing area, size and arrangement of the measuring orifices, etc.).

Another important point is the secondary importance for the flue gas volume flow rate parameter in the monitoring of air pollutants under immission control law. Tests and calibrations were carried out with comparatively little effort in the past due to the non-existent requirements on the measurement accuracy for the determination of the flue gas volume flow rate prior to the publication of EN ISO 16911. In many cases, this led to a low measuring accuracy of the installed measuring systems. It should also be noted that EN ISO 16911 published in 2013 is only mandatory in exceptional cases for the monitoring of air pollutants (e. g. in the case of limiting values for the flue gas volume flow rate or mass flow rate specified individually in thepermission).

To date, there are only a few cases of existing measurement systems for determining the flue gas velocity and existing measurement sites suitable to meet the high requirements for accuracy of emissions data acquisition in the EU ETS.

Table 5: Deficiencies identified in the acquisition, quality assurance and calibration of the required measurands

Identified deficiencies	Explanations, implications and solutions
Non-standard application of the SRM in the calibration of volume flow rate AMS	Comparative measurements within the scope of QAL2 are carried out as point or line measurements. ‣ Spatial influences such as changes in the flow velocity profile under changing operating conditions have often been insufficiently recorded only or not at all. The flue gas volume flow rate is over- or underestimated. **Solution: consistent execution of gird measurements according to EN ISO 16911 taking into account varying operating conditions and installation utilisation rates**
Missing QAL3 tests for AMS volume flow rate	No QAL3 tests implemented for the AMS volume flow rate. ‣ Drift, contamination or leaks were detected too late. Thus the determination of the flue gas volume flow rate was incorrect over longer periods and a corresponding conservative closure of data gaps is required. **Solution: regular execution of QAL3 tests.**
Unidentified incorrect measurements of the AMS volume flow rate over a longer period of time	Replacement of dynamic pressure probes or parameter changes in differential pressure transducers, without carrying out a QAL2 after a replacement or change. ‣ The original calibration function and the measured values determined were invalid. **Solution: complete documentation of changes to the AMS and timely introduction of prescribed/required quality assurance measures (particularly QAL2 after significant changes).**
Incorrect evaluation of the comparative measurements for the flue gas volume flow rate	Incorrect calculation of the calibration function by the commissioned calibration laboratory. ‣ Calculation of incorrect flue gas volume flow rates. **Solution: comparison of old and new regression parameters. In the case of significant deviations (> 10% of zero point and/or measuring range end value) a root cause analysis is mandatory. If necessary, further plausibility tests or renewed comparative measurements (QAL2) must be carried out.**
Use of a less suitable measurement method to determine the flue gas velocity	Use of a differential pressure measuring system for low differential pressures in the flue gas duct (5–10 Pa). ‣ Large standard deviation in the differences between AMS and SRM. Determined standard deviation > 10% related to the average flue gas volume flow rate. Level 1 (10%) according to MRR is not observed. **Solution: selection of a more suitable measurement method for low flue gas velocities (< 5 m/s).**

However, most of the deficiencies identified by DEHSt were related to the evaluation of emissions data and the calculation of GHG emissions amounts. In the following compilation, the authors often recommend the use of an evaluation computer certified according to Annex J of the 2017 BeP as a solution. In addition, it should be noted that a manual evaluation of the emissions data is permissible in principle, but that the testing effort is significantly higher both at the verifiers and at the competent authority. Furthermore, changes to the parameterisation must be recorded by the certified evaluation computers, which significantly increases traceability.

Table 6: Deficiencies identified in the evaluation of emissions data and calculation of GHG volumes

Identified deficiencies	Explanations, implications and solutions
Incorrect operating condition signalling	Use of a data model for monitoring air pollutants according to BImSchG. ‣ Emissions during start-up operation were not taken into account which resulted in a systematic emissions underestimation. **Solution: use of an evaluation computer certified according to Annex J of 2017 BeP. Correct parameterisation of the operating condition signalling in the evaluation computer.**
Deduction of measurement uncertainty (validation)	Use of a data model for monitoring air pollutants according to BImSchG and analogue parameterisation for GHG concentration. ‣ Systematic emissions underestimation (approx. 0.5%, in individual cases up to 2% related to annual emissions). **Solution: assigning a zero to the corresponding entry in the parameterisation of the data model in evaluation computer. Use of an evaluation computer certified according to Annex J of 2017 BeP.**
Missing substitute value creation	No or incorrect manual evaluation of invalid hourly data. ‣ No or incomplete substitute value creation. **Solution: use of an evaluation computer certified according to Annex J of 2017 BeP.**
Application of the 2/3 rule instead of the 80% validity criterion	Use of a data model for monitoring air pollutants according to BImSchG. ‣ Incorrect determination of the number of invalid hourly values. **Solution: use of an evaluation computer certified according to Annex J of 2017 BeP.**
Incorrect calculation of mass flow rate (different reference conditions of concentration and volume flow rate)	Incorrect parametrisation of the evaluation computer (baseline value calculation). ‣ Systematic over- or underestimation of emissions. **Solution: physical testing of the evaluation unit by assigning specified test signals and comparing the as-is values displayed by the evaluation computer with the target values calculated by the notified measuring station.**
Incorrect transfer of regression parameters	Incorrect transfer of the regression parameters calculated according to DIN EN 14181 to the evaluation computer. ‣ Calculation of incorrect GHG concentrations or flue gas volume flow rates. Over- or underestimation of emissions. **Solution: testing the evaluation computer after entering the new calibration functions. Physical testing of the evaluation unit by assigning specified test signals and comparing the as-is values displayed by the evaluation computer with the target values calculated by the notified measuring station.**

