Maintenance costs for European zinc and Portland limestone surfaces due to air pollution since the 1980s

Terje Grøntoft

NILU-Norwegian institute for air research, Instituttveien 18, Box 100, NO-2027 Kjeller, Norway. E.mail: teg@nilu.no, Phone: +4763898023.

Abstract

The purpose of the reported research was to estimate maintenance costs, cost savings and lifetime increases for outdoor material surfaces in Europe, obtainable by reducing air pollution. Data and methodology from the ICP-materials project were used. The results suggest that for material surfaces exposed outdoor in Europe, a hypothetical 50% reduction in air pollution from present (2014) levels, would give an average overall increase in the near future lifetimes between maintenance due to atmospheric chemical weathering, of about 25%, and savings in maintenance cost of about 10%. It was found that for zinc surfaces since 1987 until 2014, the theoretical lifetime before maintenance has, on average for the ICP-locations, increased with about 125% (from 118 to 265 years). The additional average lifetime due to 50 % pollution reduction would have been about 26%, representing maintenance cost savings sinking from about 20% in 1987 to 10% in 2014. For Portland limestone an increase in lifetime since 2002 until 2014, and additional lifetime due to 50 % pollution reduction, of 35-40% was indicated, representing maintenance cost savings of about 14%. This would have been very significant cost savings considering the total use of zinc and Portland limestone as construction and façade materials.

Keywords

Zinc, limestone, corrosion, maintenance cost, lifetime, dose-response equation, air pollution, climate change

1. Introduction

Atmospheric weathering of metals, stone and other construction materials causes huge maintenance costs. The atmospheric weathering is caused partly by air pollution (Watt et al., 2009). One expected effect of the reduced air pollution that has been observed in Europe over the last 30 years (Tidblad et al., 2017; 2014), is a reduction in maintenance costs for material surfaces, façades and built structures. This work presents estimations of probable maintenance costs for outdoor material surfaces in Europe due to the observed air pollution, and of cost savings that could have been obtained by reducing the air pollution. The estimations were made by applying data and methodology from the ICP-materials project[1] (ICP, 2018). The ICP-materials programme has since 1987 measured the atmospheric weathering of material samples and the values for the influencing environments at 55 exposure stations. Statistical dose-response functions developed in the ICP-materials programme were used in this work to estimate atmospheric chemical weathering costs.

[1] The International Co-operative Programme on Effects on Materials including Historic and Cultural Monuments, within the Convention on Long-range Transboundary Air Pollution (CLRTAP), organized under the United Nations Economic Commission for Europe (UNECE).

Increased rates of atmospheric corrosion of built structures were observed over most of Europe in the second part of the 20th century (Kreislova & Knotkova, 2017). The high corrosion was caused mainly by burning of sulfur rich hydrocarbons and consequent increased concentration in air and deposition of sulfur dioxide (SO_2), and increased acidity in precipitation. In this situation the ICP-materials programme was set up. It exposed selected metals, stone and other material samples in a European wide exposure programme, which also included a few measurement sites in North America. The North American stations were in the range of the European environments, thus enlarging the database and relevance for what could be termed a "European situation". Measurements were performed for some longer periods of mainly four and eight years, and for 19 annual periods up to the present. The measurements are now ongoing in a trend programme with measurements every third year, and with new four and eight years exposures (ICP, 2018).

Figure 1 shows a corrosion measurement site in the ICP-materials programme

Figure 1: The ICP-materials station (no. 21, Appendix) located in the urban background in Oslo, Norway (2012). The picture shows metal plate samples in unsheltered position (1), holder disks for passive pollution samplers to the left on the rack (2), shelters for samples in a box behind the metal samples (3a) and under a plastic shield to the right (3b), and a precipitation collector to the very right on the photo (4). Limestone samples mounted on a carousel can be seen through the upper left corner of the plastic shield (5a) and in the low insertion (5b).

