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A New Way of Conceiving and Dealing with Environmental Control of Process Plants by Real-Time Monitoring by Soft Sensors

STEFANO BALDACCI[1], **DILETTA MOGOROVICH**[1], **DEBORA MARIA BELLASSAI**[1], **GIANFILIPPO GUBINELLI**[1], **MICHELA DELL'INNOCENTI**[1], and **MARCELLO MOSSA VERRE**[1]

[1] ARPAT (Environmental Protection Agency of Tuscany Region), ITALY

Corresponding e-mail: stefano.baldacci@arpat.toscana.it

Abstract

The environmental control of industrial installations based on the Command & Control strategy implies high costs for national governments and companies and operative difficulties in sampling and analyzing. If not inserted in a wider context, the environmental point-by-point data give an incomplete representation of the impact of businesses. A new methodology for remote plant monitoring is proposed, which is based on the preliminary study of the process, the reconciliation of the data used in the first principle equations, the construction of models of various complexity (statistical inference or governing equation-based, CFDs, ANNs, fuzzy logic, expert systems, hybrid models), for real-time estimates of environmental critical parameters. On-line calculations detect potentially critical anomalies and allow adoption of corrective actions in favor of the environment and the companies. In this way, they could comply moment-by-moment with authorization prescriptions and achieve a better corporate image. The potentiality of this tool is shown by a case-study on waste incinerator. The expected pro is a better control efficiency that becomes preventive and continuous and gives more credibility and transparency to the overall control system. The benefits are both for the public and the companies. Methodology requires hard work for design, development and calibration of models, data analysis, cyber-security requirements, and training; nevertheless, it could reduce by 20% costs incurred by the control body. The biggest pro$_s$ are related to medium-large establishments (such as waste-incinerators or crude oil refineries) that sometimes meet difficulties in gaining public acceptance.

Keywords: environmental control, remote monitoring, soft sensors

1. Introduction

The environmental policy and legislation bring undeniable benefits: they protect, preserve and improve the environment for present and future generations, and preserve the quality of life of citizens. Positive effects of implementation of environmental law are additional jobs, better environmental standard and reduction of costs of pollution–related diseases [1]. On the contrary, poor implementation of environmental law and policies has many negative effects, such as the environmental, economic and social costs, unequal playing level field for operators and the loss of credibility of authorities.

Compliance depends on three mutually supportive sets of instruments: promotion, monitoring and enforcement. Inspection and in general, enforcement action, are a key tool in the regulatory chain. Environmental inspections enable authorities to collect information on activities that impact the environment, identify gaps in implementation and detect violation of legal obligations and contribute to avoid distortions of competition. [2]

Traditionally environmental supervision is based on a Command and control model: the site manager of an establishment must comply with all conditions detailed in environmental permit. Effectively, operator and enforcement authorities are asked to perform, among other activities, periodic measurement with the aim to assess the compliance with environmental standard, especially Emission Limit Value.

2. Problems/Difficulties

Organizing and conducting monitoring campaign implies operational / management difficulties and high costs.

Sampling phase is crucial because selected method and tools can affect the representativeness of sample; environmental conditions (air temperature and humidity, atmospheric pressure) can vary quality of sample reducing the amount of pollutant recovered (off gas sampling, in particular) and affecting replicability of measurement. The analytical method can have great effect on control outcome, the use of an unsuitable method resulting in emission value which could or could not comply with ELV and therefore require enforcement action. The choice of an appropriate method is complicated by technical and legislation obligation. For example, the sampling and analysis method to measure concentration of TOC in emission, must be selected from a set according to concentration range in the effluent and presence of VOCs subjected to special prescriptions. Inadequate calibration of analysis instruments, cross-contamination of sampling apparatus, physical sensor ageing are known to affect robustness of results.