5.2 Uncertainty consideration for CEMS in the EU ETS

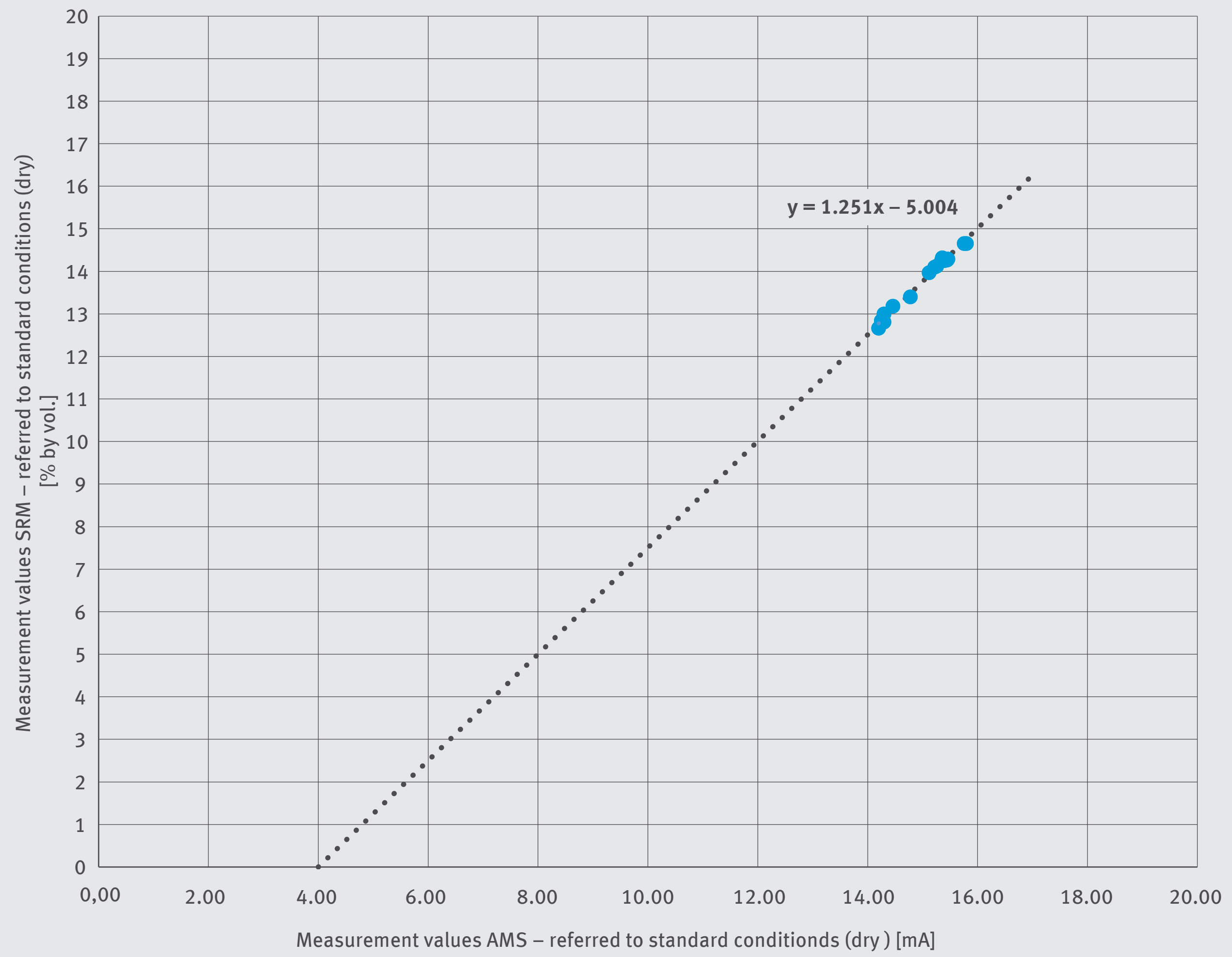
The uncertainty consideration for CEMS in the EU ETS is based on the standard deviations determined in accordance with EN 14181 within the framework of the comparative measurements, related to the respective annual mean values for concentration and volume flow rate, see diagrams in Figures 3 and 4. The parameters determined in QAL2 (standard deviation sD, test value kv) and the annual mean values for the measurands GHG concentration and flue gas volume flow rate are used to calculate the overall uncertainty of the CEMS and compare it with the uncertainty threshold value relevant for an installation.

