

# **Emissions of airborne pollutants from the municipal solid waste incineration plants of Giubiasco (TI) and Hinwil (ZH)**

## **Final Report (12/2015 - 4/2016)**

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### **Abstract**

A field campaign has been performed in two municipal solid waste incineration plants in Switzerland, at Giubiasco (TI) and Hinwil (ZH). The aim was to measure airborne pollutants at different locations of the abatement systems and those released from the stacks into the atmosphere, in order to assess the efficiency of the abatement systems and the environmental impact of these plants.

Both incineration plants were equipped with an electrostatic precipitator, a DeNO<sub>x</sub> system based on the selective catalytic reduction (SCR) technology, and a bag-house filter. The main differences between the two plants were 1) the presence of a dry scrubber at Hinwil and a wet scrubber at Giubiasco, and 2) the location of the bag-house filters within the abatement system (last step of abatement at Giubiasco, between the dry scrubber and the DeNO<sub>x</sub> at Hinwil). Measurements were performed at different locations of the abatement system of the two plants, and additional measurements were undertaken at a near-field (~ 1 km) downwind site at Giubiasco.

During this study, we deployed a large set of instruments to measure the particle number concentration and size distribution. We also sampled particles on filters for subsequent analyses of the morphology, size, elemental composition, and water soluble anions. Finally, volatile organic compounds (VOCs) and trace gases (NO, SO<sub>2</sub>, CO, CO<sub>2</sub>, and O<sub>2</sub>) were also measured.

The particle concentration decreased significantly at two locations of the plants: at the electrostatic precipitator and the bag-house filter, while the DeNO<sub>x</sub> system removed up to 97% of the nitrogen oxides. The particle concentrations measured at the stacks were very low (< 100 #/cm<sup>3</sup>), stressing the efficiency of the abatement system of the two plants. Particles released from the stacks had a relatively uniform shape and size, and were possibly constituted of ammonium chloride salts. We did not see considerable amount of this type of particles at the near-field downwind site of Giubiasco, and the concentrations of chloride were rather low there, suggesting that the incineration plants released very limited amounts of particles to the surrounding areas.

## 1. Introduction

The total amount of waste in Switzerland is around 6 million tons (year 2014), of which recycled waste is the largest fraction (3'216'000 tons) followed by incinerated waste (2'791'000 tons) [BAFU, 2014]. Municipal waste in Switzerland is estimated to be about 729 kg/person and year, of which about 390 kg is recycled and 339 kg is burned in incineration plants. The current regulation on the treatment of waste in Switzerland demands that all combustible waste has to be burned before deposition (in force since 2004). This is also the case for sewage sludge, which is not allowed to be used as fertilizer in agriculture to avoid soil contamination with heavy metals (in force since 2006).

Waste incineration processes could be an important source of airborne pollutants [Jones and Harrison, 2016, and references therein]. A limited number of studies focused on the measurement of the particle number concentration released from the stacks into the atmosphere [Buonanno and Morawska, 2015, and references therein]. The 16 MSWI plants reported in that review paper had a median value of 5'500 #/cm<sup>3</sup> for the particle concentration in the stacks, with a 1<sup>st</sup> quartile at 1'000 #/cm<sup>3</sup> and a 3<sup>rd</sup> quartile at 57'000 #/cm<sup>3</sup>. Thus, the particle concentration reported in the different studies is highly variable, and depends on the filtration techniques included in the abatement systems and the order in which the filters are located in the plant. Most of the studies performed at MSWI plants focused on the emission of specific chemical compounds which are known to be significantly present in the flue gas of the plants, such as mercury [Svoboda et al, 2016] and other selected heavy metals [Zhang et al, 2008], engineered nanoparticles [Walser et al, 2012], dioxins [Zhou et al, 2015], and volatile organic compounds (VOCs) [Liu et al, 2012].

The emission of a wide range of pollutants from the waste incineration processes resulted in sophisticated abatement systems for exhaust air. Thus, incineration plants are generally equipped with electrostatic precipitators and bag-house filters for the elimination of particles, DeNO<sub>x</sub> and scrubbers (wet or dry) for the abatement of specific gaseous species (e.g. nitrogen oxides, dioxins, furans, mercury, acidic gases, VOCs) [Le Cloirec, 2012; Vehlow, 2015]. In Switzerland, the introduction of the Ordinance on Air Pollution Control (OAPC) in 1986 led to significant investments in the infrastructure of incineration plants regarding the reduction of emissions. Especially the emission of ultrafine particles was reduced to a total of 30 t per year which corresponds to only a few per mills of the total emissions of ultrafine particles in Switzerland [Hügi et al, 2008]. On the other hand, the above mentioned development also demonstrates the importance of monitoring and control of emissions from waste incineration.

The aim of the present project was to assess the environmental impact of municipal solid waste incineration (MSWI) plants, and the efficiency of their abatement systems. For that purpose, a field campaign was conducted at two different MSWI plants in Switzerland (at Hinwil ZH and Giubiasco TI) in December 2015 and April 2016. Particles and gases were measured at different locations of the abatement systems of the two incineration plants, and additional measurements were performed at the Communal Stadium of Giubiasco, a site located < 1 km downwind of the MSWI plant of Giubiasco, in order to assess the environmental impact of that plant to the surrounding areas.

## 2. Description of the municipal solid waste incineration plants

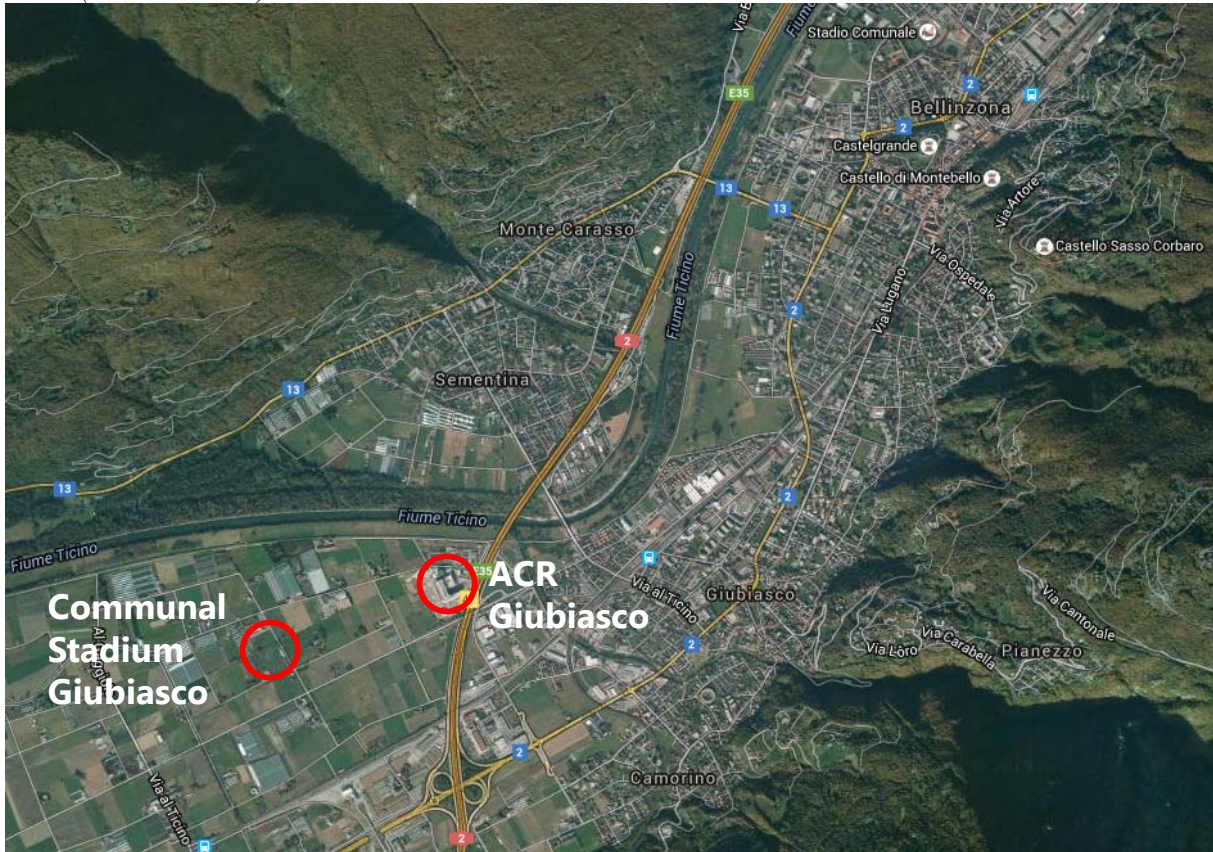
### 2.1 Giubiasco (TI)

First operated in 2010, Giubiasco's solid waste incineration plant is the only infrastructure of its kind in Ticino, Switzerland. Designed to treat 67 MW or 160'000 tons of solid waste annually, this complex facility costed over 330 million CHF [Azienda Cantonale dei Rifiuti, 2014]. It is positioned south from a waste water treatment plant and west of the A2 Highway in the municipality of Giubiasco on about 40'000 m<sup>2</sup> of land (Figure 1).

The plant uses two lines to incinerate waste on moving grates with an estimated operation of 8000 hours a year. The heat produced in the furnaces is used to generate electrical energy by a steam

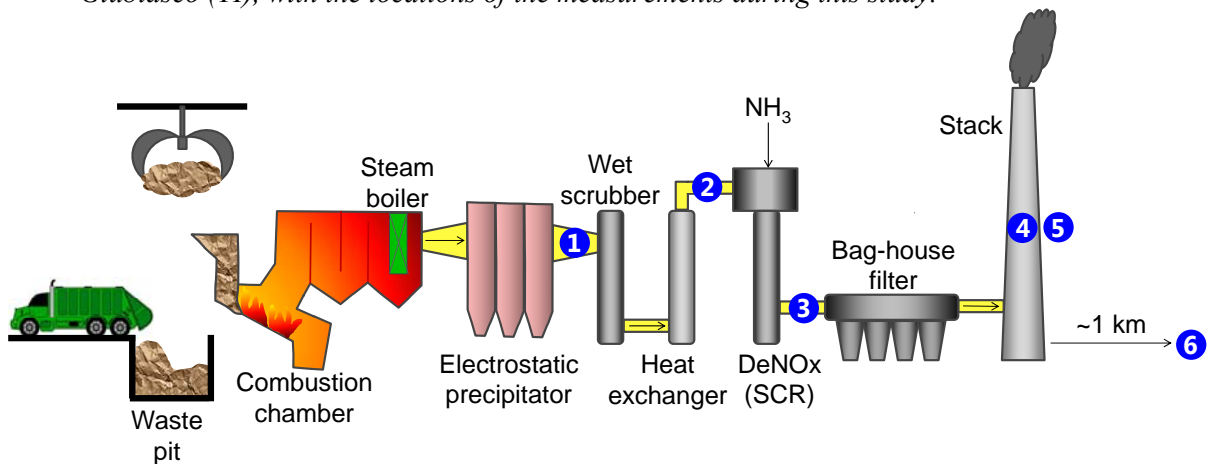
turbine, whereas the excess heat is distributed in a district heating system to various users in the form of hot water. All in, nearly 100 GWh electricity and 20 GWh heat are produced every year; this is enough to meet the average electrical energy demand of 23000 families and the average heat demand of 2300 households in the region [Azienda Cantonale dei Rifiuti, 2014].