High costs are mainly due to (1) well qualified staff employment, 80% (2) purchase, use and maintenance of sampling and analysis instrumentation, 20%, (3) analysis costs. In the end, point-by-point data, even though complying with permit conditions, should be correlated to plant operational data to gain any meaning, and anyway give a punctual representation of installation effects. Periodic measurements do not guarantee that the emission levels are valid in actual operation between the campaigns. This can be critical where a climate of mistrust has evolved between industry and public.

3. Related works

A complete review of literature related to remote monitoring of plants and processes was conducted; in the rest of this section we provide a brief discussion about aspects more pertinent to our work.

The monitoring of pollutant emission from combustion plants was addressed by Tronci et al., 2002 [3] and Korpela et al., 2017 [4], with the aim to develop a cost-effective method, alternative to traditional analytical control equipment. Tronci et al. propose neural-based inferential sensors as monitoring systems of pollutant emissions from combustion chambers. Tests on a 4.8 MW pilot power plant in operation at the Santa Gilla Enel Research Center (Cagliari, Italy) showed that soft sensor can be used to assess the compliance with environmental emission regulations and could be used as back-up systems to conventional analytical equipment [3]. Korpela et al. evaluated the potential of Predictive Emission Monitoring System application for NOx emission monitoring in practical installations and identified a set of linear regression models, which after fine tuning, provide a reliable estimate of total NOx emissions released at various operating condition in long-term operation, with better results compared to widely used nonlinear models (relative RMSE values of less than 3%).

A systematic review of on data-driven modelling and monitoring for industrial processes is reported by Z. Ge, 2017 [5]. Most works carried out on recording, collecting and analysing data were focused on plant-wide process control and optimization, followed by the applications for process monitoring. Current research are focused on nonlinear and non-Gaussian behaviour; multi-block PSA model and multi-block PLS model has been developed for decentralized plant monitoring.

Monitoring of process parameters can be conducted through traditional sensor as well as through innovative systems. Simeone et al., 2016 [6] developed an optical monitoring system to assist eco-intelligent Cleaning In Place (CIP) process control and improve resource efficiency in food and beverage industry, which includes an image acquisition system endowed with wide zoom camera and UV lights set and an image processing methodology to detect in real-time various types of surface fouling. Significant for monitoring of consequences of pollution and disaster management, the works of Unninayar and Olsen, 2008 [7] and Nagendra et al. (2013) [8], who reported the use of satellite remote sensing instrument to monitor large – scale both natural and anthropogenically induced changes in land surface, atmospheric and climatic drivers, through photonic measurement and innovative non-photonic measurements of the gravity anomaly field.

In several works, systems to remote monitor and control plant were developed. Nocoń et al. (2004) [9] describe a web-based control and monitoring methodology developed for a pilot-plants, based on the National Instruments (NI) LabVIEW environment (National Instruments, 2003). Remote access to plant is achieved via I/O server and Sequencing Controller (server side) and a Remote Panel and a Remote Control (client side). Security of data fluxes is addressed through access restriction limited to trusted IP addresses and selected TCP port (use of secure shell (SSH)).

Golob and Bratina (2013) [10] implemented a web-based monitoring and control methodology for educational purposes. Control industrial equipment (programmable logic controller) was integrated by FDI scheme with process models in Matlab/Simulink that uses OPC data communication for remote experiment realization. OLE (Object linking and embedding) for Process Control (OPC) is an established communication protocol/interface in process automation for data exchange. Atsuko Nakai et al., 2017 [11] implemented an operator/server system to minimize human error, especially in emergency situation, sharing key information between field operators and control room operators. The system consists of a web server and multiple operator PCs and tablet, linked using the local area network and a dynamic plant simulator.

4. A new way to conceive and manage the control of combustion plants by means of real-time monitoring

A methodology that allows to capture and to transmit real-time data to infer chemical plants behavior is presented.

Its role is not to replace samplings, inspections and controls but to launch alarm signals for normal behavior outside.

They should follow the insights aimed at verifying what happened and/or avoiding the recurrence of such events.

The evidence of this system may not constitute a conclusive element of a breach of law.

The proposed system belongs to the family of continuous emission monitoring systems (CEMS also known as PEMS) but does not have the ambition to substitute them nor to compete in precision.

