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EU Emission Trading Related CO_2 Monitoring in Power Plants

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Abstract: European Commission has set new regulations for the third Emission Trading System period (2013-2020) that increased requirements for risk assessment, uncertainty estimation and continuous accuracy surveillance for CO_2 monitoring system. The objective of this paper is to describe and discuss three independent methods to determine CO_2 emissions in power plants that fulfill the new requirements. The presented methods are standard method, direct measurement method and energy balance method. The methods themselves, the required measurements and their properties are discussed. The methods are demonstrated in a 500 MW_{th} pulverized coal fired CHP power plant and the results are discussed.

Keywords: Boilers, CO_2 Emission Monitoring, Uncertainty, Emission Trade System

1. INTRODUCTION

In 2005 European Commission, EC, launched Emission Trading System, ETS, in order to reduce greenhouse gas emissions in energy and industry sectors (EU 2012a). National Emission Trading Authorities of ETS member countries set national quotas according to EU guidelines for pollutants that may be emitted. The Emission Trading Authorities grant the emission permits, pursuant to which production plants have right to emit carbon dioxide CO_2 into the atmosphere. During the first and the second ETS period most of the emission allowances were allocated freely for companies involved according to their relative volumes of production. The third period turns the system to auctioning a majority of the permits instead of delivering them freely.

The authorities supervise the monitoring and reporting of emission data and maintain the Emissions Trading Registry. Companies involved are required to hold a number of permits equivalents to their emissions. The total number of the permits cannot exceed the cap limiting the total emissions. Companies that need to increase their volume of emissions must buy permits from those who require fewer permits.

The main emission component in ETS is carbon dioxide CO_2. The third ETS period (2013-2020) involves several modifications and updates compared to previous ones. In order to clarify these changes and to make the monitoring and reporting of greenhouse gas emissions more complete, accurate and transparent, the EC has adopted two new regulations; Monitoring and Reporting Regulation (EC 2012a) and Accreditation and Verification Regulation (EC 2012b) for the certification authorities under the ETS. The most important updates for power plants (Table 1; category A2, B and C) are requirements for risk assessment, uncertainty estimation and continuous accuracy surveillance for CO_2 monitoring system. Each parameter needed for the determination of emissions should be determined by a certain data quality levels. These data quality levels are called "Tiers", and their requirements depend on the type and size of the monitored power plant. Definitions of the tiers on maximum permissible uncertainty for monitoring methods and power plant categories are defined in (EC 2012c).

National authorities supervise that all power plants involved in ETS must monitor their CO_2 emissions constantly with required accuracies. This requirement is valid also during periods when a primary CO_2 monitoring method is not available. Therefore parallel and independent methods for CO_2 monitoring should be provided in order to meet the new requirements.

The conventional way to determine CO_2 emissions is a so called standard method, where annual CO_2 emissions are determined according to fuel consumption and fuel specific parameters. Secondly, CO_2 concentration can be measured directly from flue gases. In this method flue gas flow and some additional process variables need to be measured in order to convert the measured CO_2 volumetric concentration

Table 1. Definition of tiers and maximum permissible uncertainties (EC 2012c)

Tier No.	Power plant Category	Annual emissions tCO_2/a	Standard method / for activity data	Measurement-based method / for CEMS	Energy balance method
1	A1	< 25 000	± 7,5 %	± 10,0 %	± 7,5 %
2	A2	25 000 – 50 000	± 5,0 %	± 7,5 %	± 7,5 %
3	B	50 000 – 500 000	± 2,5 %	± 5,0 %	± 5,0 %
4	C	> 500 000	± 1,5 %	± 2,5 %	± 2,5 %

in a stack to CO_2 mass flow. Thirdly, CO_2 emissions can be evaluated by means of energy balance calculations. All these methods have different and complementary features and they fulfil the requirements of supervisory authorities. Application of two independent CO_2 monitoring methods simultaneously provide redundancy and enables attractive monitoring prospects for sensors and processes.

