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Criteria for Enhanced Monitoring and Control Plans for a Waste Gasification Plant

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Abstract **– The Environmental Monitoring Plan (EMP) and the Monitoring and Control Plan (MCP) are key documents required respectively in Environmental Impact Assessment (EIA) procedures and in the Integrated Environmental Authorization (IEA) for activities subjected to this procedure. Both documents aim at preventing impacts on the environment and human health and/or quickly taking actions if anomalous levels of pollutants are found in the environment. Trentino is an Italian region located in the Alps characterized by high population density in its valleys, complex terrain and, thus, a low level of dispersion of the atmospheric pollutants. The research carried out in Trentino in the last two decades has allowed identifying innovative monitoring approaches to point out issues that conventional methodologies could not detect. The present paper provides the key elements of an EMP that must be included in the EIA of a waste gasification plant. The paper proposes unconventional monitoring campaigns to guarantee a more efficient control of the areas influenced by the plant before, during and after its construction. The paper also discusses key aspects of an MCP for plants that are subjected to IEA. The final aim is to make this paper a reference document to 1) evaluate new projects of waste combustion plants, 2) suggest alternative monitoring methodologies to investigate the role of specific pollutants in peculiar contexts, and 3) prescribe a specific surveillance plan in the case of a plant that is subjected to IEA. Considerations on differences with conventional plants were also included.**

Keywords **– Air concentration; air pollutants; atmospheric deposition; emissions; heavy metals; Persistent Organic Pollutants (POPs); sediments; soil contamination.**

Nomenclature

BAT	Best available techniques	PAHs	Polycyclic aromatic hydrocarbons
BRef	BAT reference document	PCBs	Polychlorinated biphenyls
EIA	Environmental impact assessment	PCDD/Fs	Polychlorinated dibenzo-*p*-dioxins and furans
EMP	Environmental monitoring plan	POPs	Persistent organic pollutants
GHG	Greenhouse gas	rMSW	Residual municipal solid waste
IEA	Integrated Environmental Authorization	SF	Slope factor
IUR	Inhalation unit risk	VOCs	Volatile organic pollutants

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MCP	Monitoring and control plan	WtE	Waste-to-Energy
MSW	Municipal solid waste		

1. INTRODUCTION

Thermal waste-to-energy (WtE) processes are significant emission sources of various air contaminants, among which persistent organic pollutants (POPs) like polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) have contributed to develop a public opposition to the construction of new plants over the years [1]. The emissions of POPs from the waste sector show a decreasing trend over the last decades [2], thanks to the adoption of more stringent emission limit values by countries and the contemporary adoption of improved air pollution control technologies. The reduction of POP emissions has let other air contaminants to emerge as concerning pollutants, due to their demonstrated long-term toxicity to humans, their bioaccumulation potential and their non-negligible concentrations at the emission level. Among these air contaminants, inorganic (cadmium and chromium VI) and organic (polycyclic aromatic hydrocarbons) compounds have received the attention of researchers recently [3]–[5].

However, WtE processes are still crucial in integrated waste management approaches. They respond to the need for reducing the amount of municipal solid waste (MSW) that would otherwise be disposed of in landfills and, meanwhile, recovering energy from waste [6], [7]. For this reason, WtE plants must adopt accurate surveillance protocols to monitor their environmental impacts on nearby areas, verify the compliance with authorized limit values and guarantee the safety of operation. Environmental monitoring plans (EMPs) and Monitoring and control plans (MCPs) are documents that must be included respectively in the environmental impact assessment (EIA) and Integrated Environmental Authorization (IEA) procedures. Preparing solid EMPs and MCPs is the key to guarantee that a WtE plant induces acceptable impacts on human health and the environment. At a higher level, Strategic Environmental Assessment, as suggested in a recent paper [8], would provide roadmaps for planning the installation of new activities. Communicating the efforts made in the preparation of such plans and showing how all aspects are properly addressed may help to increase the public acceptance of the WtE sector.