The direct measurement of a physical or chemical parameter carried out with an instrument must always clash with problems of reliability, precision, repeatability, sturdiness, service factor, calibrations and so on.

Sometimes the measurement is very complicated or technically impossible. In these cases it may be useful to build a process model (e.g. a combustion chamber model) that can provide a series of indirect estimates of measures.

This model can be developed at various level of complexity. Fundamental elements of the system preprocessor are: the data collection routine, the builder of unmeasured flow estimates, the Data validator, the Homogenizer / Synchronizer; the Gross Error Identifier / Quantifier, the Data Reconciler and the Coaptator of the unknown flows.

The correct attribution of the system (heating, shut-down, normal regime, lock, rejection, activation burner etc. etc.) is very important. It also affects the goodness of the given data and any estimates we will go to build.

The main documents used are: Plan of establishment, Process Analysis, Block diagrams, P&IDs, Technical drawings of some mechanical components, Online variable values and trends of variables from DCS and Historical process data.

Once the process has been studied, it is necessary to identify the instruments that measure flows, temperatures and pressures that allow writing the balances of matter and energy on a section of the plant or on equipment.

The main steps that make up the process data acquisition and processing scheme are:

1) Online data acquisition: real-time or averaged data are extracted from the DCS database.

2) Data reconciliation: through application of data reconciliation the system can produce more accurate and reliable data. Uncertainty is present in all measures and actual values are hard to know.

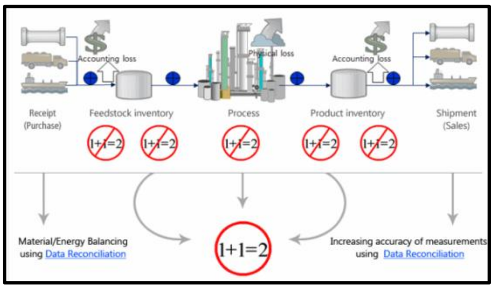

Figure 1. data reconciliation

It is possible to verify measurements consistency with respect to the conservation laws. The quantity of measurements can be used to improve their quality.

Data analysis is also essential to gain knowledge from all available measures to get information on streams that are not known or measured.

In the reconciliation phase, the data are first filtered so that their information content is synchronized.

Data reconciliation is an optimization with constraint and not an average.

$$\begin{aligned} \min_{x_i} \Phi &= \sum_{i=1}^{NM} \omega_i \left(m_i - x_i\right)^2 \\ s.t.: \quad & g(\mathbf{x}) = 0 \\ & h(\mathbf{x}) \le 0 \end{aligned}$$

(Omega elements are weights, usually $\omega_i = 1/\sigma_i^2$)

Before, all gross errors must be identified and removed. Their presence makes data reconciliation results invalid.

Finally, all unmeasured flows are calculated (unknown coaptation). In [12] an algorithm that is able to determine gross errors and determine the variance-covariance matrix of random errors of measurements from process data has been proposed.

3) Expert system: an expert system takes care of the correct identification of the plant regime allowing the management of environmental regulation constraints (for example IF (T<850°C) => “waste feed lock”) and driving reconciliation towards a more realistic result.

4) Mathematical tools. Once the reconciled data and the unknown flow values are obtained, you can use them in a set of models of varying complexity. They are able to estimate the environmental parameters from measures of flow, temperature and pressure and by the knowledge of certain chemical-physical parameters.

In other words, one can build models of individual equipment, plant sections or of the whole plant, which allow to obtain quantities but above all the quality (composition, physical-chemical properties) of all the streams entering or leaving the plant (raw materials, products, by-products, waste, emissions).

The study of the process is essential to identify parameters whose anomalies can lead to serious damage to the environment.