The standard deviations determined within the framework of QAL2 are subject to various influences and therefore strongly influence the overall uncertainty of a CEMS. Some of the influences can be controlled by targeted measurement planning, execution and evaluation of comparative measurements. For example, these include the following activities:

- Increasing the number of comparative measurements,
- Adjusting the data collective from outliers,
- Conducting network measurements for the volume flow rate with sufficient measuring time per measuring point (at least 1 minute per measuring point according to EN ISO 16911-2),
- Reducing the uncertainty contributions of baseline parameters by calibration using an SRM,
- If necessary, using a quadratic instead of a linear regression for the flue gas volume flow rate.

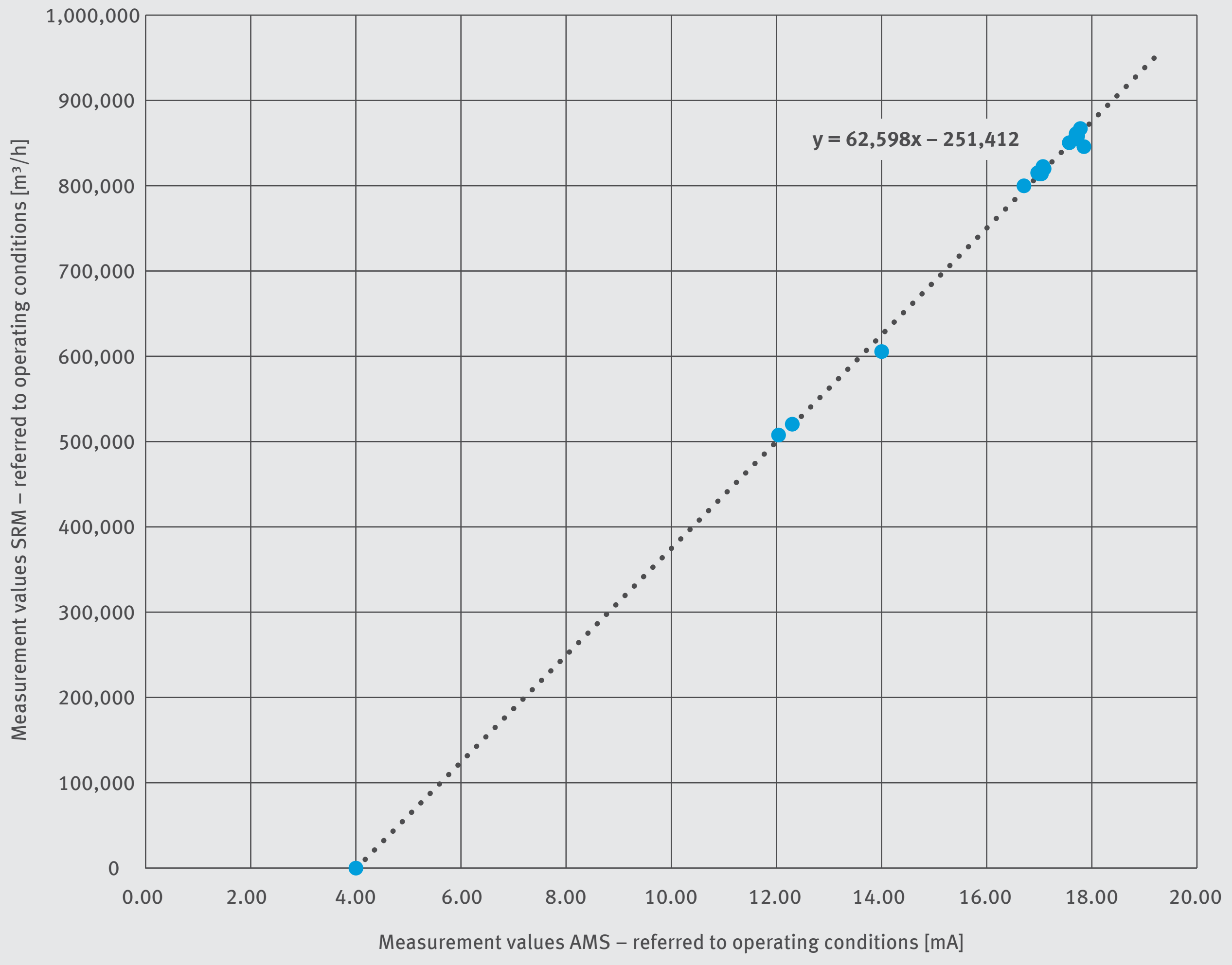
Furthermore, significant uncertainty contributions can be reduced by installing more suitable AMSs. For processes with strongly fluctuating water vapour contents in the flue gas, the determination of the concentration and the flue gas volume flow rate in the normal state (wet) often makes more sense since the uncertainty in the determination of the water vapour content in the flue gas does not matter.