*Figure 1. Map of the Bellinzona (TI) metropolitan area, with the location of the municipal solid waste incineration plant of Giubiasco and the Communal Stadium (downwind site).*



The incineration plant has a complex abatement system to remove particles and gases emitted during the incineration process (Figure 2). The abatement system contains an electrostatic precipitator with three units, a wet scrubber, a DeNOx system based on the selective catalytic reduction (SCR) technology, in which nitrogen oxides are reduced into N<sub>2</sub> with the addition of ammonia in the presence of a catalyst, and finally a bag-house filter before the release into the atmosphere through a stack.

**Figure 2.** Schematic drawing of the abatement system of the incineration plant at Giubiasco (TI), with the locations of the measurements during this study.



**Locations of the measurements:**

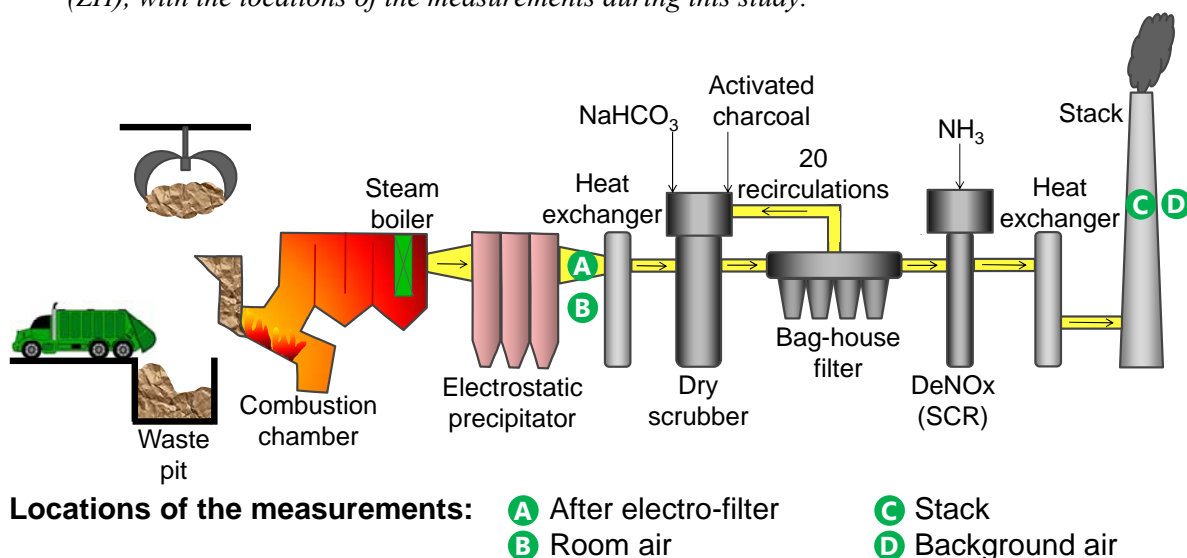
- |                           |                          |                  |
|---------------------------|--------------------------|------------------|
| ① After electro-filter    | ③ After catalyst (DeNOx) | ⑤ Background air |
| ② Before catalyst (DeNOx) | ④ Stack                  | ⑥ Downwind site  |

**2.2 Hinwil (ZH)**

The incineration plant of Hinwil (Figure 3) contains three ovens, in which the thermal decomposition of the waste takes place. Each of these ovens is followed by its own electro-filter for the removal of dust. Then, the gas coming from the three ovens are mixed, and then separated in two parallel paths. On each path, the gas is first treated with sodium bicarbonate ( $\text{NaHCO}_3$ ) in order to remove  $\text{HCl}$ ,  $\text{SO}_2$ ,  $\text{SO}_3$ , and  $\text{HF}$ . The gas recirculates 20 times in the reactor to high efficiency of removal of these compounds. The last step is the elimination of nitrogen oxides with a DeNOx. The system used at Hinwil is also based on the SCR technology (like at Giubiasco), in which ammonia ( $\text{NH}_3$ ) is added to reduce  $\text{NO}$  and  $\text{NO}_2$  into  $\text{N}_2$ . The remains of dioxins and furans are also destroyed during this step. The operating temperature of the catalyst is quite low at Hinwil, around  $180\text{-}190^\circ\text{C}$ , compared to other incineration plants where the temperature reaches  $230\text{-}240^\circ\text{C}$ . However, when the catalyst is used at “low” temperature, it needs to be periodically regenerated by heating it up to  $320^\circ\text{C}$  with a propane burner during a few hours. Finally, the gas is released into the atmosphere through two stacks.



**Figure 3.** Schematic drawing of the abatement system of the incineration plant at Hinwil (ZH), with the locations of the measurements during this study.



In summary, the two incineration plants are equipped with an electrostatic precipitator, a DeNOx using the SCR technology, and bag-house filters before the release of airborne pollutants into the atmosphere. The two main differences between them are 1) the presence of a wet scrubber at Giubiasco and a dry scrubber at Hinwil (after the electrostatic precipitator in the two cases), and 2) the location of the bag-house filters within the abatement systems (before the stack at Giubiasco, between the dry scrubber and the DeNOx at Hinwil).

### 3. Methods

Measurements and samplings have been performed at different locations in the two incineration plants. At Giubiasco (Figure 2), measurements were performed **1** between the electrostatic precipitator and the wet scrubber, **2** between the wet scrubber and the catalyst, **3** between the catalyst and the bag-house filter, and finally **4** at the stack. The measurement **1** between the electrostatic precipitator and the wet scrubber has been done in two conditions: with the electrostatic precipitator running and with one of the three units of the electrostatic precipitator stopped, in order to check the efficiency of the electrostatic precipitator in the removal of particles. In addition to these measurements within the incineration plant, two measurements have been done, **5** the first one for background ambient air next to the stacks of the plant, and **6** the second one at the Communal Stadium of Giubiasco, when the wind direction was bringing plumes from the incineration plant to the Stadium. This location is considered as a “downwind site”, and was chosen based on the wind direction the day of the measurement in order to assess the environmental impact of the plant to the surrounding areas. At Hinwil (Figure 3), measurements were performed only **A** after the electrostatic precipitator and **C** at the stack. Here again, additional measurements have been done, **B** the first one for the room air next to the conduit after the electrostatic precipitator, and **D** the second one for the background ambient air next to the stack. These two additional measurements have been done with all the flanges of the conduit and of the stack closed.

Instruments deployed at each location are summarized in Table 1. On one hand, we deployed a series of instruments measuring in real time the particle concentration (CPC) and size distributions, from the ultrafine fraction (SMPS) up to coarse particles (APS). On the other hand, particles and VOCs were sampled, either on filters or on adsorbing cartridges, for subsequent analyses in the lab. After the samplings, filters were cut in three parts. First, approximately 10% of each filter was analyzed by scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDX) for the morphology, size, and elemental analysis. The remaining parts of each filter were then cut in two equal

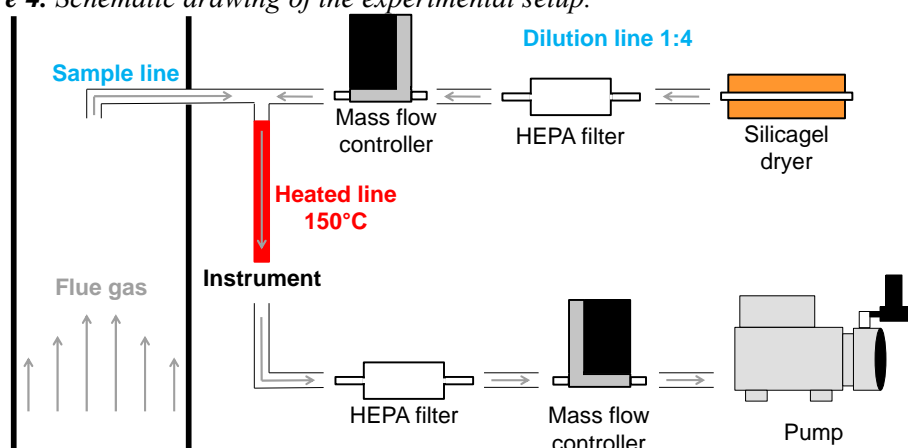
pieces (so approximately 45% each) and one piece was analyzed by ion chromatography (IC) for the measurement of 7 selected water soluble anions. The last piece of each filter is stored in the fridge, and is still available for another analysis if necessary, or to redo one of the above-mentioned measurements (SEM/EDX or IC) in the case of an analytical problem. Finally, we deployed a portable gas analyzer to monitor NO, SO<sub>2</sub>, CO, CO<sub>2</sub>, and O<sub>2</sub>. The list of all the measurement periods is given in Table A1 (in the Annex), while the details of all the filter and VOCs cartridges samplings are given in Tables A2 and A3, respectively.