The objective of this paper is to describe and discuss about the three parallel methods to determine CO_2 emissions in power plants. The principals of the methods as such are fuel generic, but the discussion in this paper is focused on pulverized coal fired combustion systems. The monitoring task is more demanding with solid fuels than liquid or gaseous fuels because of the measurement uncertainties of solid mass flow and non-homogeneity of different fuel batches. Chapter two introduces the principals of the three discussed monitoring methods, chapter three introduces methods to define monitoring related uncertainties, chapter four presents the results calculated for a real 500 MWth pulverized coal fired CHP power plant, and in chapter five the results are discussed. The discussion is concluded in chapter 6.

2. DETERMINATION OF CO_2 EMISSIONS IN SOLID FUEL FIRED BOILERS

2.1 Standard Method

The standard method is based on so called *activity data*, which means the amounts of used fuels and case specific coefficients. The coefficients are fuel specific emission factor, net calorific heat value, and process specific oxidation or conversion factor. The standard method is straightforward in cases where fuel properties are well known and constant, and mass flows of all fuel types are individually measured. Precision scales used for mass flow measurements are typically verified by duplicated sensors and are located by the conveyors transporting fuel from field storages into buffer silos inside the boiler house. Thus the standard method provides an accurate indication of CO_2 emissions but the indication is not in real time because of the delays caused by the volumes of buffer silos.

In the standard method the CO_2 emission is calculated according to (1)

$$Em = AD \cdot NCV \cdot EF \cdot OF \cdot (1 - BF) \tag{1}$$

where *Em* stands for emissions [tons CO_2], *AD* for activity data [TJ, ton or Nm^3], *NCV* for net calorific value [TJ/t or TJ/Nm^3], *EF* for emission factor [t CO_2/TJ, t CO_2/t or CO_2/ Nm^3], *OF* for oxidation factor [-] and *BF* for biomass fraction [-]. The notation is adopted from the (EC 2012a). In the ETS biomass is treated as carbon neutral and the amount of biomass is subtracted from the total fuel amount.

2.2 Direct Measurement from Flue Gases

Direct CO_2 measurement from flue gases provides an online method for emission monitoring. Since the start of the third ETS period the direct measurement method is recognised as an equivalent method with calculation-based approaches. CO_2 concentration is typically measured with IR-absorption based analysers indicating the amount of CO_2 molecules in a measurement volume (%_vol or ppm). The analysers are usually in-situ type devices measuring the concentration directly across the flue gas channel in process conditions. The measured concentration must be converted to CO_2 mass flow in a stack. This requires additional measurements such as flue gas flow and some other measurements for unit conversion and normalizing the measured values to standard conditions. The applied sensors typically exist in power plants, but their accuracy and therefore their calibration frequency should be increased so that the quality requirements set for authoritative emission monitoring are fulfilled. Direct measurement is suitable for boilers using several types and and mixed fuels, if all the used fuels are included in the ETS. If biofuels are used, their CO_2 emissions should be subtracted from the total measured emissions.

Normalized CO_2 concentration $x_{CO_2,norm}$ [%] and flue gas flow $\dot{V}_{FG,norm}$ [Nm^3/s] are calculated as follows

$$x_{CO_2,norm} = x_{CO_2,meas} \cdot \frac{100}{100 - x_{H_2O,FG}} \cdot \frac{20,9 - x_{O_2,ref}}{20,9 - x_{O_2,dry}} \tag{2}$$

$$\dot{V}_{FG,norm} = v_{meas} \cdot \frac{100 - x_{H_2O,FG}}{100} \cdot \frac{20,9 - x_{O_2,dry}}{20,9 - x_{O_2,ref}} \cdot \frac{T_{ref}}{T_{ref} + T_{FG}} \cdot \frac{p_{FG}}{p_{norm}} \cdot A_{stack} \tag{3}$$