Models can be categorized into different categories:

- Statistical correlations, PLS, PCA.
- Hybrid models that link a statistical equation to the material and energy balance, equilibrium, state, chemical kinetics equations.
- Rigorous models (Process simulation, CFD and similar). If necessary, simulation of certain equipment should be provided.
- Contour modeling consisting of expert systems based on company know-how. For example, starting from the components of a mixture, to obtain an estimation of a specific parameter one must integrate the experience of the senior technical staff into the "expert system”.
- Artificial Neural Networks
- Fuzzy logic

ANNs are the most used tool. The sensor receives the same inputs that "enter" the process and estimate (predicts) online (in real time) the desired quality/performance index, which would otherwise be measured only in the laboratory. The most critical phases of the development of a software sensor are:

- Acquisition of plant data for neural model

training; data must be representative of the operating conditions, even the future ones.
- Data preprocessing and choice of input variables to be used as inputs to the neural network; Input variables must provide sufficient information to identify changes in the system's layout.
- Network training as it is necessary to take some precautions regarding to the choice of training data and to avoid overtraining problems.

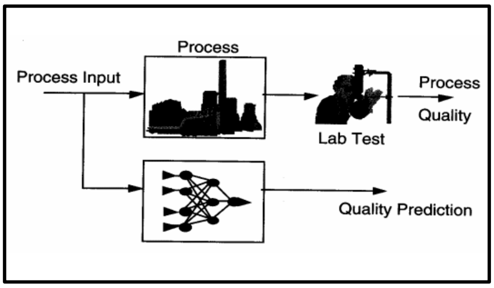

Figure 2. environmental estimates by ANNs

The calibration phase of a software sensor includes:

- network training and cross validation; Typically 2/3 of the historical data is used for the training (1/3 of these data is utilized for cross validation);
- offline validation: Typically, 1/3 of historical data is used for this phase.

In the training phase, 2/3 of the historical data is further divided: 2/3 of the data is used to calculate the parameters of the model and the remaining 1/3 is utilized to calculate the accuracy in anticipation. This strategy is known as *cross validation*. The optimization is stopped when the cross validation error becomes smaller than the assigned tolerance.

5. Models and soft sensors

All these tools are known as *soft sensors*.

In order to develop and validate these soft sensors, campaigns of measures of environmental parameters are required. The models reside at the processing centers at supervisory authorities but their outputs are shared with companies. Plant and soft sensor data are transmitted in an encrypted form. The benefits of soft sensors which the Company should consider are:

- delay problems in laboratory measure detecting are avoided;
- the possibility of having a parallel estimation of the laboratory measure allows to devise strategies for validating field measures;
- soft sensors are reliable back-up measurement system when the Analytical Analyzer is out of service;

In the development of soft sensors it is necessary to identify secondary process variables (easily accessible measures) to estimate the primary process variables (difficult to reach or too expensive measures).

The elaborations of the soft sensors and the models are used to determine in real time possible critical situations that could evolve in overcoming the limits to emissions (atmosphere, water, olfactory).

The estimates provided by the models do not have to be very accurate. It is sufficient that they provide an order of magnitude of the parameters checked in real time.

Remote monitoring of these parameters must be carried out. The model outputs must report the leaving from a normal operating range of critical parameters and eventually allow the company to initiate targeted control.

The communication channel with the company should be always active and would allow an immediate verify and a possible preventive intervention in real time.

So, the collaboration relationship between control bodies and companies needs to grow further.

6. Cybersecurity aspects

The communication channel between company and enforcement authorities is a very delicate aspect.

The protection of the IT assets of a company is achieved through measures of a technical and organizational nature, both of prevention and of protection, aimed at ensuring the “CIA Triad”:

- secure and controlled access to data, to ensure the confidentiality of the information processed (confidentiality properties)
- data consistency, understood as completeness and correctness of the same (property of integrity)
- data access in times and places (availability properties)

Data integrity, confidentiality, and availability (CIA) properties are the basic assumption on which all subsequent security assessments are performed.

Data flow has to be defended by some techniques as sniffing, passive interception of data passing through a telematic network, or port scanning, an IT technique designed to probe a server or host to determine which ports are listening to the machine.