**Table 1.** List of instruments deployed at the two incineration plants.

Instrument	Time resolution	Parameter
Condensation particle counter (CPC)	1 sec	Particle number concentration
Scanning mobility particle sizer (SMPS)	2.5 min	Particle size in the range 7-700 nm
Aerodynamic particle sizer (APS)	20 sec	Particle size in the range 0.5-20 μm
Filter holder, Nuclepore polycarbonate filters (Ø 47 mm, pore size 0.2 μm), and Sterlitech polycarbonate filters (Ø 47 mm, pore size 0.4 μm)	30 min	Particle morphology, size, and elemental analysis by SEM/EDX 7 selected anions by ion chromatography
VOCs sampling system with Tenax TA and Carboxen 569 cartridges	20 min	Volatile organic compounds by TD-GC/MS
Portable gas analyzer	1 sec	NO, SO <sub>2</sub> , CO, CO <sub>2</sub> , O <sub>2</sub>

Figure 4 shows a schematic drawing of the experimental setup, and Figure 5 a few pictures of the sampling sites and the equipment. Several apertures are available on the sides of the conduits which fit the standard Empa flanges. The instruments were connected to the conduits with a similar flange, but containing two 1" connections (Figure 5c). Before the start of the measurements, the position of the inlet of the sampling line was tested with the CPC. For that purpose, we connected the CPC directly to the sampling line, and we pushed little by little the line into the conduits. The final position of the inlet in the conduits was the one for which the particle concentration was the highest. The particle concentration varied within 20%, depending on how deep the line was pushed into the conduit, and the best position was each time close to the center of the conduits (around 70-90 cm from the side of the conduits). In order to avoid water condensation in the sampling line, we diluted the sample air by a factor of 4 with dried and filtered air, and we used a line heated up to 150°C. We also reduced the total flow across the system by using one instrument at a time (Figure 4).

**Figure 4.** Schematic drawing of the experimental setup.



**Figure 5.** Installation of the equipment at Hinwil (ZH) a) after the electrostatic precipitator, and b), c), d) at the stack, and at Giubiasco (TI) e) after the catalyst, f) after the electrostatic precipitator, g) at the stack, and h) at the Communal Stadium of Giubiasco with the incineration plant and the plume in the background.

a)



b)



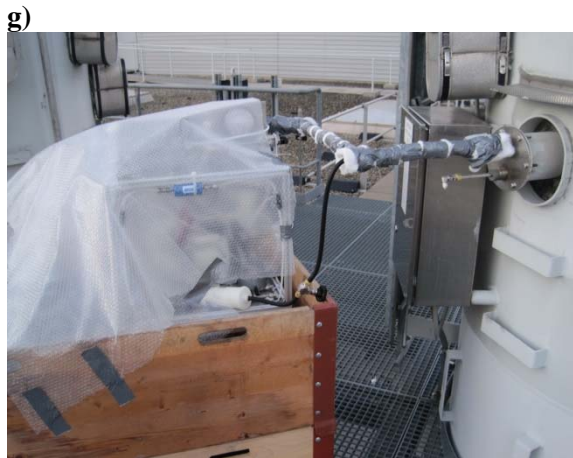
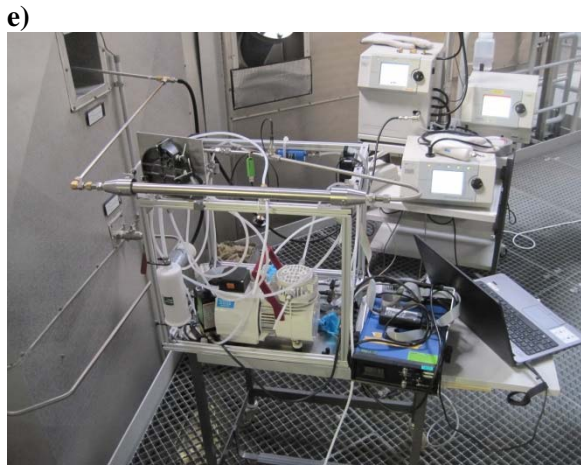
c)



d)







## 4. Results and discussion

### 4.1 Particle number concentrations

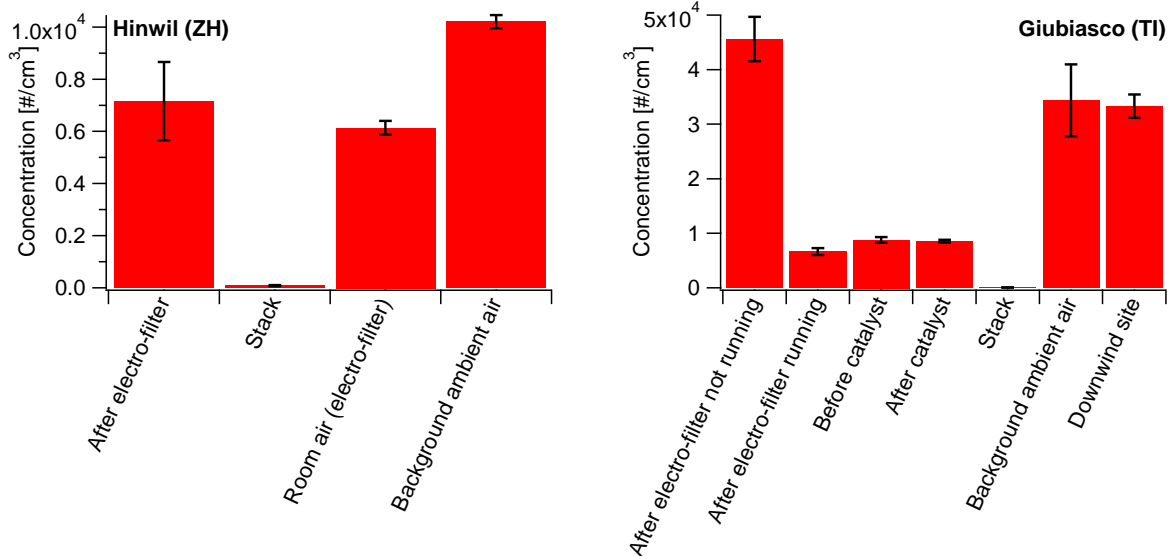
The particle number concentration was measured with a CPC, but this parameter could also be calculated from the SMPS size distributions. Figure A1 (in the Annex) shows a scatterplot of the total particle number concentration obtained by integrating the SMPS size distributions vs the particle number concentration measured by the CPC. Results obtained with the two instruments were very well correlated ( $r^2 = 0.997$ ), with a slope of 1.28, which means that the SMPS was giving a higher concentration than the CPC by 28%. The difference may be due to different size cut-off between the two instruments. Indeed, for the CPC, the minimum detectable size is 10 nm, while with the SMPS, we went sometimes down to 6 nm, depending on the location.

Figure 6 shows the particle number concentration at each location of the two incineration plants. We clearly notice that the particle concentration decreased significantly at two locations: after the electrostatic precipitator and after the bag-house filter. At Giubiasco, the particle concentration after the electrostatic precipitator was  $45'000 \text{ \#/cm}^3$  when two of the three units were running (i.e.  $2/3$  of the total capacity of the electrostatic precipitator), and decreased by a factor of 7, down to  $7'000 \text{ \#/cm}^3$ , when the third unit was turned on. Then, the particle concentration remained constant after the wet scrubber and the DeNO<sub>x</sub>, and dropped drastically (down to  $< 100 \text{ \#/cm}^3$ ) after the bag-house filter. An important result is the very low particle concentration at the stacks ( $< 100 \text{ \#/cm}^3$ ) at Giubiasco as well as at Hinwil. This result is confirmed by the measurements performed with probes located after the bag-house filter and belonging to the MSWI Hinwil, which show that the particle mass concentration is  $0.00 \text{ mg/Nm}^3$  during most of the time, except during some spikes (Figures A2 and A4 in the Annex). This result suggests that emission level of the plants in terms of the particle concentration is very low



when the systems function normally. Compared to previous studies, these results are the lowest concentrations ever reported for the stacks of MSWI plants, the lowest concentration reported so far being 350 #/cm<sup>3</sup> in a refuse derived fuel incinerator equipped with bag-house filter [Buonanno et al, 2011]. In comparison, measurements performed outside showed higher particle concentrations, around 10'000 #/cm<sup>3</sup> at Hinwil and 35'000 #/cm<sup>3</sup> at Giubiasco. Concentrations measured next to the stack (background ambient air) and at the Communal Stadium (downwind site) were very similar.

**Figure 6.** Average particle number concentrations measured at the different locations of the incineration plants of Hinwil (left panel) and Giubiasco (right panel). Error bars correspond to the standard deviation (1σ). Data is from the CPC 3007.



#### 4.2 Particle number size distributions

Figure 7 shows size distributions of submicron particles measured in the two incineration plants with the SMPS. We notice that after the electrostatic precipitator, which is at the beginning of the abatement systems, the particle size was mainly around 300 nm, with a very narrow size distribution (width at half maximum around 150 nm). Size distributions at this location were very similar at Giubiasco and Hinwil (Figure 7c), and also comparable to previous studies in which the particle number size distributions were centered at 140 nm [Maguhn et al, 2003] and 200 nm [Buonanno et al, 2011]. A very large fraction of these particles at 300 nm was removed in the following steps of the system, where particles were much smaller and had a very broad size distribution (from 20 to 300 nm). Size distributions measured at the stacks were only noise, given the very low particle concentration there. In the background air next to the stack and at the downwind site, particles were mainly in the ultrafine range (< 100 nm), with a mode at around 30-40 nm and a broad size distribution.

**Figure 7.** Average particle size distributions in the range 7-800 nm measured at the different locations of the incineration plants of (a) Hinwil (ZH) and (b) Giubiasco (TI). Comparison between the two plants (c) after the electro-filter. Data come from the SMPS.