Compared to waste incineration, gasification and post-combustion of the generated syngas have some advantages: greenhouse gas (GHG) emissions are lower thanks to higher conversion performances and because no additional fuel is needed to sustain the process [9]; the formation of organochlorinated compounds is lower because of the reducing conditions occurring during the gasification process [10]; the emissions of nitrogen oxides are reduced because syngas combustion is more easily adjustable than direct combustion [11]. Waste gasification also opens to different ways of syngas exploitation: besides combustion, syngas can be converted to chemicals and fuels [12]. These reasons justify the recent interest in waste gasification processes.

The present paper aims at presenting the contents of solid EMPs and MCPs to guarantee safety and the minimization of the risk for health during the operation of a waste gasification plant. A reference plant, located in a province in the Italian Alps (Trentino), will be adopted as an example of waste gasification in the Alpine region. The presence of human settlements in valleys and the limited atmospheric dispersion caused by orography make this area a challenging geographical context from the point of view of air quality and health risk. The same considerations could be adapted to other WtE technologies. A series of publications, produced in Trentino in the last decades, will be presented to discuss alternative monitoring methodologies that may be adopted to improve the conventional monitoring approaches in use. The final aim is to produce a document to evaluate proposals for EMPs and MCPs and guide the elaboration of monitoring and surveillance plans for WtE plants, suggesting novel monitoring methodologies.

2. METHODS AND METHODOLOGY

To provide the key elements of an EMP, both a conventional and an advanced approach will be proposed. The conventional approach is based on previous EMPs carried out in EIA procedures for WtE plants. In particular, the elements of an EMP of a waste gasification plant with local combustion of the syngas generated from waste will be considered as an example. The plant has not been constructed for administrative issues, but a detailed EIA was carried out on it. Advanced methodologies for emission and environmental monitoring will be discussed based on the results of a 10-year research activity carried out in Trentino on WtE plants and on a steel-making plant located in a valley. Some of the unconventional methodologies that will be described were considered in the EMP of the waste gasification plant taken as an example. A comprehensive multi-step scheme will be presented, including both basic and novel environmental monitoring procedures.

The reference gasification plant would have been located in the main valley that crosses Trentino, oriented North-South. The expected plant location is about 10 km far from the northern boundary of Trentino. In that location, the valley is about 2.5 km wide. Small villages are present and are located at a distance > 1 km from the plant. In the surroundings of the plant's location, other industrial activities and an important highway are present. In that point, the valley hosts agricultural activities based on the cultivation of apples and grapes for making wine. According to its project proposal, the plant would have treated refuse-derived fuel and sorted non-hazardous waste. However, advances in the gasification sector are expected to make this technology able to treat residual MSW (rMSW) directly in the incoming years [12]. A plant with this size would be able to cover the production of rMSW by a community of 500 000 inhabitants performing a high-level selective collection of MSW like the Province of Trento [13], [14].

The same approach will be applied to present the key elements of an MCP. Typical monitoring and control activities will be presented, based on the requirements of the European legislation 166/2006 [15]. Direct references to the environmental impact study of the reference waste gasification plant will also be included. Additional considerations will be made to improve the conventional monitoring and control approach.

3. RESULTS

3.1. EMP

An EMP requires the definition of monitoring protocols for environmental pollutants in the area of influence of the plant and at the main emission sources. A solid EMP should start from the results of a dispersion modelling, i.e. maps of annual mean (and/or maximum, depending on the pollutant) ambient air concentrations and atmospheric deposition to soil (for persistent pollutants). These results alone are enough to identify hotspots for different air pollutants emitted by the plant, i.e. the cells of the computational domain where the ambient air concentrations and deposition are the highest. Hotspots are certainly points where ambient air concentrations or atmospheric deposition and soil concentrations should be monitored, depending on the pollutant and on the land use in that specific location.