In this context there are widespread authentication techniques (Kerberos) and cryptography as countermeasures at sniffing. On the technical front, network security measures come true with the use of appropriate network protocols such as HTTPS, SSL, TLS, IPsec, and SSH, which do nothing but apply cryptographic methods to one or more layers of network.

7. Feasibility and ROI

The development of this new methodology of controls has a multiannual horizon. Expected development costs are mainly due to the need for data acquisition campaigns for the calibration, development, verification and validation of models and inferential analyzers of the analytical parameters regulated by environmental laws, the training of a pool of expert technicians, and the resolution of cyber security problems on data transfer.

Other costs are expected for the periodic measurement campaigns necessary for the assessment of the adequacy of the models and sometimes for their calibration.

Possible savings can be obtained on the costs of travel, on analytical costs, on the costs of chemical reagents.

In this way it is estimated that the variable costs of environmental control of companies supported by control bodies could be cut by around 20%.

In the long period, possible savings could also be obtained in the fixed quote of costs (personnel).

8. Case study: Evaluation of R1 energy efficiency index for Incineration plant in accordance with Directive 2008/98/CE (WTE) [19]

Municipal waste incinerator (MWI o WtE), in accordance with the Annex II of the 2008/98/CE Directive (Waste Framework Directive) as amended by the Directive 2015/1127 [20] could be classified as energy recovery plant (R1 status) unlike disposal plant (D10 status) if their energy efficiency index, calculated with R1-formula, is equal or above:

— 0.60 for installations in operation and authorized before January 1^{st}, 2009,

— 0.65 for installations authorized since December 31, 2008.

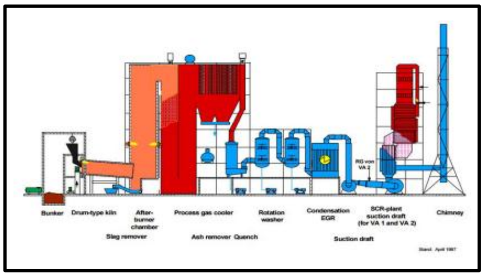

Figure 3. A waste incinerator schematic

The R1 evaluation must be worked out on an annual basis database, using factors representative of the actual operative plants conditions and defined through a continuous evaluation process.

The governmental authority is responsible for the assessment of the evaluation process and the acceptance of the related results and the propriety of the R1 status.

In this framework the quantification of the Ew factor, mostly influenced by lower heating value of the burned waste, plays an important role.

As stated in the EC guidelines [21] the most reliable method for the estimation of the LHV parameter is the indirect method, especially in the case of undifferentiated urban waste incineration, due to the high variance of the waste quality over the time and the appropriate but not cheap semi-continuous sampling and analysis procedure.

This approach is based on the resolution of energy and mass balance developed considering the system constituted by the oven and the boiler. The real plant section thus defined is used as a real laboratory calorimeter. This measurement system should be properly developed in the field, correctly calibrated and validated, and properly defined even in terms of reliability and robustness.

This method has been implemented by the site manager and formally approved by the local authority, through the supervision of the Environmental Protection Agency, in the context of the authorization process of an existing plant in Tuscany (Italy).

The first fundamental step has been the correct definition of site-specific energy and mass balance equations. To properly set the balance equations, the UNI 9246:88 [22] Italian technical standard has been applied; even if actually withdrawn, this standard is considered an important reference in the field.

Below the equations for the actual case:

Mass balance: $Mr+Mc+Ma+Mft1=Ms+Mf+Mft2+Msp$

Energy balance: $Pr+Pc+Pa+Pe=Pu+Psp+Pf+Ps+Pd+Pi$

To properly define the 'model' characteristic of the plant and thus all the factors above is necessary to identify:

- the reference system limits based on the actual plant configuration;
- Plant data (continuously measured data, estimated and literature data, discontinuous data measurement).

Continuous data measurements: the plant is generally equipped with instruments used to recollect useful process data through a well-defined DCS. All measured data are recorded and archived. Each measurement system is checked through specific control and maintenance procedure. Data are subjected to a validation test; if data are missing the LHV value is invalidated.