A direct comparison of the determined uncertainties of different CEMS applications with each other does not always allow a conclusion on the “correctness” of the determined measurement results. In practice, a distribution of the comparative measurements between the AMS and the SRM over a wide utilisation range often leads to a higher variability and thus to a higher uncertainty. However, measurement accuracy can often be improved despite the supposedly higher uncertainty, especially if the variability in the spatial distribution of the measurand is justified. Uncertainty contributions, which are due to inhomogeneous or changing flow velocity profiles, can be minimised, for example, by designing the AMS sampling as a multi-path or grid measurement.



Measuring range (calibrated)	0.00 – 20.02% by vol.	referred to standard conditions (dry)
S_D (Variability – determined standard deviation)	--% by vol.	referred to operating conditions
S_D (Variability – determined standard deviation)	**0.08% by vol.**	**referred to standard conditions (dry)**
Number of value pairs of the comparison measurements	16	without function test readings
k_v-value	0.9777	
Mean value CO_2 concentration	--% by vol.	referred to operating conditions
Mean value CO_2 concentration	**13.80% by vol.**	**referred to standard conditions (dry)**

Figure 3: Example for the representation of the results of the calibration of a CO_2 AMS



Measuring range (calibrated)	−1,019 – 1,000,551m³/h	referred to operating conditions
S_D (Variability - determined standard deviation)	8,018m³/h	referred to operating conditions
S_D (Variability - determined standard deviation)	**5,215m³/h**	**referred to standard conditions (dry)**
Number of value pairs of the comparison measurements	16	without function test readings
k_v-value	0.9777	
Mean value volume flow	733,883m³/h	referred to operating conditions
Mean value volume flow	**504,982m³/h**	**referred to standard conditions (dry)**

Figure 4: Example for the representation of the results of the calibration of a volume flow rate AMS

The uncertainties for the CO_2 concentration, the flue gas volume flow rate and the CO_2 mass flow rate shown in Table 7 are calculated from the QAL2 data as follows:

$$U_{\text{GHG mass flow rate}}[\%] = \sqrt{U^2_{\text{GHG concentration}}[\%] + U^2_{\text{flue gas volume flow rate}}[\%]}$$

Formula 1: Expanded uncertainty of the GHG mass flow rate

$$U_{\text{GHG concentration}}[\%] = \frac{\dfrac{S_D * 2}{k_v}}{\text{Mean value}_{\text{GHG concentration}}} * 100$$

Formula 2: Expanded uncertainty of the GHG concentration

$$U_{\text{flue gas volume flow rate}}[\%] = \frac{\dfrac{S_D * 2}{k_v}}{\text{Mean value}_{\text{flue gas volume flow rate}}} * 100$$

Formula 3: Expanded uncertainty of the volume flow rate

Table 7: Illustration for calculating the uncertainty of a CEMS application with the measurement data from QAL2 according to Figure 3 and Figure 4

GHG concentration			
CO_2 concentration referred to standard conditions (dry), extractive sampling			
S_D	0.08	% by vol.	Variability (determined standard deviation) of CO_2 concentration
N	16		Number of value pairs of the comparative measurements
k_v	0.9777		test value
X_{CO2}	13.80	% by vol.	Mean value CO_2 concentration with X_{CO2} – valid measurements and n – number of measurements
$U_{GHG\ conc,\ CO2}$	1.15	%	Expanded uncertainty CO_2 concentration

Volume flow rate			
Volume flow rate referred to standard conditions (dry), in-situ measurement, raw signal based on operating conditons, normalization with t, p and H_2O			
S_D	5,215	m^3/h	Variability (determined standard deviation) of the volume flow
N	16		Number of value pairs of the comparative measurements
k_v	0.9777		test value
$X_{flue\ gas\ volume\ flow}$	504,982	m^3/h	Mean value volume flow with $X_{flue\ gas\ volume\ flow}$ – valid measurements and n – number of measurements
$U_{flue\ gas\ volume\ flow}$	2.11	%	Expanded uncertainty of volume flow rate

GHG mass flow rate			
$U_{GHG,\ CO2}$	2.40	%	Expanded uncertainty CO_2 mass flow

5.3 Comparison of emissions data from CEMS and from the calculation approach

5.3.1 International examples and authors' assessment

The following section will quote the results of international investigations and publications on the comparison of emissions data from CEMS and calculations. The approach and focus of the studies and investigations is sometimes very different. The same applies to their conclusions. Therefore, only individual aspects can be derived from the publications. The quality of the data on which the individual publications are based is not known to the authors. Furthermore, there are no known research projects in which extensive comparative measurement programmes have been carried out in the field, on the basis of which generally valid results could be derived. Therefore, the following section will present only the basic conclusions of the publications and will try to place them in relation to the authors experiences in the EU ETS.