where $x_{H_2O,FG}$ refers to flue gas moisture concentration in stack [%_vol], $x_{O_2,ref}$ to reference O_2 concentration [%_vol] (e.g. for coal fired power plants 6% in dry flue gases), $x_{O_2,dry}$ to dry flue gas O_2 concentration in stack [%_vol], T_{ref} to reference temperature [273 K], T_{FG} to flue gas temperature [K], p_{FG} to flue gas pressure in stack [Pa], p_{ref} to standard atmospheric pressure [101325 Pa], v_{meas} to measured flue gas velocity [m/s] and A_{stack} to flue gas stack cross-sectional area [m^2]. The total cumulative CO_2 emission is

$$m_{CO_2} = \int_{t_1}^{t_2} \rho_{CO_2} \cdot x_{CO_2,norm} \cdot \dot{V}_{FG,norm} \, dt \tag{4}$$

where ρ_{CO_2} refers to CO_2 density in standard conditions.

Thus, the total CO_2 emission is aggregated from information obtained from several sources. A special attention should be paid to the validity of each measurement. This method requires more activities concerning cross-checks with calculations as well as instructions for data processing and other quality assurance requirements compared with the standard method (EC 2012b).

2.3 Energy balance method

Monitoring of CO_2 emissions by energy balance method is based on estimation of fuel flow rate according to an energy balance of the boiler. The amount of the released CO_2 emission is then calculated according to the elemental

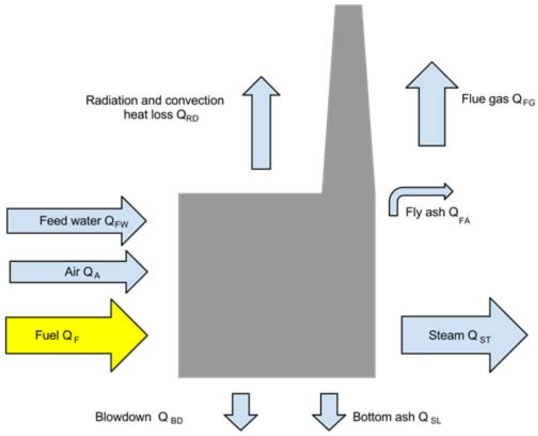

Fig. 1. Boiler energy flows.

composition of the fuel. Energy balance method is implemented according to the methodology and principles of the European standard EN 12952-15. Energy flows of a boiler are presented in Fig. 1. The generated steam power $\dot{Q}_{ST}$ is

$$\dot{Q}_{ST} = \dot{m}_{ST} \cdot h_{ST} \tag{5}$$

where $\dot{m}_{ST}$ is steam mass flow and h_{ST} is live steam enthalpy.

The flue gas heat loss $\dot{Q}_{FG}$ is

$$\dot{Q}_{FG} = \dot{m}_{FG} \cdot c_{FG} \left(T_{FG} - T_{ref}\right) \tag{6}$$

where $\dot{m}_{FG}$ refers to flue gas mass flow [kg/s], c_{FG} to specific heat capacity of flue gas [J/(kg·K)], T_{FG} to flue gas temperature and T_{ref} to reference temperature [K] (in standard EN 12952-15 T_{ref} is 298 K) (Coskun 2009). The boiler blow down loss $\dot{Q}_{BD}$ is

$$\dot{Q}_{BD} = \dot{m}_{BD} \cdot h_{SS} \tag{7}$$

where $\dot{m}_{BD}$ is mass flow of blow down steam and h_{SS} is the enthalpy of the saturated steam in drum pressure. Boiler ash loss $\dot{Q}_{Ash}$ is

$$\dot{Q}_{Ash} = \dot{m}_{Ash} \cdot ((c_{Ash} \cdot \left(T_{Ash} - T_{ref}\right) + x_{UBC} \cdot H_C) \tag{8}$$

where $\dot{m}_{Ash}$ is the mass flow of ash, c_{Ash} is the specific heat capacity of ash, x_{UBC} is the concentration of unburned carbon in the ash and H_C is the heat value of carbon.