The management system of all process measurements must ensure complete data traceability and avoid data modification. These conditions must be periodically checked by the Authority.

Discontinuous data measurements: is the case of low sensitivity of the overall model with respect to some variables. In these cases a discontinuous measurement could be approved. Some examples related to the case study are listed below:

1) heavy dust temperature - an annual sampling procedure has been approved, to quantify this parameter in nominal process condition;
2) Losses from unburned waste - an annual sampling procedure has been approved, to quantify this parameter in nominal process condition;
3) Pd = Thermal power lost by irradiation - measured through an initial dedicated thermographic campaign under nominal operating conditions and whose evaluation will not be repeated. Pd was experimentally carried out using a FLIR 40 thermal imager for both the furnace and each section of the boiler [23] following the directives given in [22]. The analysis was carried out during February 2016 which is typically the coldest period of the year. The overall Pd value is 3.26% of the heat exchanged, with a 1.3% thermal chamber error.

Estimated process values: some parameters could not be properly measured (thus defining a feasible measurement system), for example the heavy dust and boiler dust mass flows. In the case of well-defined and stable parameters literature data could be used. In this case study these flows has been estimated to be respectively 18% and 1.28% in mass with respect to the waste inlet flow.

In other cases, the required parameter could be estimated using energy or mass balances based on system sub-model. For example, due to the installation configuration, it was not possible to directly and properly measure the Mf factor. So it has been derived developing the energy balance on a boiler subsystem (the economizer): $Pf=Pu+P_{economizer}$

Pu evaluated through the continuous water and combustion gas flows and temperatures measurements and the estimation of the combustion gas composition; $d_{economizer}$ estimated as described above.

Literature data: some chemical and physical parameters have been evaluated with the use of literature data, by example for various inlet and outlet flow parameters: enthalpy, specific heat, calorific power of unburned residues [24].

it is essential to underline that some terms were neglected:

- Ps → on the basis of the data analysis about the reintegration to the degasser; it has been estimated to be less than 1% of the vapor produced;

- Pe → with the exception of the sealing periods, it is zero, because the machinery is fed with part of the energy produced by the turbo-alternator. The amount of energy imported and documented in the annual IPPC reports refers to the entire plant and not to the only waste-to-energy plant since the selection and composting plant sections continue to operate during the plant shutdown phases.

- Pc → as under normal conditions the auxiliary burners are not used. An internal procedure for recording consumed fuel quantities is envisaged, which takes into account the state of the kiln's running from the reading of the oil level performed by an ultrasonic meter. This aspect should be yearly revised.

Once all the inputs of the model are defined it has been possible to introduce the properly system in the plant DCS (in an anchored system) to obtain continuous Waste LHV values. These systems should be treated as a matter of fact as the continuous air emissions measurements systems installed on this same plant. Thus this system should be properly calibrated over the time for the various operational conditions. This required the definition of the appropriate procedures based on the direct method (sampling and analysis of the waste input) evaluation of the LHV over a well-defined period of time and implemented with a specific frequency (every three months for the first year, and every sixth-month after this starting period)

As for continuous analyzer, even in this case has been necessary to define the uncertainty associated with the model output so that the appropriate comparison of the monitored value with the authorized limit could be evaluated.

The uncertainties associated with LHV waste and R1 values were defined using uncertainties composition related to each terms of the mass and energy balances and adopting the following hypothesis [22] [25]:

- continuous measured variables uncertainties have been assumed equal to the maximum errors identified in the 0-span calibration routines;
- discontinuous measured variables uncertainties have been assumed equal to that reported in the analytical certificate;
- literature-based variables uncertainty has been considered zero or equal to that reported in the literature references.

Under these assumptions, the uncertainty relative to the indirect method calculation of LHV was 1.05%, while that relative to R1 was 2.13 (%).

The direct method involves the sampling and analysis of waste to be incinerated according to a procedure developed by the company and based on the technical standard UNI 10802: 2013. The LHV uncertainty calculated in this way is 7%.