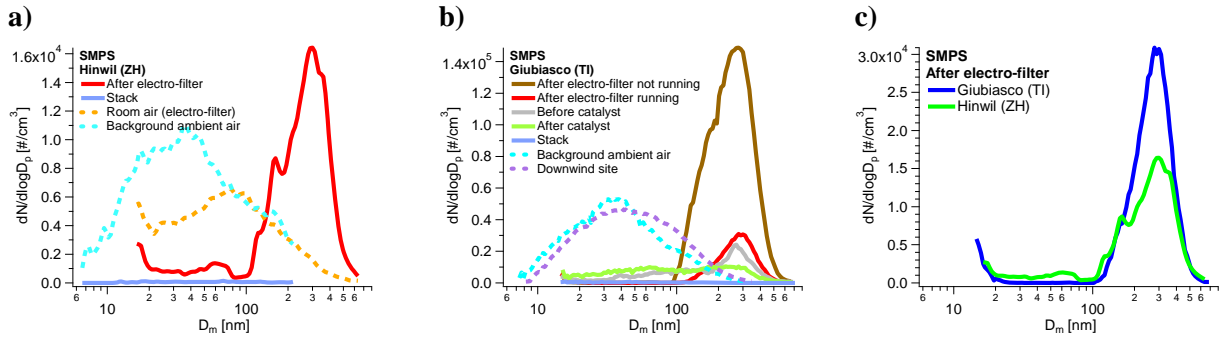
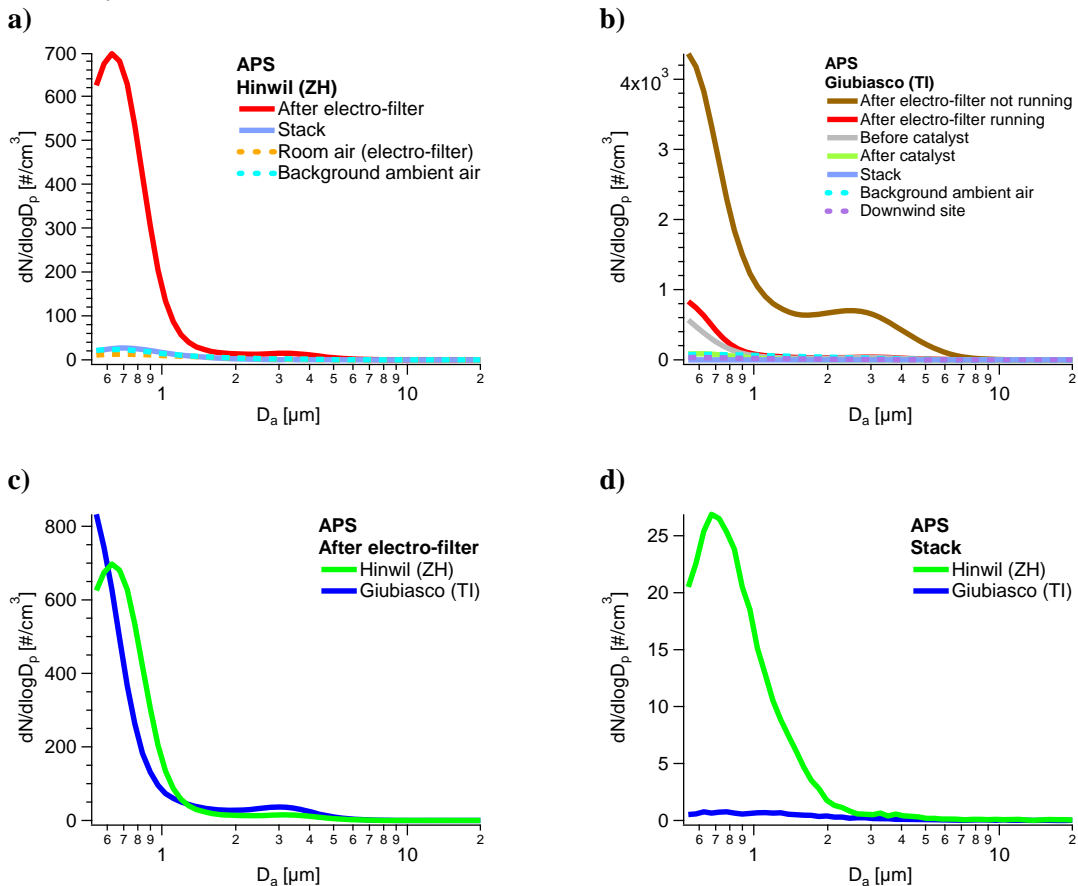


Figure 8 shows size distributions obtained with the APS, which measures larger particles than the SMPS (in the range 0.5-20  $\mu\text{m}$ ). We notice that when the electrostatic precipitator was not running, a large fraction of the particles was smaller than 1  $\mu\text{m}$ , with also the presence of a significant amount of coarse particles at around 2.5  $\mu\text{m}$ . When the electrostatic precipitator was running, most of the coarse particles larger than 1  $\mu\text{m}$  were removed from the system, and particles observed in the rest of the conduit were mostly in the submicron range. This result was obtained at Giubiasco as well as in Hinwil (Figures 8c and 8d). It is important to mention for Figure 8d that even if a clear peak appeared in the size distribution at Hinwil, the total particle concentration was very low.

**Figure 8.** Average particle size distributions in the range 0.5-20  $\mu\text{m}$  measured at the different locations of the incineration plants of (a) Hinwil (ZH) and (b) Giubiasco (TI). Comparison between the two plants (c) after the electro-filter and (d) at the stack. Data come from the APS.



### *4.3 Particle morphology, size, and elemental analysis*

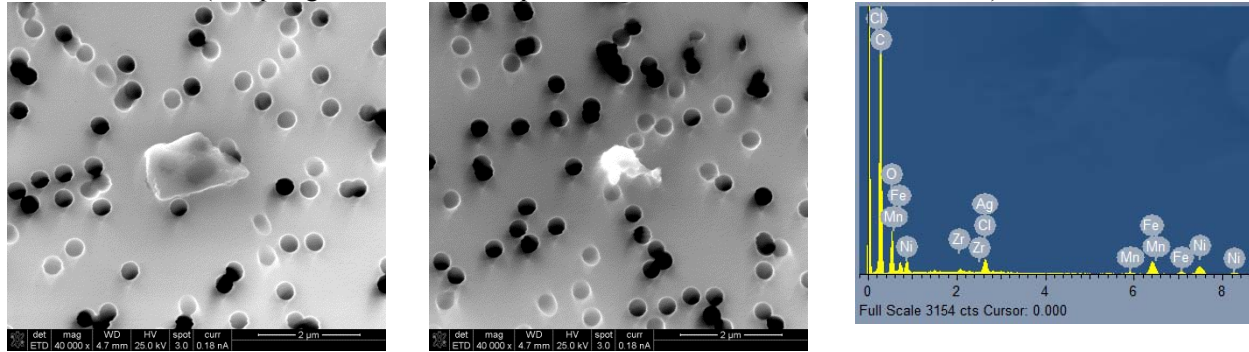
As mentioned earlier, a small part of each filter was used for a SEM/EDX analysis. Figure 9 shows selected images and EDX spectra for each location. For each sample, between 10 and 35 individual particles were chosen for the measurement of EDX spectra, and spectra given in Figure 9 correspond to the most representative ones for each sample. In each SEM image of Figure 9, the small black dots correspond to the pores of the polycarbonate filters. At Giubiasco, particles collected at different locations downstream of the electrostatic precipitator had variable shapes, but their sizes were usually smaller than 1  $\mu\text{m}$ , which confirms results obtained with the APS. EDX spectra obtained for particles collected between the electrostatic precipitator and the DeNOx show the presence of a few elements, such as Al and Si (presumably from aluminosilicate), C and O (mainly from the polycarbonate filters), Mg, Ca, Na. The presence of C could also be due to soot or organics, and O to metal oxides or oxygenated organics, but this cannot be confirmed with the EDX analysis. In a previous study performed by our group in MSWI plants, high concentrations of Ca, Na, and Al were found in fly ash [Buha et al, 2014], suggesting that compounds containing these elements could condense in the flue gas and be later removed by the bag-house filter. It is interesting to notice that particles collected at the stack were very different than those collected upstream in the abatement system. Indeed, the shape and size of these particles were much more uniform, and EDX spectra contain only a signal of chlorine and nitrogen. The absence of Na in these spectra suggests that these particles were maybe ammonium chloride salts. Particles collected at the stack at Hinwil had also a signal of chlorine and no signal of Na, suggesting that ammonium chloride could also be present there.

An important part of this project was to compare particles released from the stack with those collected at the downwind site (Communal Stadium of Giubiasco), in order to assess the environmental impact of these plants. Particles collected at the downwind site had a very large variability in the size, shape, and chemical composition, but we did not see a considerable amount of particles similar to those collected at the stack, or having similar EDX spectra.



**Figure 9.** SEM images and EDX spectra of particles sampled at various locations of the incineration plants of Giubiasco (TI) and Hinwil (ZH) on polycarbonate filters (black dots in each image correspond to the pores of the filters).

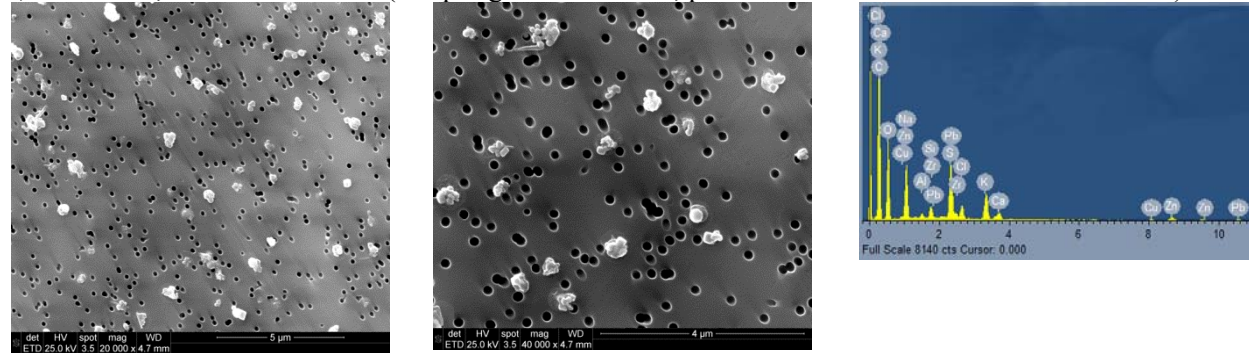
**a) Hinwil, stack (sampling volume: 1038 l; particle concentration around 100 #/cm<sup>3</sup>)**



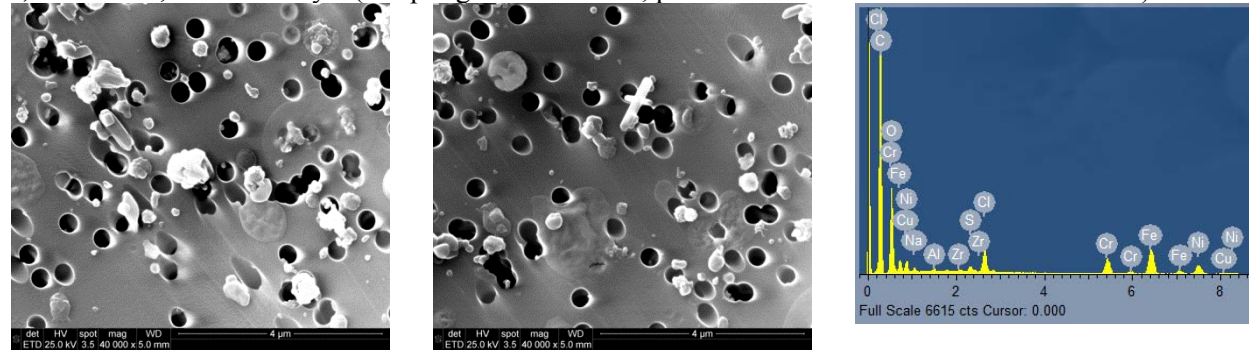
**b) Hinwil, ambient background air in front of the stack (sampling volume: 3899 l; particle concentration around 10200 #/cm<sup>3</sup>)**