According to the monitoring guidelines of the EU Commission (2007/589/EC), until the end of 2012, a measurement-based emissions determination could only be used if the measurement could be proved to provide more accurate results than the calculation method and at the same time incurring disproportionately high costs when using the calculation method. In addition, the accompanying calculation had to comply with the level requirements of the calculation method. The legal preference of calculation approaches over direct measurements resulted from the assumption that continuous emission measurement systems were not accurate.

However, findings from the US EPA's Acid Rain Program, encouraging experience in monitoring other pollutant emissions, the introduction of N_2O monitoring (which can only be accurately detected when using CEMS) and announcing CEMS as an approved method of the 2006 IPCC Guidelines probably had an influence on the European revision processes for the Monitoring Regulation. The MRR (601/2012/EU) declared for the first time that continuous emission measurement was equivalent to the calculation method for the third trading period of 2013–2020. There is no detailed study available to compare the two approaches as only a few comparative data sets have been available due to previous restrictions of CEMS.

USA

Two databases on CO_2 emissions from coal-fired power plants are available in the USA. The EIA (U.S. Energy Information Administration) [18] database contains CO_2 emissions calculated based on calculation approaches and the CAMD (EPA's Clean Air Markets Divisions) database contains calculated CO_2 emissions based on CEMS. The data was compared by different researchers (Ackermann and Sundquist (2008) [19], Evans et al. (2009) [20], Quick (2014) [21], Gurney et al. (2016) [22]). All studies have come to the conclusion that the data sets differ considerably. On average across all facilities, the differences were explained by uncertainties. For individual data sets, however, ±20% deviations could not be explained by uncertainties. Reasons and conclusions recorded for this case were very different:

Evans et al. (2009) assumed that the determination of coal quantity was incorrect due to unreliable belt scales and that CEMS provided more reliable data due to QA/QC requirements and improvements under the Acid Rain Program.

Quick (2014) concluded that the calculation method provided more reliable emission data than CEMS based on the analysis of the specific emissions and a detailed analysis of the calibration of the flue gas volume flow rate measurement.

Ackermann and Sundquist (2008) and Gurney et al. (2016), on the other hand found that no conclusion could be made about which is the more accurate method.

Bryant et al. (2015), National Fire Research Laboratory (NFRL) at National Institute of Standards and Technology (NIST) [23], looked into both investigation methods for the ideal case of a gas-fired burner. According to uncertainty considerations, the accuracy of the calculation method (about 1%) was lower by a factor of 3 than that of CEMS (just under 4%). The calculation method yielded about 5% more CO_2 emissions. This deviation could be explained by uncertainties. In the study, however, it was also found that the extraction system did not include all combustion emissions in certain cases. Although an attempt was made to take this circumstance into account, this may be one of the reasons for the lower emissions determined using CEMS.

South Korea

Lee et al. (2014) [24] reported on the comparison of emission measurements for the greenhouse gases carbon dioxide, methane and nitrous oxide between the two determination methods in a case study of a heat generation plant burning hard coal. In terms of CO_2 emissions, it was found that the calculation method resulted in 12–19% lower CO_2 emissions as opposed to CEMS. In their study the authors describe that uncertainties in the IPCC standard factors “calorific value” and “emission factor” greatly contributed to the overall uncertainties of emission calculation. They identified the measurement of flue gas volume flow rate as the main cause of overall uncertainty for the measurement of CO_2 emissions. In particular, they refer to changes of flue gas velocities in the respective measurement sections. Regardless of the preferred determination method, the authors recommended investigations into the respective influencing parameters for the overall uncertainties and measures to reduce the main influencing parameters.

Assessment by the authors

If operators in the EU ETS determine emissions directly via CEMS, they must compare the result to the calculation approach so that two independent data sets are available. The data available in Germany provides a similar picture as the investigations in the USA and Korea. Since, unlike in the 1st and 2nd trading periods (2005–2007 and 2008–2012), there are no level requirements for the calculation when using CEMS, the quality of the calculation data is very different. The comparison of the two data sets shows that the higher the proportion of proxy data, the greater the deviation.

The documentation of EIA data (Documentation for Emissions of Greenhouse Gases in the United States 2008) shows that standard emission factors (provenance, coal quality) are included in the calculation. In some cases, analyses from deposits or fixed carbon analyses are also used, which require a conversion to the baseline condition of the measured coal. In our experience, use of these proxy data sets and the experience of Evans et al. (2009) that in some cases non-quality-assured quantity measuring instruments were used, explain the deviations found. This becomes all the more clear since differences of up to 5% can occur in the CO_2 calculation even when using quality-assured quantity measurement and analysis of calorific value and emission factor if the locations of sampling and quantity determination (e.g. quantity determination at the port of loading and analysis at the port of unloading) take place separately and not at the same location.