For the year 2016, the calculated value of R1 turned out to be equal to 0.619 ± 0.013 (limit value = 0.6).

9. Conclusion

A system based on a pool of technologies for remote monitoring of critical industrial installations for the environment has been proposed.

Its aim is to overcome the Command and Control strategy. It requires the achievement of high levels of transparency by the public control Bodies and the controlled Companies.

This new control methodology will never be able to replace the activity of acquiring objective elements to prove compliance assessment with the emission limits laid down by the standard.

However, these systems can give considerable benefits to both public and company.

The Company will acquire a better knowledge on certain aspects of its processes by the activity on data reconciliation and model development, a safe return in terms of image with a consequent better inclusion in the territory and an increase in the transparency of Controls.

With the proposed system, the Company is challenged to improve its performance and its transparency over time, also in relation to the public and the stakeholders. On the other hand, Companies could avail themselves of the data certified by the environmental authority that could be more reliably valued by the public. In addition, the number of scheduled controls with the presence of the institution staff in establishment could be strongly reduced.

The major advantages will be for settlements that find it difficult to be accepted by the public such as incinerators of waste, refineries, plants with combustors and other chemical plants.

On the other hand, the public will increase the degree of knowledge on the real impact of the Establishment and be certain of the veracity of the data.

From the operational point of view, the new control methodology is a multiannual project. Expected development costs are mainly due to the need for data acquisition campaigns for calibration, development, verification and validation of models and inferential analyzers of the analytical parameters regulated by environmental laws, for the training of a pool of expert technicians, and for the resolution of cyber security problems on data transfer.

Other costs are expected for the periodic measurement campaigns necessary to assess the adequacy of the models and sometimes for their calibration.

The authors are convinced that this methodology is the new challenge of environmental control for which both control Bodies and Companies might strive. The new control scheme proposed carries out a continuous monitoring of potential impacts on the environment, minimizing costs for the community. It is the most suitable tool to build a better environment and ensure a sustainable development in the future.

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11. Nomenclature

ELV	Emission Limit Value
TOC	Total Organic Carbon

VOCs	Volatile Organic Compounds
CFD	Computational Fluid dynamics
ANN	Artificial Neural Networks
PLS	Partial Least Squared
PCA	Principal Component analysis
CEMS	Continuous Emission Monitoring Systems
PEMS	Portable Emissions Measurement Systems
P&IDs	Process & Instruments Diagrams
DCS	Distributed Control System
RMSE	Root Mean Squared Error
ROI	Return Of Investment
CIA	Confidentiality, Integrity, and Availability
LHV	lower heating value
i	is the i^{th} measurement device
NM	is the total number of measurement devices
m	are the measured values
x	are the reconciled values of measures and it points out the degrees of freedom of the optimization problem
s.t.	stay for subject to
g and h	are the constraints of the optimization problem
g(x)	are equality constraints
h(x)	are inequality constraints
Ep	means annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2,6 and heat produced for commercial use multiplied by 1,1 (GJ/year)
Ef	means annual energy input to the system from fuels contributing to the production of steam (GJ/year)
Ew	means annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year)
Ei	means annual energy imported excluding Ew and Ef (GJ/year)
0,97	is a factor accounting for energy losses due to bottom ash and radiation
CCF	is climate correction factor calculated in accordance with Directive 2015/1127
Pr	Thermal input by waste (Mr * LHV)
Pc	Thermal input by auxiliary fuel
Pa	Thermal input by combustion air
Pe	Electrical operating energy
Pu	Useful thermal power
Psp	Thermal power with boiler blowdown
Pf	Heat loss by flue gas
Ps	Heat loss with slag
Pd	Heat loss by convection and radiation
Pi	Heat loss by unburnt in waste and flue gas
R	waste burned;
C	auxiliary fuel;
A	combustion air;
ft1	feedwater;
s	slag;
f	flue gas;
ft2	steam;
sp	boiler blowdown