Atmospheric deposition and soil concentrations should be monitored for persistent pollutants (POPs and heavy metals) in hotspots or if it is likely that those pollutants entail a significant risk for health due to the presence of sensitive buildings/areas or agricultural/livestock activities in those locations. As a matter of fact, persistent pollutants may enter the human body through different routes, like accidental soil ingestion (in the case of children playing outside a school/kindergarten or in a playground), dermal contact with soil or contaminated fruit/vegetables, ingestion of contaminated fruit/vegetables and consumption of locally grown animal-derived food that may contain POPs due to exposure of the animals to these substances. Land use data are also key information to carry out a solid health risk assessment, which may highlight the pollutants that most contribute to the cancer risk or to non-carcinogenic long-term effects in the exposed population. Obviously, the EMP should not neglect those compounds. Indeed, a hotspot may fall in an area with no agricultural/livestock activities or sensitive buildings/areas, but those areas may nevertheless receive significant contributions of POPs and/or heavy metals and may deserve the installation of sampling points. In addition, sampling points should be located in residential and recreational areas falling in the area of influence of the plant. Although the contaminants emitted by the plant may not contribute to food-chain contamination or accidental soil ingestion, and dermal contact with soil are unlikely to occur, the residential population may be exposed to the emitted air pollutants through inhalation. The health risk assessment highlights the routes and the pollutants that contribute most to the cancer and non-cancer risk in the area. An EMP should also contain monitoring protocols for noise pollution. In this case, the definition of the monitoring locations is based on the verification of the compliance of the results of acoustic modelling with the limits imposed by legislation and noise zoning plans. Finally, the monitoring of water pollutants should also be included in an EMP. In the case of waste gasification, however, water is not considered as the primary route of exposure. For this reason, in this paper the monitoring of air pollutants will receive greater attention.

The toxicological characteristics of carcinogenic compounds should also be considered. Some carcinogenic pollutants produce effects only through inhalation, some only through ingestion and dermal contact, and some through all the exposure routes. Knowing the dominant route of exposure for each pollutant, it is possible to define which environmental compartment to sample and avoid setting up monitoring activities on environmental compartments that may not be relevant for a specific substance. This would simplify the management of environmental monitoring activities and reduce the costs. Table 1 presents the values of the inhalation unit risk (IUR) values and the ingestion/dermal slope factors (SFs) for the carcinogenic compounds regulated by the environmental legislation on waste incineration plants [16].

TABLE 1. CANCER SLOPE FACTORS FOR THE CARCINOGENIC COMPOUNDS REGULATED BY THE EUROPEAN LEGISLATION [18]

Substance	**IUR, $(\mu g\ m^{-3})^{-1}$**	**Ingestion/dermal SF, $(mg\ kg_{bw}^{-1}\ d^{-1})^{-1}$**
Arsenic	4.3E-03	1.5E+00
Cadmium	1.8E-03	–
Chromium VI	8.4E-02	5.0E-01
Polycyclic aromatic hydrocarbons (PAHs)	6.0E-04	1.0E+00
PCDD/Fs	3.8E+01	1.3E+05
Dioxin-like PCBs	3.8E+00	1.3E+04

The IUR is defined by the U.S. Environmental Protection Agency as the 'upper-bound excess lifetime cancer risk estimated to result from continuous exposure to an agent at a concentration of 1 µg/m³ in air'. The SF is defined as 'an upper bound, approximating a 95 % confidence limit, on the increased cancer risk from a lifetime exposure to an agent' [17].