If quality-assured quantity measurements and analytical values determined suitably often are used for the calculation and CEMS complies with the highest level, the deviations found are minimal at approx. 1–2%.

5.3.2 Requirements for a comparable determination of CO_2 emissions using CEMS and calculation approach

In principle, the calculation approach and continuous measurement of CO_2 emissions provide comparable results. The prerequisite is that all metrological requirements are implemented in practice. However, a general proof of comparability (i. e. by small deviations) based on data available so far, is only possible to a very limited extent since no "reliable" comparative data sets are available for both methods in practice in the majority of applications.

MRR does not specify the uncertainty of the accompanying calculation when using CEMS. The overall uncertainty of the accompanying calculation is, in most cases, significantly greater than 5% according to the authors.

A comparison based on the level concept of MRR is also only possible to a limited extent since the approaches to the uncertainty consideration for the two determination methods differ fundamentally. For CEMS, uncertainty calculation is based on a direct method (see 5.2), i. e. on the results of the comparative measurements of QAL2. MRR's level requirement for CEMS also refers to the GHG mass flow. In contrast, only the uncertainty in the determination of the fuel or material used is initially decisive for the calculation approach. Further uncertainties which are included in the overall uncertainty through calorific values and emission factors when calculating the GHG mass flow, are only taken into account qualitatively in the level concept using standardized procedures and an analysis frequency to be met. They are not included in an overall uncertainty assessment. Furthermore, the calculation approach generally uses an indirect method for uncertainty calculation. Input parameters used for the uncertainty balance are often of a general nature and are standard uncertainties determined specifically for the measuring instrument in only a few cases.

However, it should be noted that the highest level under MRR for both determination methods is technically achievable and is also accomplished.

Possible systematic differences underlying the individual application of the methodology may need to be taken into account in order to better compare the results between CEMS and the calculation approach. For CEMS applications for example, they are as follows:

- Co-determining CO_2 from the combustion air with a volumetric concentration of approx. 0.04% by volume. In total, the combustion of solid fuels (coal) results in additional average emissions of up to approx. 0.3% due to the air-inherent CO_2 proportion.
- Use of different factors to convert the volumetric concentration into a mass concentration (ideal or real gas equations). The resulting difference may be up to 0.7%.

The following systematic deviations may also occur in the calculation approach depending on local conditions and the method used:

- Changes in the quantities/qualities of the fuels used during transport or storage outside or inside the installation (e. g. due to changes in coarse moisture, oxidation processes, volatilisation). In this case, the quantities/qualities on which the calculation is based may differ from the quantities/qualities actually supplied to combustion (up to 5% for calorific value and carbon content in some cases).
- In combustion plants, the oxidation/conversion factor for fuels can deviate "significantly" from 1 in practice. Systematic deviations from the assumption of complete oxidation/conversion of the fuels and input materials may occur depending on the process technology, fuels and input materials used. In individual cases, the deviations may be up to 1%.

A reliable comparison of the two methods is only possible if the uncertainty contributions of all influencing parameters that lead to systematic measurement deviations are reduced as far as possible. Table 8 gives an overview of the essential prerequisites for determining emission data as accurately as possible.

Table 8: Prerequisites for a reliable comparison of the CO_2 emission determination methods

CEMS	Calculation approach
Guarantee of high availability of the measuring equipment used (› 95%)	Guarantee of high availability of the measuring and sampling equipment used (› 95%)
Suitable installation situation of the volume flow rate AMS (sufficient undisturbed inlet and outlet sections)	Recording quantities and qualities in close time and spatial context
Selection of a suitable measuring method for volume flow rate measurement	Determining quantities and qualities as closely as possible to the emission process
Carrying out the volume flow rate AMS as a grid measurement in a representative measuring cross-section	Representative sampling and compliance with the required analysis frequency
Regular testing according to QAL2, AST and QAL3	Full application of the relevant European or international standards for sampling, sample preparation and analysis
Implementation of continuous functional checks and plausibility checks in order to detect drifts/mismeasurements at an early stage.	Implementation of continuous function/plausibility checks when using quantity measurements (e. g. conveyor belt scales) in order to detect drifts in the measuring equipment at an early stage.

Both the application of the calculation approach and CEMS have certain advantages and disadvantages. Some of the advantages and disadvantages listed in Table 9 apply depending on the available conditions at the respective installation/emission source. The advantages of the respective determination method are highlighted in bold in Table 9. The comparison made here was deliberately generalised; it cannot be applied to all individual cases.