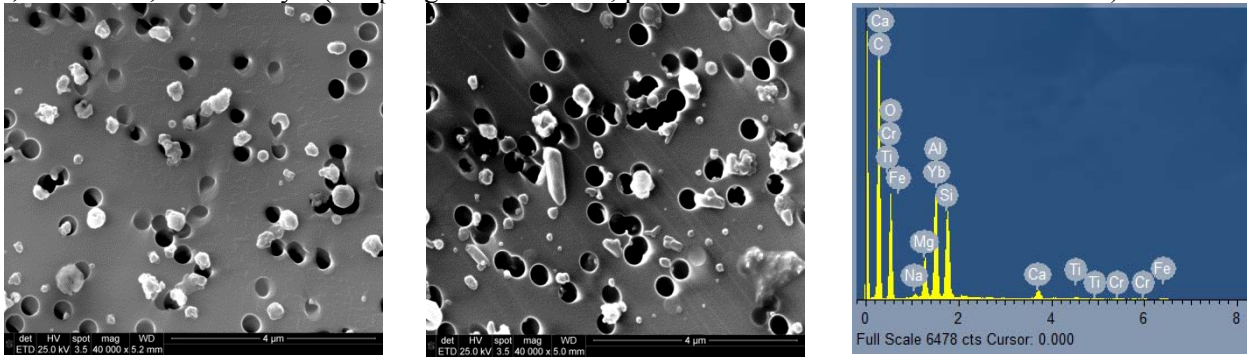
**c) Giubiasco, after electro-filter (sampling volume: 119 l; particle concentration around 6600 #/cm<sup>3</sup>)**



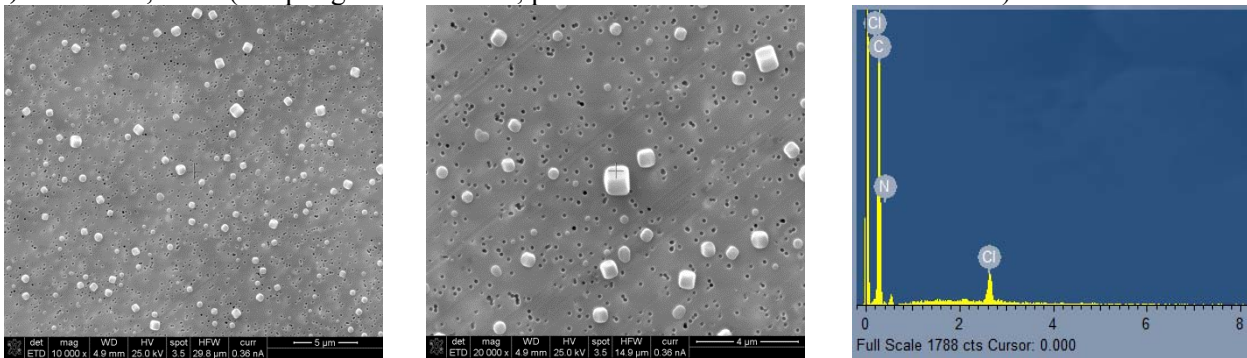
**d) Giubiasco, before catalyst (sampling volume: 851 l; particle concentration around 8800 #/cm<sup>3</sup>)**



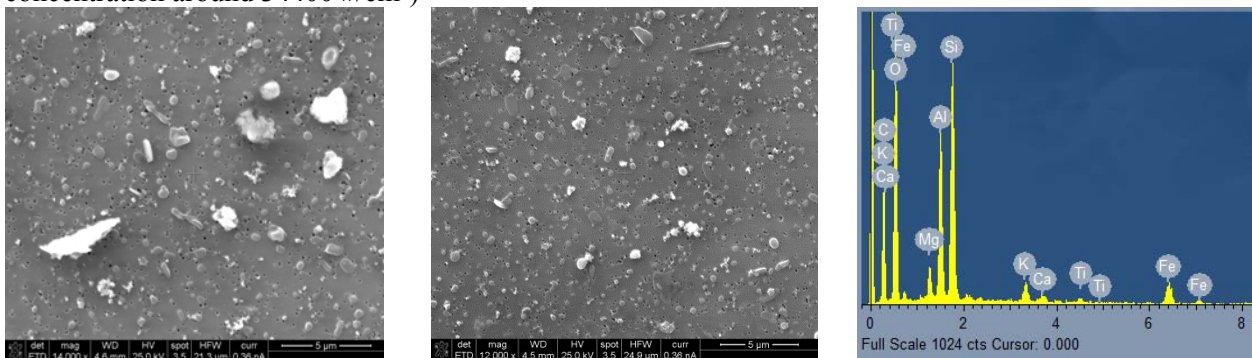
e) Giubiasco, after catalyst (sampling volume: 125 l; particle concentration around 8500 #/cm<sup>3</sup>)



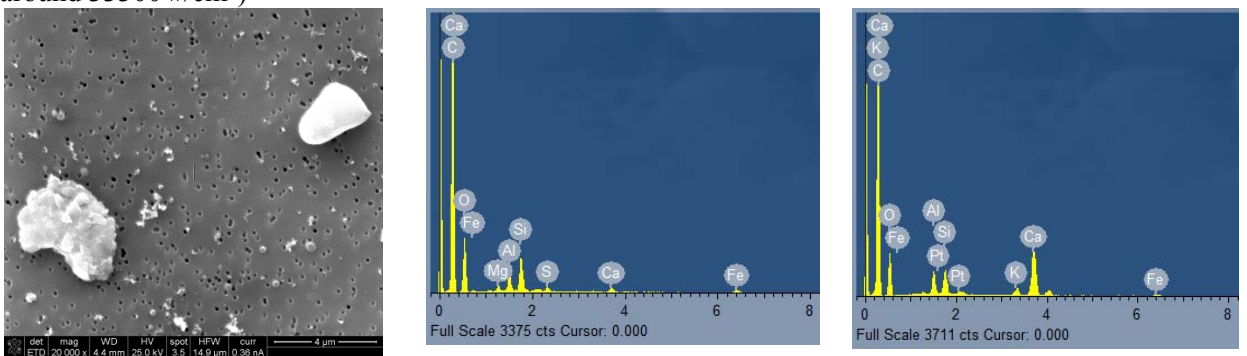
f) Giubiasco, stack (sampling volume: 882 l; particle concentration around 100 #/cm<sup>3</sup>)



g) Giubiasco, ambient background air in front of the stack (sampling volume: 4023 l; particle concentration around 34400 #/cm<sup>3</sup>)



h) Giubiasco, Communal Stadium (downwind site) (sampling volume: 3646 l; particle concentration around 33300 #/cm<sup>3</sup>)





#### 4.4 Water soluble anions

Seven selected water soluble anions ( $F^-$ ,  $Cl^-$ ,  $NO_2^-$ ,  $Br^-$ ,  $NO_3^-$ ,  $PO_4^{3-}$ , and  $SO_4^{2-}$ ) were measured by ion chromatography (IC) on the same filters as in the previous section. Two different series of IC analyses were performed: filters sampled in December 2015 were analyzed in March 2016, while those sampled in April 2016 were analyzed one week after the field campaign. A blank sample was included in each series of IC analysis, and results shown in Table A4 (in the Annex) take into account a blank subtraction performed for all the samples.

An important result in Table A4 is the presence of significant amounts of  $Cl^-$  at the different locations within the MSWI plant of Giubiasco, especially in the stack. This result confirms those obtained with the SEM/EDX analysis of these samples (Section 4.3), which also showed signals of chloride. We know from the measurements performed by the MSWI plant of Giubiasco that the conduit before the wet scrubber contained high concentrations of HCl, in the range 400-800  $mg/Nm^3$ , generated by the waste combustion (H.-J. Ittig, personal communication). This HCl was certainly converted into  $NH_4Cl$  after the DeNOx, where high quantities of  $NH_3$  were introduced, even if our results do not clearly determine the speciation of chloride in the filter samples. The concentrations of  $Cl^-$  in the two samples taken at the stack of Giubiasco were 430.6 and 148.9  $\mu g/m^3$  (Table A4, samples MSWI 14 and 16), which would correspond to 649.7 and 224.7  $\mu g/m^3$   $NH_4Cl$ , if the entire  $Cl^-$  was present under this form. Beside  $Cl^-$ , we also notice the presence of  $PO_4^{3-}$ ,  $SO_4^{2-}$ , and  $NO_3^-$ , while most of the samples were below the blank values for  $F^-$ ,  $NO_2^-$ , and  $Br^-$ .  $PO_4^{3-}$  is known to be significantly present in sewage sludge, mainly from detergents and food additives [Comber et al, 2013].

Given the results obtained at the stack, chloride may be used as a tracer of particles emitted by the incineration plant. We notice that small concentrations of chloride were found at the downwind site (0.9-4.5  $\mu g/m^3$ ), but also in the background air next to the stack (4.8  $\mu g/m^3$ ). This result suggests that the chloride measured in ambient air was mainly coming from other sources.

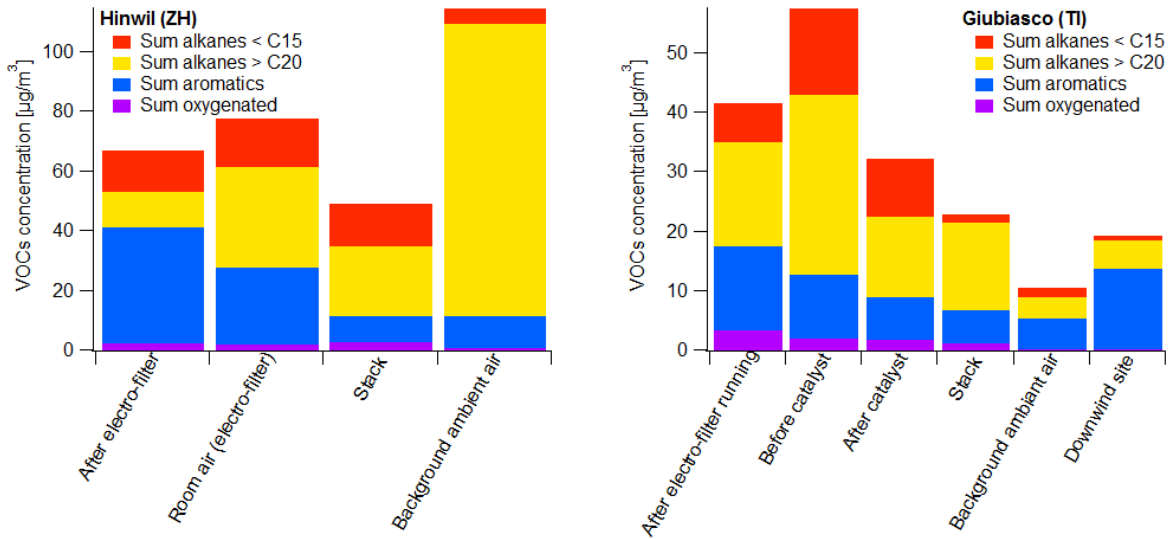
#### 4.5 VOCs

A total of 5 samples have been taken at Hinwil, and 7 at Giubiasco. Each sample consists of a Tenax TA cartridge connected in series with a Carboxen 569 cartridge (total: 24 cartridges). These samples were analyzed by thermal desorption gas chromatography/mass spectrometry (TD-GC/MS) immediately after the campaign at Giubiasco in December 2015.