Boiler radiation and convection losses $\dot{Q}_{RD}$ can be estimated according to EN 12952-15 by definition $\dot{Q}_{RD} = C \cdot \dot{Q}_{max}$, where C stands for standard coefficient (for pulverized coal fired boilers = 0.0220) and $\dot{Q}_{max}$ for maximum heat power of the boiler. The thermal efficiency of the boiler η_B is determined as follows

$$\eta_B = \frac{\dot{Q}_N}{\dot{Q}_N + \dot{Q}_{L,tot}} \tag{9}$$

where $\dot{Q}_N$ stands for the net thermal power of the boiler and $\dot{Q}_{L,tot}$ for total losses. The net thermal power is $\dot{Q}_{\mathrm{N}} = \dot{m}_{\mathrm{ST}}(h_{\mathrm{ST}} - h_{\mathrm{FW}}) + \dot{m}_{\mathrm{BD}}(h_{\mathrm{BD}} - h_{\mathrm{FW}})$, where h_{FW} is the enthalpy of feed water. The total loss is $\dot{Q}_{\mathrm{L,tot}} = \dot{Q}_{\mathrm{FG}} + \dot{Q}_{\mathrm{Ash}} + \dot{Q}_{\mathrm{BD}} + Q_{\mathrm{RD}}$.

Estimated fuel flow into the boiler according to energy balance is

$$\hat{\dot{m}}_F = \frac{\dot{Q}_N}{\eta_B H_{fuel}} \tag{10}$$

where H_{fuel} refers to the net calorific value of the fuel. After defining the fuel mass flow estimate, the CO_2 emission can be calculated similarly with the standard method by multiplying the estimated fuel flow with case specific coefficients (see (1)). It should be noticed, that (10) must be solved iteratively together with (9), because boiler efficiency depends on flue gas losses, which as for depends on the fuel flow (Senegacnik 2009).

3. MONITORING ACCURACY

For quality assurance purposes power plant operators must establish a procedure that ensures the calibration, adjustment and checking of measurement devices at regular intervals. All the measurements should be implemented according to international standards (EC 2012a):

- EN 14181 Stationary source emissions – Quality assurance of automated measuring systems
- EN 15259 Air quality – Measurement of stationary source emissions – Requirements for measurement sections and sites and for the measurement objective, plan and report
- EN ISO 14956 Air quality – Evaluation of the suitability of a measurement procedure by comparison with a required measurement uncertainty

CO_2 emission monitoring is based on information aggregated from several process measurements, laboratory analysis and process parameters. To assure the quality of the monitoring results it is very important to use high quality sensors and analysers and maintain their quality by annual surveillance tests as defined in EN14181, QAL 3.

Accuracy of the measuring device or sensor does not mean the accuracy of the measurement instalment. Measuring devices are typically very accurate according to equipment data sheets. However, in industrial applications it is difficult to achieve the declared accuracies (Poyry 2007). Determination of the total error can be made step by step starting from accuracies of individual measurements proceeding to calibration procedures and calculations merging different data sources and finally aggregate the total uncertainty from different sources. If uncertainties of balance calculations are determined using equipment data sheet accuracies, level of ± 1.5 % can be achieved. However, if the process measurements are put into practice poorly, effects to the total accuracy of the monitored quantity can be remarkable. E.g. poorly installed, calibrated and compensated live steam mass flow measurement may easily generate more than ± 10 % error to the energy balance of the boiler (Poyry 2007).

Uncertainties for activity data are defined by using maximum sensor uncertainty for the determination of the cumulative fuel flow. The eligibility of the monitoring and reporting system must be demonstrated to the supervisory authority.

3.1 Calculation of uncertainty

The normal procedure to determine the uncertainty of an expression is to differentiate the equations used in calculations partially as for every variable and multiply these derivatives by the uncertainty of the variable in question and finally get the total uncertainty by summing all the recognized uncertainties together. However, for energy balance method this procedure is not applied, because boiler efficiency (Eq. 9) and fuel mass flow (Eq. 10) must be solved using iterative computation.