Table 9: Advantages and disadvantages of the two determination methods in direct comparison (advantages are marked in bold, disadvantages in normal font)

CEMS	Calculation approach
One measurement system per emission source, i. e. processing a small amount of primary data	Frequent processing of various primary data from different sources is necessary (quantity measuring instruments, stock balances, laboratory analyses etc.).
Determining emissions directly at their source.	Depending on the determination method, the relevant data is also collected and aggregated outside the installation.
Dedicated normative specifications for the collection, evaluation, quality assurance and documentation of data.	Various individual QA systems. No uniform specifications for the evaluation and documentation of test results in many areas.
High degree of automation in the evaluation of emission data possible.	A rather large number of manual data processing steps is often necessary.
Availability of the primary data at any time. There are systems for the automatic data transmission to the supervisory authority.	Primary data often comes from various sources (e. g. external laboratories or service providers) and must be requested separately for in-depth testing purposes.
No relevant additional expenditure if different and/or inhomogeneous fuels are used.	High sampling and analysis costs when using different and/or inhomogeneous fuels.
Little experience exists about the correct implementation of the “complex” evaluation regulations (but can be solved by using certified evaluation computer).	**Data evaluation methods established over many years, usually broad knowledge available to operators, authorities and verifiers.**
Only information on the flue gas flow is available. No evaluation is possible based on individual substances used.	**Information is available on the individual substances used and their properties (e. g. calorific values, emission factors). Evaluations based on substance information possible.**
Higher risk of systematic errors, e. g. due to improper operation/maintenance of the measuring instruments or incorrect parameterisation of the evaluation computer.	**Risk of systematic errors in the aggregation of individual measurements from different measuring instruments is generally small if the individual measurements are independent of each other (e. g. calibration marks for levelling different seagoing or inland waterway vessels).** (However, there may be a higher risk of systematic errors in the direct determination of the quantity consumed, e. g. when using conveyor belt scales.)
As a rule, personnel must be separately trained and sensitised to inherent risks.	**Frequently established structures, responsibilities and technical knowledge available.**
As a rule, retrofitting/optimisation of existing measuring systems is necessary.	**Synergies can often be used. Multiple use of billing and energy data (e. g. from areas legally regulated) making cost-efficient processes possible.**
Use only for guided sources such as ducts and smokestacks possible, not suitable for diffuse sources.	**Also suitable for diffuse sources.**

Irrespective of the aforementioned advantages and disadvantages, however, it should also be noted that a “mutual validation” of the two methods for determining CO_2 emissions is always possible by using two independent determination systems!

6 Summary and recommendations for the use of CEMS

We generally consider the calculation and measurement methods (CEMS) for CO_2 emission determination equally suitable for high-quality monitoring. The prerequisite for this is a comprehensive and consistent quality assurance, which is different in the two monitoring approaches. In addition, the emission data from both approaches can be well supported by plausibility checks and reckoning with alternative methods.

A comparison of available data sets from CEMS with the calculation method shows that when standard factors or estimates for the calculation factors of calorific value and emission factor are used, deviations between the determined emission loads and the results of the measurement increase. Similarly, some systematic differences between the methods can be attributed to the use of industrial measurements to determine the quantities of fuels and input materials that are not subject to regular calibration. Results from individual emission sources also show, however, that using data of comparable high quality for CEMS and the calculation approach provides a very good agreement between the two methods.

Clear advantages of the calculation approach compared to continuous measurement are particularly evident in installations that only use a few homogeneous fuels. For example, by using the available data on fuel quantities and gas parameters for natural gas-fired combustion plants, whose data quality is regulated by law in the European gas market, the calculation approach can provide a very precise and cost-efficient determination of CO_2 emissions.

In contrast, the use of CEMS is recommended for installations that use various inhomogeneous fuels. If, in addition to coal, a power plant uses other fuels e. g. waste or substitute fuels, the effort in sampling and analysis of the input materials increases significantly in order to comply with the requirements of MRR when determining CO_2 emissions in the calculation approach. In such cases, the application of continuous emission measurement technology offers a more cost-effective and simpler solution to the monitoring task over the long term. The decision about the choice of the determination method depends primarily on the specific conditions at the respective installation.

A regular comparison of CEMS CO_2 emission data with the calculation approach may be more useful than other available plausibility checks (such as comparison with production or sale rates of specific processes) due to the independence of the two methods in accuracy assessment. Larger discrepancies between the two data indicate, in our opinion, systematic errors/measurement deviations in one or both systems and should be further investigated.

Based on the experience and information described above about the application of the two approaches for determining CO_2 emissions from stationary installations, we arrive at the following preliminary assessment:

The quality of emissions determined for an installation essentially depends on the normative requirements themselves and their stringent and complete implementation as well as on ongoing quality assurance. It does not depend on the basic choice of the determination method.