It is possible to observe that substances like POPs, PAHs and arsenic may deserve attention in an EMP both in terms of ambient air and deposition/soil monitoring (possibly integrated with unconventional monitoring approaches discussed in Table 2) if their role in the determination of the cancer risk is verified by the health risk assessment. On the contrary, for heavy metals like cadmium and chromium VI (Cr VI), the main exposure route is inhalation; thus, monitoring approaches that consider the dietary and dermal routes of exposure are of secondary importance. For these compounds, the EMP should rather carefully focus on ambient air monitoring. Cr VI, in particular, exceeds cadmium in terms of cancer potency by almost two orders of magnitude. This makes Cr VI a heavy metal of particular concern in terms of inhalation. However, the detection limit of Cr VI in air samples was found to be 0.33 ng/m^3 by Huang *et al.* [19]. According to the health risk assessment carried out for the waste gasification plant considered as an example in this paper, Cr VI would give an acceptable cancer risk (conventionally assumed as one excess cancer case in a million people) when its maximum air concentration is about 1/10 of the detection limit. This means that the compliance with the acceptable cancer risk could not be verified by on-field measurement. For this reason, it is crucial to monitor Cr VI at the emission level, where Cr VI concentration is higher. A methodology for the monitoring of Cr VI at the stack of a waste combustion plant and for the tentative definition of an emission limit value was recently developed [20]. Normally, the total Cr concentration is monitored at the stack of a WtE plant. Cr speciation is challenging for the high costs of analysis and for the need to obtain reliable results at relatively low concentrations. However, different methodologies for Cr speciation are available [21]–[25]. Fig. 1 shows a general conceptual scheme that helps to understand the workflow behind the preparation of an EMP. The scheme clearly shows how land-use information, topological data and the dispersion and health-risk modeling chains are crucial for the definition of environmental monitoring protocols in the area influenced by a large emission source like a waste gasification plant.

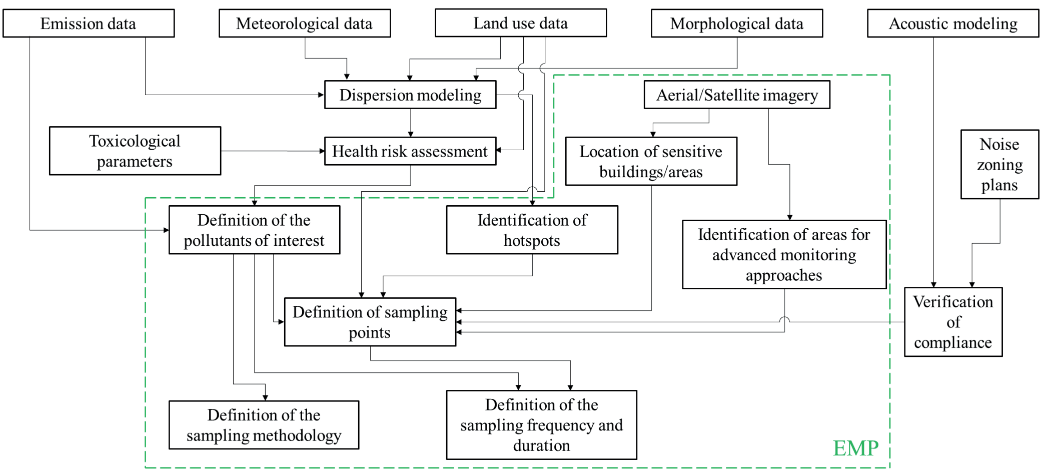

Fig. 1. Conceptual scheme for the definition of an EMP with inclusion of advanced monitoring methodologies.

The sampling frequency is another important aspect to be defined. Emissions must be monitored according to the regulation in force in each country but, preferably, a higher sampling frequency should be adopted. This increased frequency could be reduced if the stack concentrations were significantly lower than the guaranteed emission values. Concerning other environmental compartments of interest for air pollutants, in the specific case of the waste gasification plant considered in this paper, the frequency was set at one sampling per month (sampling duration: 7 days) for ambient air and deposition monitoring. Annual frequencies were assumed for sediment and soil sampling. The monitoring frequency of noise levels was set at once or twice per year, depending on the sampling point. The monitoring of water (sewage water, receiving water body, groundwater) was assumed to take place monthly for oils and suspended solids, and every two weeks for metals, hydrocarbons, sulfates, nitrates and chlorides.