Figure 10 shows results obtained for the VOCs. 25 compounds have been identified in total (details in Table A5 in the Annex). These compounds have been classified into four chemical families: short-chain alkanes ( $< C_{15}$ ), long-chain alkanes ( $> C_{20}$ ), aromatics and oxygenated compounds. We did not include alkanes between  $C_{15}$ - $C_{20}$ , because their concentrations were very close to those in the field blanks. Samples were usually dominated either by aromatics or by alkanes, with low contributions of oxygenated compounds. Alkanes and aromatics come mainly from combustion, and were expected to be found in incineration plants. An interesting observation is the regular decrease of the total VOCs concentration along the abatement system, except before the catalyst at Giubiasco, where the VOCs concentration increased compared to the previous section (electrostatic precipitator). We also noticed that the flue gas before the catalyst had a higher temperature (200°C) compared to the other sections of the incineration plant of Giubiasco (150-180°C). The temperature is an important parameter driving the gas to particle partitioning of chemical compounds. Thus, the higher temperature before the catalyst may explain why more organic compounds were in the gas phase.



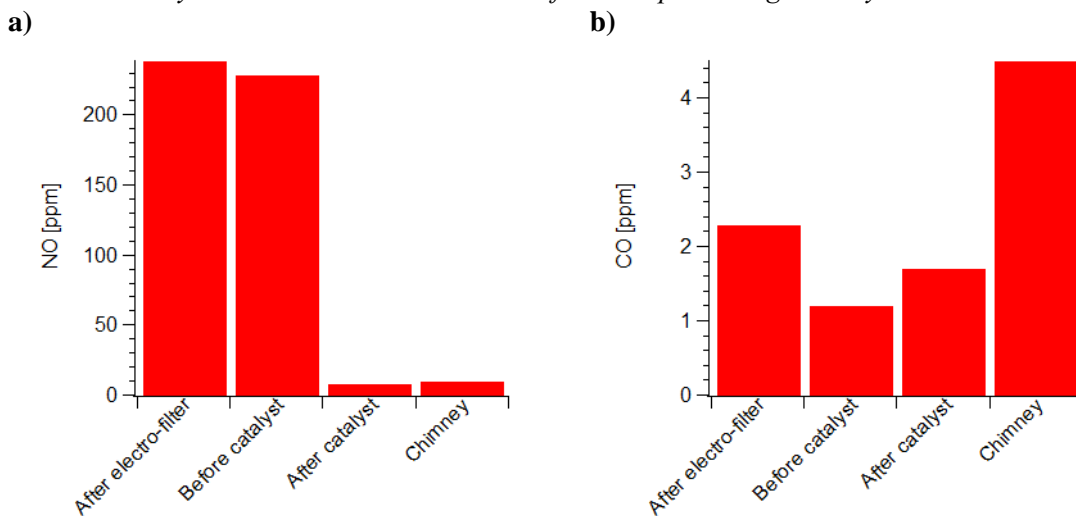
**Figure 10.** Concentration of VOCs at the different locations of the incineration plants of Hinwil (left panel) and Giubiasco (right panel). Data come from VOCs cartridges analyzed by TD-GC/MS.

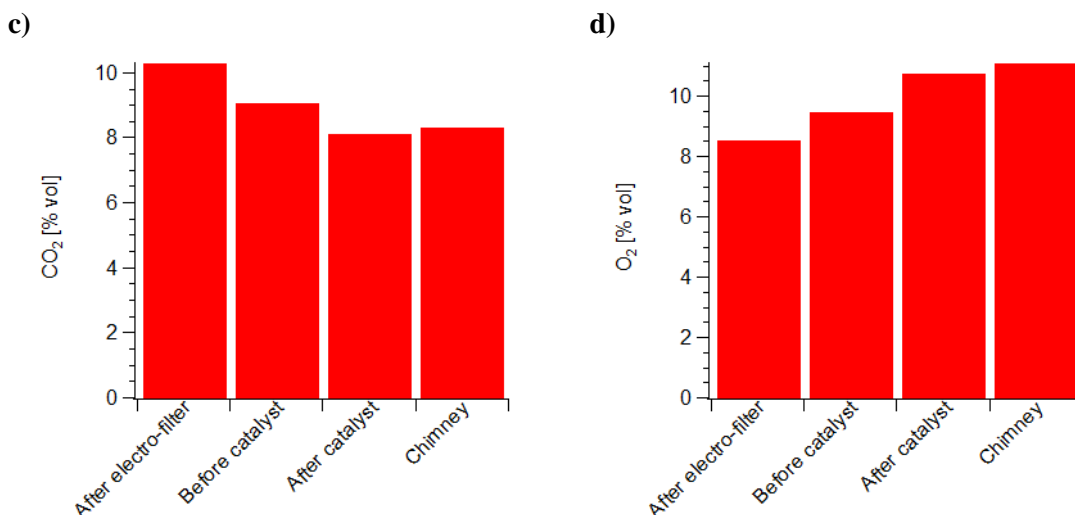


#### 4.6 Gases

Figure 11 shows the concentration of the main gases at the different levels of the abatement system at Giubiasco, the instrument being not available during the campaign at Hinwil. We notice that the concentration of NO decreased drastically after the DeNOx (from 229 to 8 ppm), demonstrating the efficiency of this technology in the abatement of nitrogen oxides. We also notice some fluctuations for some gases (CO, CO<sub>2</sub>, O<sub>2</sub>) between the different locations of the plant. This is certainly due to the fact that the portable gas analyzer could not be calibrated at each location. This certainly induced a drift in the response of the gas analyzer between the different locations.

**Figure 11.** Concentration of the main gases measured at the different levels of the abatement system at Giubiasco. Data come from the portable gas analyzer.





## 5. Conclusion

A field campaign has been performed in two municipal solid waste incineration plants. The aim was to measure particles at different locations of the abatement system and those released from the stacks into the atmosphere, in order to assess the efficiency of the abatement system and the environmental impact of these plants.

The two incineration plants chosen for this study were located at Hinwil (ZH) and Giubiasco (TI). Their abatement system was constituted of an electrostatic precipitator, a DeNO<sub>x</sub> and a bag-house filter. In addition, Hinwil was equipped with a dry scrubber and Giubiasco a wet scrubber. Another important difference between them was the location of the bag-house filters within the abatement system (last step of abatement at Giubiasco, between the dry scrubber and the DeNO<sub>x</sub> at Hinwil). The particle number concentration dropped significantly at two locations of the plant: after the electrostatic precipitator and after the bag-house filter. The particle concentration at the stacks was very low,  $< 100 \text{ \#/cm}^3$ , stressing the efficiency of the abatement systems. Particles released from the stacks into the environment were compared to those collected at a downwind site. At the stacks, particles with a relatively uniform shape and size were observed, and were possibly constituted of ammonium chloride salts. We did not see considerable amount of this type of particles at the downwind site, and the concentrations of chloride were rather low there, suggesting that the incineration plants released very limited amounts of particles to the surrounding areas.

## 6. Acknowledgements

We would like to thank the Swiss Federal Office for the Environment (Bundesamt für Umwelt [BAFU]) and the Swiss Waste Industry Association (Verband der Betreiber Schweizerischer Abfallverwertungsanlagen [VBSA]) for the financial support. We are also grateful to Jakob Hunsperger (Hinwil) and Hans-Jörg Ittig (Giubiasco) for having allowed us to perform these measurements at their incineration plants and for their assistance during this study, Tatiana Bergomi-Mourou (Giubiasco) for her assistance during the measurements at the Communal Stadium of Giubiasco, and Mirco Moser (OASI) for having provided ambient measurements data from the local air quality monitoring network. Finally, we would like to thank Renato Figi, Melanie Bürki, and Claudia Schreiner (Empa, Dübendorf) for the ion chromatography analysis, and Joachim Mohn (Empa, Dübendorf) for having lent us some equipment for the samplings.

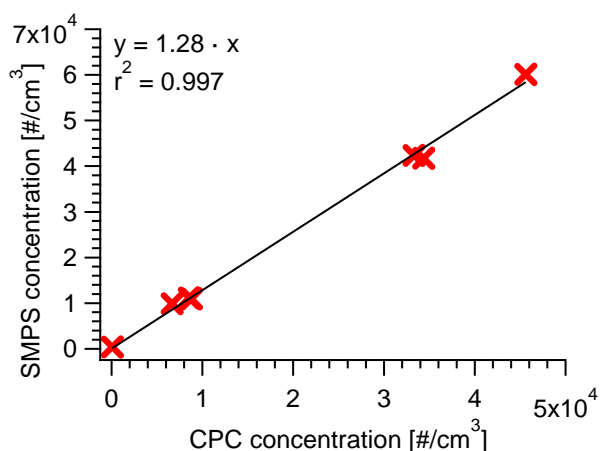
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## 8. Annex

**Figure A1.** Scatterplot of the total particle concentration calculated by integrating SMPS size distributions vs particle concentration measured by the CPC.