In a continuous emissions measurement, systematic deviations most frequently result from a “stratification” (inconsistency) of the flue gases/flows in the measuring cross-section. This often leads to unrepresentative results when measuring the flue gas velocity. Typical examples of such “stratifications” are cyclonic (e. g. turbulence) and non-axial flows. In addition, if the concentration of the desired measurand is also distributed inconsistently over the measuring cross-section, the correct acquisition of the emissions data is further impeded. Normally, the flue gases from combustion plants are well mixed in channels. However, if flue gases with different temperatures are brought together in a collection duct, or if leakages occur, this can lead to “stratification” of the flue gas concentrations or so-called “strand formation”. In general, such conditions significantly reduce the accuracy of continuous measurement systems.

These problems can probably be reduced by targeted investigations (recording the velocity and concentration profile in the measuring cross-section, calculation of the mass flow densities, determination of representative measuring axes in the measuring cross-section) and by applying suitable sampling strategies for the AMS. It may be possible to place sampling probes in areas of the measuring cross-section where there is little "stratification". Furthermore, measures to normalize the flow using flow conditioners and flow straighteners (e. g. straightening buckets in the stack) are possible (a common practice for pressure differential devices according to ISO 5167-1 Appendix C). It is important to note that "stratification" of the flue gases and/or change in the flow profile is often associated with process or load changes. In case of doubt, the measuring distances and measuring stations should be relocated to another more suitable location.

Another frequently underestimated influencing factor is the determination of the cross-sectional area of the exhaust duct. The uncertainty in the determination of the cross-sectional area should be reduced by applying proven methods (e. g. measurements of at least four diameters at approximately equal angles to each other and consideration of the thermal expansion of an exhaust duct).

The availability of CEMS compared to the measuring equipment used in the calculation approach (e. g. for automatic sampling of solid fuels or for normalisation of natural gas quantities) is generally not significantly poorer. Within the scope of the QAL1 tests, the automatic measuring equipment must demonstrably provide an availability of >95% in the field test. It can therefore be assumed that this requirement will also be met in individual applications if the measuring system is correctly selected and installed on site. If failures or erroneous CEMS measurements occur, the length of the downtime and thus the resulting data gap depends to a large extent on the quality assurance measures installed and implemented in-house. In cases where longer downtimes occurred or where measurements failed to provide reliable data over a long period of time, this was often due to inadequate continuous quality assurance (e. g. missing QAL3 and/or plausibility checks).

For a reliable acquisition of the emissions using CEMS, the regular and well documented execution of continuous quality assurance (QAL3) of the AMS, which is within the area of the operator's responsibility, is absolutely necessary. Warning and alarm thresholds for maintenance and repair work should be set appropriately in the light of the much stricter requirements on the measurement uncertainty in the EU ETS compared to the monitoring of immissions protection law. For the continuous control of the AMS volume flow rate, procedures should be used that can be traced back to international standards.

In the final result of our evaluation we draw the following conclusion:

With correct installation and consistent performance of all necessary quality assurance levels, continuous measurement offers an accurate and efficient method for determining CO_2 emissions for many scopes, especially when a high number of partially inhomogeneous fuels or materials are used.

In such cases, an extension of the measurement technology already used for monitoring air pollutants such as sulphur dioxide or carbon monoxide can provide a cost-effective solution to the additional monitoring tasks for emissions trading schemes.

In addition, the official monitoring of emissions data can be significantly simplified and improved through automatic evaluation and direct transmission to the competent authorities. In the case of implausible emissions data, e. g. over the period of an entire operating week, incorrect measurements could be identified by official evaluations of the transmitted emissions data and additional quality assurance measures could be initiated at short notice.

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[26] Ordinance on the implementation of the Greenhouse Gas Emissions Trading Act in the 2013 to 2020 trading period (Emissions Trading Ordinance 2020 – EHV 2020)

Supplementary publications:

[27] German Emissions Trading Authority: Guideline for the preparation of monitoring plans and emission reports for stationary installations in the 3rd trading period (2013–2020, as of 11/2018)

[28] Wagner, D.: Requirements for the continuous emissions determination and evaluation
(“Anforderungen an die kontinuierliche Emissionsermittlung und –auswertung”)
Immission Protection 4/2016, p. 160–16434 (no English version available)

[29] Lenzen, B.: Cost-effective monitoring of greenhouse gas emissions – method comparison, quality assur¬ance, emissions data evaluation (“Kosteneffizientes Monitoring der Treibhausgasemissionen – Methoden¬vergleich, Qualitätssicherung, Emissionsdatenauswertung”), VDI Report No. 2280 (October 2016), p. 137–154 (no English version available)

[30] Lenzen, Burkhard, Göttel, Holger, Schneider, Christian, Garvens, Hans-Jürgen: EU Emissions Trading – Monitoring and reporting using continuous emissions measurement (“EU-Emissionshandel – Überwachung und Berichterstattung mittels kontinuierlicher Emissionsmessung“),
Immission Protection 01/2018, p. 15–21 (no English version available)

German Emissions Trading Authority (DEHSt) at the German Environment Agency
Bismarckplatz 1
D-14193 Berlin

www.dehst.de/EN | emissionstrading@dehst.de