Alternative approaches to conventional air, soil and deposition monitoring have been developed in Trentino in the last two decades. Most of them concern the monitoring of POPs in unconventional environmental compartments like sediments, sewage sludge and conifer needles. The characterization of PCDD/F and PCB atmospheric deposition, rather than bulk deposition data, may also reveal the contribution of different sources of these pollutants in the sampling locations. Table 2 describes the alternative methodologies developed in Trentino on monitoring approaches for POPs and heavy metals and for the monitoring of Cr at the emission level.

TABLE 2. DESCRIPTION OF THE UNCONVENTIONAL METHODOLOGIES DEVELOPED IN TRENTINO FOR THE ENVIRONMENTAL MONITORING OF POPS AND HEAVY METALS

Method	**Description**	**Reference**
Characterization of the sediments of a pond	PAHs, PCDD/Fs and PCBs can accumulate in soils and sediments. Natural or artificial ponds are interesting reservoirs of POPs being trapped in sediments. By analyzing the different layers of a sediment sample, if the sedimentation rate is known, it is possible to obtain the trend of past depositions and understand if changes in the emissions from nearby sources occurred. In addition, the characterization of sediment samples in terms of PAH, PCDD/F and PCB speciation may provide useful information on the origin of contamination, since each combustion activity is characterized by defined ratios between single PAHs and dioxin congeners.	[26]
Characterization of municipal sewage sludge	POPs may enter the food chain and be excreted by humans. Eventually they reach wastewater treatment plants, where they concentrate in sewage sludge. Analyses on dewatered sewage sludge at specific time frequency may detect potential anomalies in the human exposure to POPs with respect to background levels.	[27]
Determination of heavy metals and POP content in conifer needles	Quali-quantitative analyses on conifer needles may allow obtaining indications on the influence of local combustion activities. Scanning electron microscopy (SEM) can reveal the presence of heavy metals on dusts and the origin of the latter. High-resolution capillary column gas chromatography and mass spectrometry (HRGC/HRMS) can be used to obtain the concentration of POPs in the needles, while inductively coupled plasma atomic emission spectroscopy (ICP-AES) allows determining the concentration of metals. Analyzing needles of different ages on the same tree allows reconstruct the temporal trend of emissions and deposition over the years.	[28]
Characterization of deposition samples	The speciation of PCDD/Fs and PCBs in deposition samples allow determining the profiles of PCDD/F and PCB congeners. These can be compared with typical congener profiles of various industrial/civil combustion activities that can be retrieved in the literature. The comparison may reveal the main source responsible for the deposition of POPs in the area. Monthly	[29]

Method	Description	Reference
	analyses on the deposition samples allow for the identification of different sources that may give variable contributions over a year.	
Monitoring of Cr VI at the stack	If Cr speciation is feasible, the following procedure should be adopted: 1) calculate the Cr VI ambient air concentration at ground level that corresponds to the acceptable cancer risk for single pollutants (10^{-6}); 2) calculate (through dispersion modeling or dilution factors) the Cr VI stack concentration that gives the acceptable ground level concentration; 3) set a sampling frequency at the stack; 4) monitor the Cr VI concentration at the stack; 5) verify the compliance with the acceptable Cr VI stack concentration. If Cr speciation is not feasible: 1) assume that the content of Cr VI in total Cr is 20 %, i.e. the highest content found in the literature [30]; 2) calculate the Cr VI ambient air concentration at ground level that corresponds to the acceptable cancer risk for single pollutants; 3) calculate the Cr VI stack concentration that gives the acceptable ground level concentration; 4) calculate the corresponding total Cr stack concentration through the previous assumption; 5) verify the compliance with the acceptable total Cr stack concentration.	[20]

In the case of the waste gasification plant taken as an example of application of an EMP, the results of the dispersion modelling, combined with the health risk assessment, allowed defining the locations of the sampling points for the monitoring of air pollutants adopted in the EMP. Two sampling points were considered for both ambient air concentrations and atmospheric deposition, two points were selected for soil monitoring and one point was chosen for sediment sampling, thanks to the presence of a nearby pond (Fig. 2).