In this work the uncertainties of both energy balance and direct measuring methods were estimated by Monte Carlo simulations. Monte Carlo simulation is perhaps the most common technique for propagating the uncertainty in various aspects of a system to predict overall uncertainty. The accuracy of the Monte Carlo simulation is a function of the number of test runs. The confidence bounds on the results can be computed according to the number of simulation runs. (Binder & Heermann 2010).

4. CO_2 MONITORING AT A CASE POWER PLANT

The case process is a pulverized coal fired CHP power plant which is classified as category C power plant (see Table 1). The power plant consists of two blocks; a steam boiler with capacity of 160 MW_e and 300 MW_{th} (K1 in Fig. 2) and a hot water boiler with capacity of 180 MW_{th} (K7 in Fig. 2). Flue gases from the boilers are mixed and processed in a semi-dry desulphurization process. For simplicity, the results presented in this paper consider the situation where only the steam boiler K1 has been in operation. The structure of the power plant and locations of flue gas measurements are shown in Fig.2.

The data collected for the analysis is obtained from a 26 days period with data sampling interval of 1 hour (mean values). During the test period the plant was operated at 55-100 % load range. The official CO_2 reporting system is based on the standard method. New ETS regulations were not yet in action at the time the test was carried out, thus some of the calibrations of the measurement devices used for calculations of the direct measurement and energy balance methods were outdated. Therefore, results should be considered preliminary, and the results show the potential of the methods compared to standard method.

4.1 Comparison of the methods

The relative uncertainty of the standard method applied here is adopted from uncertainty assessment reports applied in the official emission reporting of the case plant. For the direct measurement method and the energy balance method, standard deviations were calculated applying Monte Carlo simulation method by varying all the measurement values with evenly distributed white noise at their uncertainty ranges and obtaining the 95 % confidence interval for the

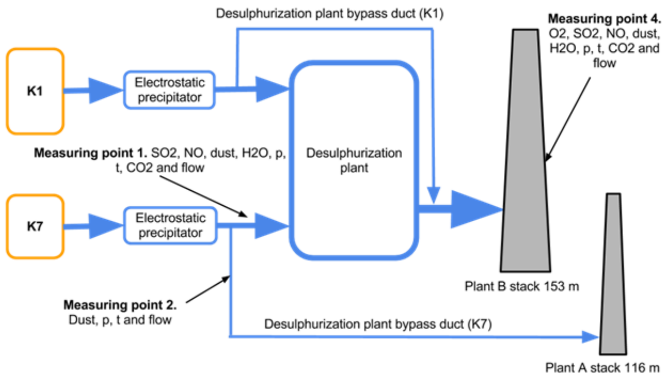

Fig. 2. Locations of flue gas measurements.

uncertainty result. The results are calculated according to 1000 test runs. The uncertainties of measurement devices applied in Monte Carlo simulation are listed in Table 2.

Table 2. Applied measurement devices and their declared accuracies.

Meas. device	Meas. magn.	Meas. Princip.	Ranges	Accur.
Sick GM 31	SO_2, NO, Temp.	In-situ, DOAS	T: 0-200 °C SO_2:0-2100 ppm NO:0-600 ppm	± 2%
Sick GM 35	CO_2, H_2O	In-situ, IR	CO_2: 0-20 % H_2O: 0-30 %	± 2%
Sick GM 302	O_2	ZrO_2	0-21 %	± 0.2 %
Foxboro	Press.	Capacitive	800–1200 mbar (abs.)	± 0.5%
Sick Flowsic 100	Flow	Ultra-sonic	0-40 m/s	± 0.1 m/s
SKS	Temp.	PT100	0-250 °C	± 0.5%

The impacts of uncertainties of individual measurements to the calculation of CO_2 emission with direct measurement and energy balance methods are shown in Tables 3 and 4. Calculation models for both monitoring methods are excited with sensor uncertainties and the caused uncertainties to the calculated CO_2 emissions are analysed.

Simulation results for statistic behaviour of calculated CO_2 emission based on the direct method are depicted in Fig. 3.

Table 3. Effects of individual measurements to accuracy of the direct measurement method. (Uotila 2013).