**Table A1.** List of measurement periods with real time instruments.

Site	Location	Start time	End time
Hinwil	Stack	02/12/2015 11h15	02/12/2015 14h00
Hinwil	After electro-filter (room air)	02/12/2015 16h50	02/12/2015 17h30
Hinwil	After electro-filter	03/12/2015 11h00	03/12/2015 15h45
Hinwil	Stack	04/12/2015 12h00	04/12/2015 14h00
Giubiasco	Stack	15/12/2015 10h00	15/12/2015 18h30
Giubiasco	After catalyst	16/12/2015 09h50	16/12/2015 14h00
Giubiasco	Before catalyst	16/12/2015 15h00	16/12/2015 18h00
Giubiasco	After catalyst	17/12/2015 09h45	17/12/2015 13h30
Giubiasco	After electro-filter running	17/12/2015 14h30	17/12/2015 16h10
Giubiasco	After electro-filter stopped	17/12/2015 16h10	17/12/2015 17h00
Giubiasco	After electro-filter running	17/12/2015 17h00	17/12/2015 19h30
Giubiasco	Communal Stadium (downwind site)	18/12/2015 10h15	18/12/2015 15h00
Hinwil	Stack	31/03/2016 12h30	31/03/2016 17h15
Hinwil	Stack	01/04/2016 09h45	01/04/2016 16h00
Giubiasco	Stack	06/04/2016 14h30	06/04/2016 18h30
Giubiasco	Stack	07/04/2016 09h15	07/04/2016 17h00
Giubiasco	Communal Stadium (downwind site)	08/04/2016 09h45	08/04/2016 15h50

**Table A2.** List of filter samples.

Filter N°	Site	Location	Start time	End time	Flow rate [l/min]	Volume [l]
1	Hinwil	Stack	02/12/2015 13h23	02/12/2015 14h00	1.0	37
2	Hinwil	After electro-filter	03/12/2015 13h50	03/12/2015 14h28	1.0	38
3	Giubiasco	Ambient background	15/12/2015 12h34	15/12/2015 17h46	13.0	4056
4	Giubiasco	Stack	15/12/2015 18h53	16/12/2015 08h30	1.0	817
5	Giubiasco	After catalyst	16/12/2015 11h55	16/12/2015 13h34	1.0	99
6	Giubiasco	Before catalyst	16/12/2015 18h19	17/12/2015 08h30	1.0	851
7	Giubiasco	After catalyst	17/12/2015 11h16	17/12/2015 13h21	1.0	125
8	Giubiasco	After electro-filter	17/12/2015 17h25	17/12/2015 19h24	1.0	119
9	Giubiasco	Stack	17/12/2015 20h32	18/12/2015 08h10	1.0	698
10	Giubiasco	Communal Stadium	18/12/2015 10h55	18/12/2015 14h57	13.0	3146
11	Hinwil	Stack	31/03/2016 13h58	31/03/2016 17h09	1.5	287
12	Hinwil	Stack	01/04/2016 09h53	01/04/2016 15h39	3.0	1038
13	Hinwil	Ambient background	01/04/2016 10h03	01/04/2016 15h10	12.7	3899
14	Giubiasco	Stack	06/04/2016 15h16	06/04/2016 18h04	2.0	336
15	Giubiasco	Ambient background	06/04/2016 16h21	06/04/2016 17h59	10.4	1019
16	Giubiasco	Stack	07/04/2016 09h49	07/04/2016 17h10	2.0	882
17	Giubiasco	Ambient background	07/04/2016 10h44	07/04/2016 17h00	10.7	4023
18	Giubiasco	Communal Stadium	08/04/2016 09h46	08/04/2016 15h47	10.1	3646

**Table A3.** List of VOCs cartridges.

Sample N°	Site	Location	Start time	End time	Flow rate [ml/min]	Volume [l]
1	Hinwil	After electro-filter	03/12/2015 14h46	03/12/2015 15h06	200	4.0
2	Hinwil	Room air in front of electro-filter	03/12/2015 15h23	03/12/2015 15h43	200	4.0
3	Hinwil	Stack	04/12/2015 12h14	04/12/2015 12h28	200	2.8
4	Hinwil	Ambient background	04/12/2015 12h34	04/12/2015 13h29	200	11.0
5	Hinwil	Stack	04/12/2015 13h42	04/12/2015 14h02	200	4.0
6	Giubiasco	Ambient background	15/12/2015 12h16	15/12/2015 14h22	200	25.2
7	Giubiasco	Stack	15/12/2015 17h22	15/12/2015 18h02	200	8.0
8	Giubiasco	After catalyst	16/12/2015 11h19	16/12/2015 11h51	200	6.4
9	Giubiasco	Before catalyst	16/12/2015 16h30	16/12/2015 16h59	200	5.8
10	Giubiasco	After catalyst	17/12/2015 10h39	17/12/2015 11h12	200	6.6
11	Giubiasco	After electro-filter	17/12/2015 17h03	17/12/2015 17h22	200	3.8
12	Giubiasco	Communal Stadium	18/12/2015 12h20	18/12/2015 14h22	200	24.4

**Table A4.** Results of the ion chromatography analysis of the filter samples.

Sample	IC analysis date	Site	Location	Start time	End time	Sampling time [mn]	Flow rate [l/mn]	Sampling volume [l]	[μg/ml] (water in IC)							[μg/m <sup>3</sup> ] (air)												
									F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	Br <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>	F <sup>-</sup>	Cl <sup>-</sup>	NO <sub>2</sub> <sup>-</sup>	Br <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	PO <sub>4</sub> <sup>3-</sup>	SO <sub>4</sub> <sup>2-</sup>						
Filter blank	03.03.2016								0.1	0.2	0.2	0.2	0.2	0.3	0.5													
MSWI 3	03.03.2016	Giubiasco	Background air next to stack	15.12.2015 12:34	15.12.2015 17:46	312	13	4056	0.1	1.6	0.2	0.2	1.1	0.3	0.7		4.8					3.1					0.8	
MSWI 4	03.03.2016	Giubiasco	Stack	15.12.2015 18:53	16.12.2015 08:30	817	1	817	Sampling failed, filter not analyzed																			
MSWI 5	03.03.2016	Giubiasco	After catalyst	16.12.2015 11:55	16.12.2015 13:34	99	1	99	0.1		0.2	0.2	0.2	0.3	0.7							6.7					33.7	
MSWI 6	03.03.2016	Giubiasco	Before catalyst	16.12.2015 18:19	17.12.2015 08:30	851	1	851	0.1	1.6	0.2	0.2	0.2	0.3	1.9		22.7										22.7	
MSWI 7	03.03.2016	Giubiasco	After catalyst	17.12.2015 11:16	17.12.2015 13:21	125	1	125	0.1	0.3	0.2	0.2	0.2	0.3	0.5		16.0											
MSWI 8	03.03.2016	Giubiasco	After electro-filter	17.12.2015 17:25	17.12.2015 19:24	119	1	119	0.1	0.4	0.2	0.2	0.2	0.3	0.5		28.0		5.6									
MSWI 9	03.03.2016	Giubiasco	Stack	17.12.2015 20:32	18.12.2015 08:10	698	1	698	Sampling failed, filter not analyzed																			
MSWI 10	03.03.2016	Giubiasco	Communal Stadium (downwind site)	18.12.2015 10:55	18.12.2015 14:57	242	13	3146	0.1	1.2	0.2	0.2	1.1	0.3	0.6		4.5					4.0					0.6	
Blank water	12.04.2016								0.1	0.2	0.2	0.2	0.2	0.9	0.5													
MSWI 12	12.04.2016	Hinwil	Stack	01.04.2016 09:53	01.04.2016 15:39	346	3	1038	0.1	0.8	0.2	0.2	0.2	1.6	0.6		8.3					0.6	9.6			1.9		
MSWI 14	12.04.2016	Giubiasco	Stack	06.04.2016 15:16	06.04.2016 18:04	168	2	336	0.1	11	0.2	0.2	0.2	1.7	0.5		430.6					2.0	33.7					
MSWI 16	12.04.2016	Giubiasco	Stack	07.04.2016 09:49	07.04.2016 17:10	441	2	882	0.2	10	0.2	0.2	0.2	1.5	0.6	2.3	148.9						9.8		2.3			
MSWI 18	12.04.2016	Giubiasco	Communal Stadium (downwind site)	08.04.2016 09:46	08.04.2016 15:47	361	10.1	3646	0.1	0.4	0.2	0.2	0.3	1.7	0.6		0.9					0.5	3.1		0.5			

Red cases: below blank values

**Table A5.** List of VOCs identified and quantified by TD-GC/MS. Results are in μg/m<sup>3</sup>.

Date	Site	Location	p-xylene	nonane	benzaldehyde	1,3-diethyl benzene	limonene	undecane	dodecane	tridecane	tetradecane	tributyl phosphate	methyl tetradecanoate	pentadecanoic acid	hexadecanoic acid	octadecanoic acid	eicosane	heneicosane	docosane	tricosane	tetracosane	pentacosane	hexacosane	squalene	heptacosane	octacosane
17.12.2015	Giubiasco	After catalyst	0.94	0.95	5.37	0.47	0.28	0.96	1.98	2.69	2.37	3.99	0.03	0.42	0.40	0.01	0.92	1.19	1.15	0.95	0.50	0.31	0.15	6.61	0.09	0.09
16.12.2015	Giubiasco	After catalyst	0.88	0.83	11.86	0.75	0.25	2.81	7.46	7.76	4.42	18.97	0.08	0.85	0.10	0.03	2.51	6.35	12.30	17.32	17.48	15.81	10.54	2.92	6.75	3.53
16.12.2015	Giubiasco	Before catalyst	0.90	0.75	8.44	0.83	0.58	1.49	3.54	4.57	3.22	7.48	0.15	0.71	0.13	0.01	1.70	2.32	2.80	3.75	3.29	3.07	2.07	14.11	1.32	0.68
15.12.2015	Giubiasco	Stack	1.01	0.26	4.05	0.33	0.11	0.20	0.00	0.17	0.11	0.71	0.07	0.10	0.18	0.02	0.73	1.04	1.36	1.60	1.22	0.85	0.52	1.59	0.33	0.19
04.12.2015	Hinwil	Stack	1.17	3.75	9.17	1.06	0.29	0.34	0.00	0.20	0.10	0.64	0.00	0.39	0.00	0.41	0.31	0.47	0.43	0.15	0.00	0.00	0.00	1.69	0.00	0.00
18.12.2015	Giubiasco	Communal Stadium	2.63	0.17	10.48	0.31	0.08	0.14	0.00	0.11	0.10	0.76	0.00	0.02	0.02	0.00	0.06	0.11	0.20	0.30	0.46	0.57	0.42	0.49	0.24	0.08
17.12.2015	Giubiasco	After electro-filter	1.49	1.75	11.83	0.22	0.25	0.52	0.53	1.24	1.07	7.60	0.00	1.33	0.00	0.45	0.44	0.52	0.54	0.51	0.42	0.39	0.37	5.64	0.13	0.00
04.12.2015	Hinwil	Background ambient air	3.21	3.64	6.75	0.53	0.37	0.34	0.19	0.22	0.12	0.87	0.00	0.21	0.00	0.00	1.94	6.53	14.11	19.87	19.30	15.48	8.89	0.25	4.94	2.25
04.12.2015	Hinwil	Stack	3.21	12.09	4.09	0.53	0.83	0.48	0.00	0.24	0.13	0.61	0.00	0.46	0.00	0.42	0.34	0.67	0.98	1.19	0.51	0.15	0.15	0.00	0.00	0.00
15.12.2015	Giubiasco	Background ambient air	1.88	0.40	3.10	0.14	0.16	0.29	0.31	0.24	0.12	0.96	0.00	0.01	0.00	0.00	0.13	0.19	0.31	0.32	0.25	0.14	0.05	0.31	0.01	0.00
03.12.2015	Hinwil	After electro-filter	30.08	6.70	7.20	0.98	6.55	1.26	1.29	1.95	1.21	11.65	0.00	0.75	0.23	0.01	0.53	0.51	0.52	0.02	0.00	0.00	1.86	0.00	0.00	0.00
03.12.2015	Hinwil	Room air (after electro-filter)	17.49	8.87	6.54	1.06	7.73	1.43	1.39	2.02	1.28	12.37	0.00	0.22	0.37	0.00	1.58	2.48	3.19	4.14	3.67	2.81	1.58	0.00	0.75	0.23