3.2. MCP

Directive 96/61/CE [31] introduced the procedure for issuing the Integrated Pollution Prevention and Control (IPPC) to the main European industrial production activities. Control, according to IPPC, 1996, constitutes a form of verification of the conformity of a given object (plant, apparatus, activity, product) to a predetermined regulatory paradigm. It can be carried out in a preventive form, anticipating the realization of the object and evaluating in advance the requirements on the basis of the project, or subsequently, once the object is in operation. Each IPPC procedure must be described through the verification of the application of best available technologies (BAT) reference documents (BRefs). Among the BRefs already approved, a reference document on general principles was edited regarding monitoring, defining the minimum contents of an MCP. MCP specifies the methods and frequency of measuring pollutants, the fundamental parameters of the production processes and abatement systems, as well as the relative evaluation methodology. In particular, the frequency of the analyses that the operator must carry out (self-checks) and those that must be guaranteed by the competent authority are established, the costs of which are in any case paid by the operator. As an example, Table 3 depicts the monitoring activity for different environmental components in the case of a plant that treats urban waste with a lower heating value on average equal to 10.5 MJ/kg (2500 kcal/kg). It is built on two lines, each with a treatment capacity of 15.5 t/h, over a period of approximately 325 days/year, equal to 7700 hours per year per line, operating at 90 % of the design capacity. It follows that each line burns approximately 100 000 t/y. The heat produced is used to generate electricity.