Measurement	Uncertainty to CO_2 %
CO_2 concentration	1.00
Flue gas flow	2.00
Oxygen	0.50
Flue gas moisture	0.22

Table 4. Effects of individual measurements to the accuracy of the energy balance method. (Uotila 2013).

Measurement	Uncertainty to CO_2 %
Heating value of fuel	1.45
Steam flow	0.92
Steam temperature	0.27
Feed water temperature	0.20
Flue gas moisture	0.07
Flue gas O_2	0.04
Flue gas temperature	0.04
Ash	0.03
Steam pressure	0.03
Combustion air temp.	0.01

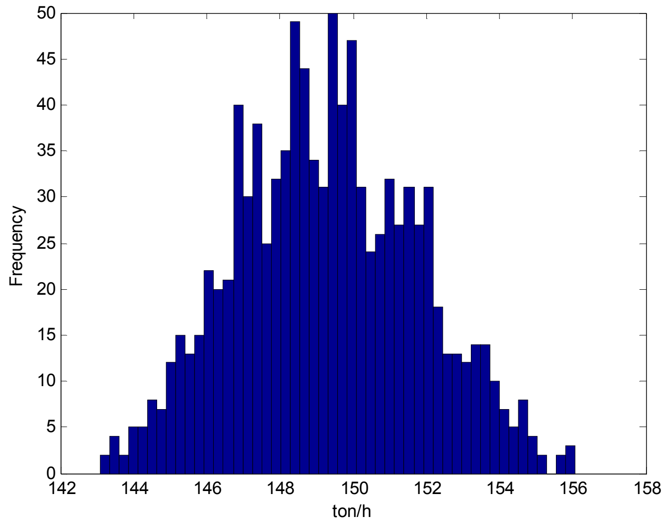

Fig.3. Uncertainty of CO_2 mass flow calculated with Monte Carlo simulation with 1000 runs (Uotila 2013).

Table 5 presents the monitored CO_2 emissions and their uncertainties in the case example in addition with the ETS requirements set for C-category power plants (Tier 4).

In the estimation of uncertainty only type A (statistically estimated standard deviation) measurement uncertainties were considered. Therefore, validity and correctness of measurements should be verified by calibrations and online monitoring to reveal possible bias type errors. According to Table 5, the direct measurement method provides some 7 % higher values (6000 tCO_2) than the standard method. The reason for this difference was the outdated calibration of the CO_2 analyser which was confirmed in a later calibration. However, the relative uncertainty exceeds the tier 4 requirement just slightly, as the uncertainty is calculated according to Table 2 uncertainties.

The energy balance method gives almost equal amount of CO_2 emissions compared with the standard method.

Table 5. Monitored CO_2 emissions and their uncertainties with different methods (Uotila 2013).

	CO_2 emissions [tCO_2]	Absolute uncertainty [tCO_2]	Relative uncertainty [%]	Tier 4 reqs. [%]
Std. method	85 000	± 1100	± 1,2	**± 1,5**
Direct meas.	91 000	± 2 600	± 2,8	**± 2,5**
Energy balance	84 000	± 2 900	± 3,4	**± 2,5**

However, the relative uncertainty exceeds the tier 4 requirement. Thus, in order to use this method as an official monitoring method, accuracies of some measurements or analyses should be improved.

5. DISCUSSION

The third ETS period sets new requirements for risk assessment, uncertainty estimation and continuous accuracy surveillance for CO_2 monitoring and reporting systems. In practice this means that CO_2 emissions should be monitored simultaneously at least with two independent methods, so that if the primary method fails, the secondary method is able to provide all the required information for emission reporting.