Figure A2. Time series of  $\text{NO}_x$ ,  $\text{O}_2$ , dust, and volume of air measured at Hinwil (ZH) on 12/2/2015 after the bag-house filter with probes belonging to the MSWI plant.

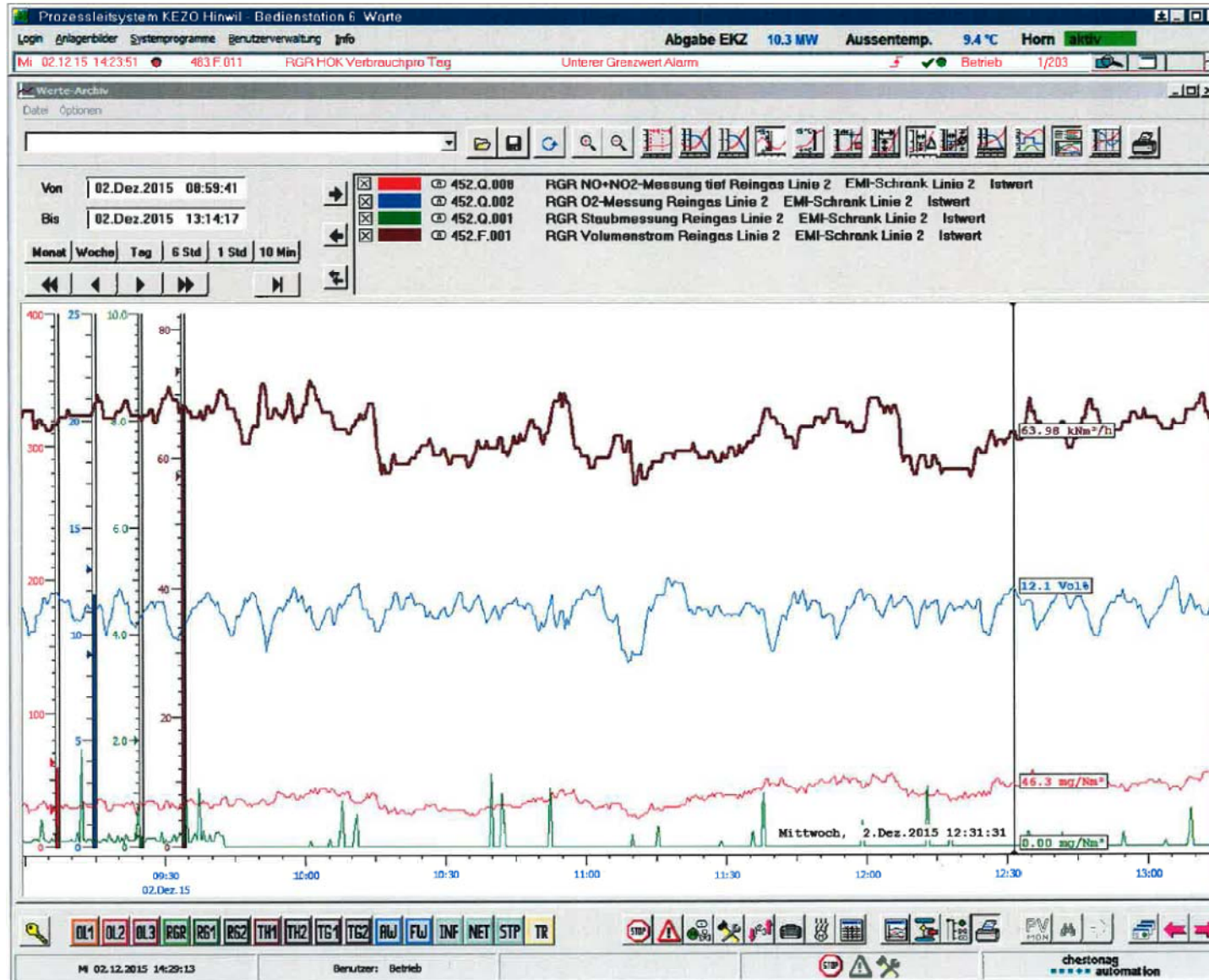
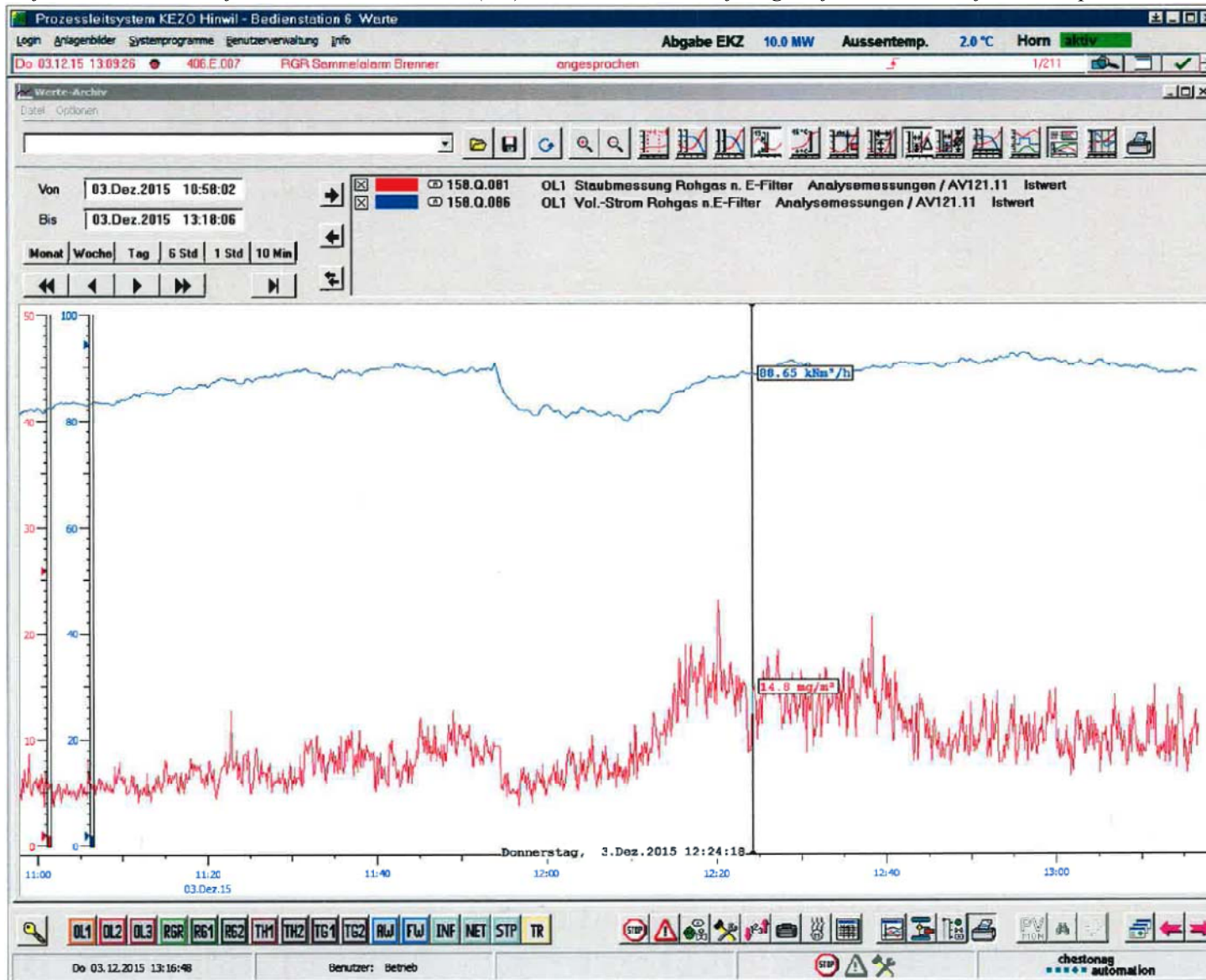




Figure A3. Time series of dust and volume of air measured at Hinwil (ZH) on 12/3/2015 in the flue gas after the electro-filter with probes belonging to the MSWI plant.



**Figure A4.** Time series of  $\text{NO}_x$ ,  $\text{O}_2$ , dust, and volume of air measured at Hinwil (ZH) on 12/4/2015 after the bag-house filter with probes belonging to the MSWI plant.



**Table A6.** Typical concentrations of selected parameters at Giubiasco (TI) in the flue gas between the electro-filter and the wet scrubber.

Parameter	Concentration
SO <sub>2</sub> (H <sub>2</sub> SO <sub>4</sub> )	200-400 mg/Nm <sup>3</sup>
HCl	400-800 mg/Nm <sup>3</sup>
Dust	1 mg/Nm <sup>3</sup>
HF	50-100 mg/Nm <sup>3</sup>
NO <sub>x</sub>	500-600 mg/Nm <sup>3</sup>
H <sub>2</sub> O	15-20%
Temperature	170°C