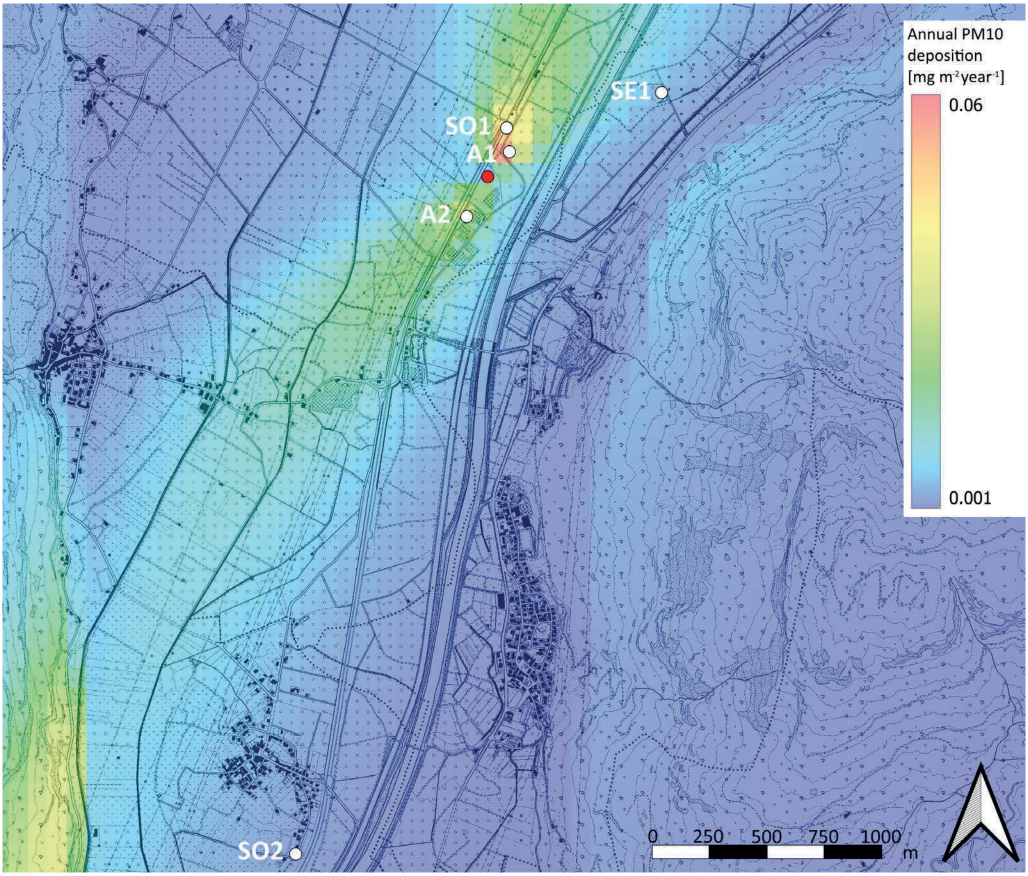

Fig. 2. Locations of the waste gasification plant and of the ambient air and deposition (A1, A2), soil (SO1, SO2) and sediment (SE1) sampling points defined by the EMP, overlapped to the PM10 annual mean deposition map; white circles represent the sampling points, the red circle represents the location of the stack.

TABLE 3. SYNOPTIC OVERVIEW OF MONITORING AND CONTROL ACTIVITIES

Self-check		**Environmental component**	**Authority**		
Measure	**Report**		**Inspection**	**Measure**	**Report**
		Resources			
Upon receipt	Annual	Raw materials	Annual		Annual
Monthly	Annual	Water resources	Annual		Annual
Daily	Annual	Energy	Annual		Annual
Monthly	Semi-annual	Fuel	Annual		Annual
		Air			
Daily/ quarterly	Annual	Continuous measures	Annual	Annual	Daily/annual
Monthly	Semi-annual	Periodic measures	Annual	Annual	Annual
		Water			
Quarterly	Annual	Periodic measures	Annual	Annual	Annual

		Noise environment		
3-years	3-years	Periodic measures to the point sources	Annual	3-years
		Waste		
Quarterly		Incoming waste	Annual	Annual
Monthly		Produced waste	Annual	Annual
		Process parameters		
Daily	Annual	Continuous measures	Annual	Annual
Annual	Annual	Performance index		Annual
Event-related	Annual	Extra-ordinary emission		Annual

In general, the EMP provides for monitoring by the plant operator for activities that may generate a possible environmental impact and whose assessments in the winter of an environmental impact assessment need post-operam verification with respect to the impact assumptions made. The MCP, on the other hand, also provides for an active role of the control authority that verifies over time its performance and all process parameters that may generate environmental and health impacts.

4. CONCLUSIONS

Solid EMP and MCP guarantee that the emissions and the operation of an industrial/civil plant are compatible with the geographical context where the activity is located, including the presence of resident population, sensitive buildings/areas and farming. In addition, the monitoring campaigns carried out before the construction of a plant, included in the EMP, are crucial to obtain the baseline to which the contribution of the plant will add. New monitoring approaches are available and allow pointing out anomalous levels of POPs, PAHs and heavy metals that conventional methodologies may not be able to detect. The present paper contributed to presenting such methodologies in a unified way, making them available to environmental consultants and assessors, and proposing new criteria (i.e., new data from novel methodologies) for a more rigorous assessment of project proposals.

Regarding WtE technologies, in the specific case of waste gasification, the emissions of GHGs, POPs and nitrogen oxides are lower compared to incineration. Thus, preparing a comprehensive EMP may even increase the level of trust of the local community in gasification plants subject to EIA. Analogously, a well-detailed MCP is expected to reassure the local community during the plant operations.

Considered the impacts of waste gasification and other waste combustion processes in terms of climate change, future strategies to be included in EMPs should consider the monitoring of GHG emissions. This would allow obtaining GHG emission factors for this sector, which is currently affected by uncertainties in the quantification of the non-biogenic carbon emitted. This way, it would be also possible to compare different WtE technologies in terms of GHG emissions.

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