The monitored information should fulfil the quality requirements set by the ETS regulations. The uncertainty of reported emissions must be below the levels defined in Tiers. However, validation of the accuracy of the monitoring system is not straightforward and unambiguous. Every monitoring method is based on several process measurements and presumptions about e.g. fuel characteristics and properties of combustion processes. It is very difficult to define the real accuracy of the installation. Equipment manufacturers give values for sensors and/or analysing methods in optimal circumstances, but the real performance of the installed system can be far from the optimal ones. Calibration of in-situ flue gas analysers is also very challenging. With the new ETS regulations there has already gained some practical experience about the calibration of CO_2 analysers, and many problems have been detected. Nowadays it is also very common that power plants use mixed combustion with different fuels, some of them very nonhomogeneous and low quality. Thus, it is very difficult to estimate the average properties of used fuels. And the situation will be even more difficult, if some of the used fuels are not included to the ETS, e.g. biomass based fuels.

Monitored emissions are calculated aggregating information from several sources and all the uncertainties in the information processing chain cumulate to the emission value with different weights. So it is very difficult to reach the accuracy goals set by the tiers. As shown in this paper, even when applying quite high accuracy assumptions for individual measurements, total uncertainties for direct measurement and energy balance methods exceeded the limits set by the Tiers. So the new requirements set for the third ETS period will be very difficult to fulfil in practice. It would be very interesting to see, how the authorities will respond to these problems and increased third period requirements. Just now there is a transition period going on.

However, applying two or three parallel monitoring methods is very useful in the sense of continuous accuracy surveillance. Redundant information generated from emissions will help to detect and identify sensor and analyser faults. Fig. 4 shows an example of the case where the CO_2 output of the emission monitoring system (MEAC by SICK) was momentarily frozen. The redundant estimate for CO_2 emissions was generated with energy balance model.

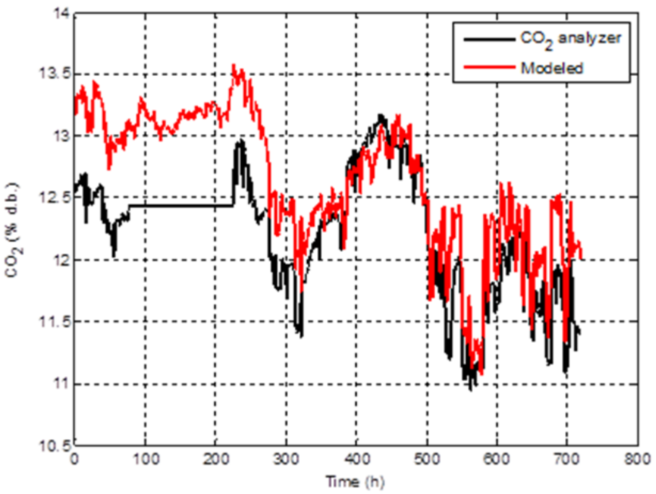

Fig. 4. Directly measured and energy balance based estimated CO_2 emissions during a test run. (Uotila 2013)

The frozen output of the analyser may be very difficult to detect just by looking (unlike in this example), because in many cases the indicated signal is processed with compensating and normalizing measurements, which are alive and generating fluctuation to the frozen analyser signal. Thus, redundant information generated by independent methods will remarkably help in maintaining the required performance of the monitoring system.

6. CONCLUSIONS

The topic of this paper was the monitoring of CO_2 emissions in power plant environment and how the new requirements set for the third ETS period effect on the monitoring routines. Requirements of uncertainty estimation and continuous accuracy surveillance lead to the use of at least two independent monitoring methods. In this work three alternative monitoring methods were demonstrated in a case power plant. Uncertainties of direct measurement based and boiler energy balance based methods were calculated using Monte Carlo simulation. Uncertainty of the standard method was adopted from the official emission reports of the case plant.

The biggest problem for applying different monitoring methods is the verification and the continuous surveillance of the accuracy of the systems. It is very difficult to verify the actual accuracy of the instalment of the process measurement system. Also the calibration of in-situ analysers is very challenging. The demonstrations of different monitoring methods in the case process showed, that the required relative accuracy is very hard to achieve.

However, the redundant and independent information from monitored variables gives useful information for diagnostic purposes to detect faulty sensors or false presumptions used in the information processing chain. If this additional information is utilized wisely, this may lead to the biggest benefits about the new requirements set for the third ETS period.

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