The aim of ICP-materials has been to explain the corrosion, to assess trends in, and tolerable levels of the corrosion, to calculate maintenance cost, and to map such parameters over the European geographical area (ICP, 2018; Watt et al., 2009). Towards the end of the century, control of SO_2 emissions and other changes in the industrial sector lead to reduction in SO_2

concentrations in air (EEA, 2017). A change to a multipollutant situation was generally observed, where the atmospheric corrosion of many materials were significantly influenced by several other air pollutants in addition to SO_2 (Tidblad, 2014; Kucera 2005).
The reporting from ICP-materials since 1987, shows a significant decrease in atmospheric metal corrosion and maintenance cost over the recent 30 years, correlating with decrease in the concentrations of corrosive air pollutants, especially sulfur dioxide, SO_2 (Tidblad et al., 2017; 2014).

This new situation lead to the development, within the ICP-materials programme and in several EU projects (Kucera, 2007; Kucera, 2005) of multi-pollutant dose-response functions for a range of metals and Portland limestone, based on statistical analysis of the measured corrosion and the impacting environmental parameters (Tidblad, 2014; Kucera et al., 2007). The programme today recommends the use of one of two sets of dose-response functions. One set for an "SO_2 dominated" situation and another set for a "multipollutant situation", depending on the air pollution situation.
The dose-response functions have been used to calculate maintenance costs for buildings and monuments due to atmospheric chemical weathering of their surfaces, depending on levels and changes in air pollution and climate loads (Grøntoft, 2017, 2011; Doytchinov, Spezzano, Screpanti, & Leggeri, 2013; Watt et al., 2009). This paper goes a step further by applying ICP-materials zinc and Portland limestone dose-response functions to calculate changes in such maintenance cost, over recent years and due to hypothetical pollution reduction, for selected ICP measurement sites and for the average of all the European, and three North American, ICP sites, representing a "European situation". Large total areas of zinc and limestone are exposed in facades and monuments in Europe (Figure 2), and the total cost of their maintenance is clearly large. A significant part of this cost would be due to atmospheric weathering and corrosion impact on the surfaces (Grøntoft, 2017).

Figure 2: Weathering of a limestone facade in Palermo, Italy, of zinc roofs in Paris, France (Wikipedia), and of a zinc monument (19th century, from a German workshop) in Oslo, Norway.

Atmospheric weathering of materials can, generally, be caused by chemical, physical and biological processes. Corrosion processes have been studied since the early 20th century. Atmospheric corrosion of metals is an electrochemical process with oxidation of the metal and inclusion of different anions, which are available in the environment, such as for example carbonate, sulfate and chloride (Graedel & Leygraf, 2000). The term "atmospheric corrosion" is also used for stone materials. It then involves chemical dissolution reactions, but could also include physical and biological processes (Watt et al., 2009).

In this work the terms “atmospheric chemical weathering” and “atmospheric corrosion” are used, interchangeably, but depending on context, such as type of materials and usage in referenced literature. The terms will, as used, not include major physical and biological degradation processes. Small-scale physical and biological processes that may occur together with experimental chemical weathering is however not excluded. The rate of the atmospheric chemical weathering depends on climatic factors, such as rain amounts and temperature, and on the chemical composition of the atmosphere, especially the amount of air pollution (Watt et al., 2009; Gaedel & Leygraf, 2000).

2 Methods

This work applies dose-response functions reported from the ICP-materials programme, to estimate historical (since 1987) changes in maintenance costs due to atmospheric chemical weathering, and savings that could have been obtained due pollution reduction.

The calculations represent a selection of 23 urban, 8 industrial and 21 rural ICP-sites for zinc, and of 9 urban, three industrial and 8 rural ICP-sites for Portland limestone (Figure 3 and Appendix). Of the “zinc-sites”, one (no 32, Appendix) is termed urban-industrial, and one (no 57, Appendix) “urban-rural” in the ICP-materials data base (Tidblad et al., 2014). Station no. 32 was therefore included in both the “urban” and “industrial” categories, and station no. 57 in both the “urban” and “rural”, categories, when making separate calculations for the categories. The three North American stations were included in the study to fully represent the data available from ICP-materials.

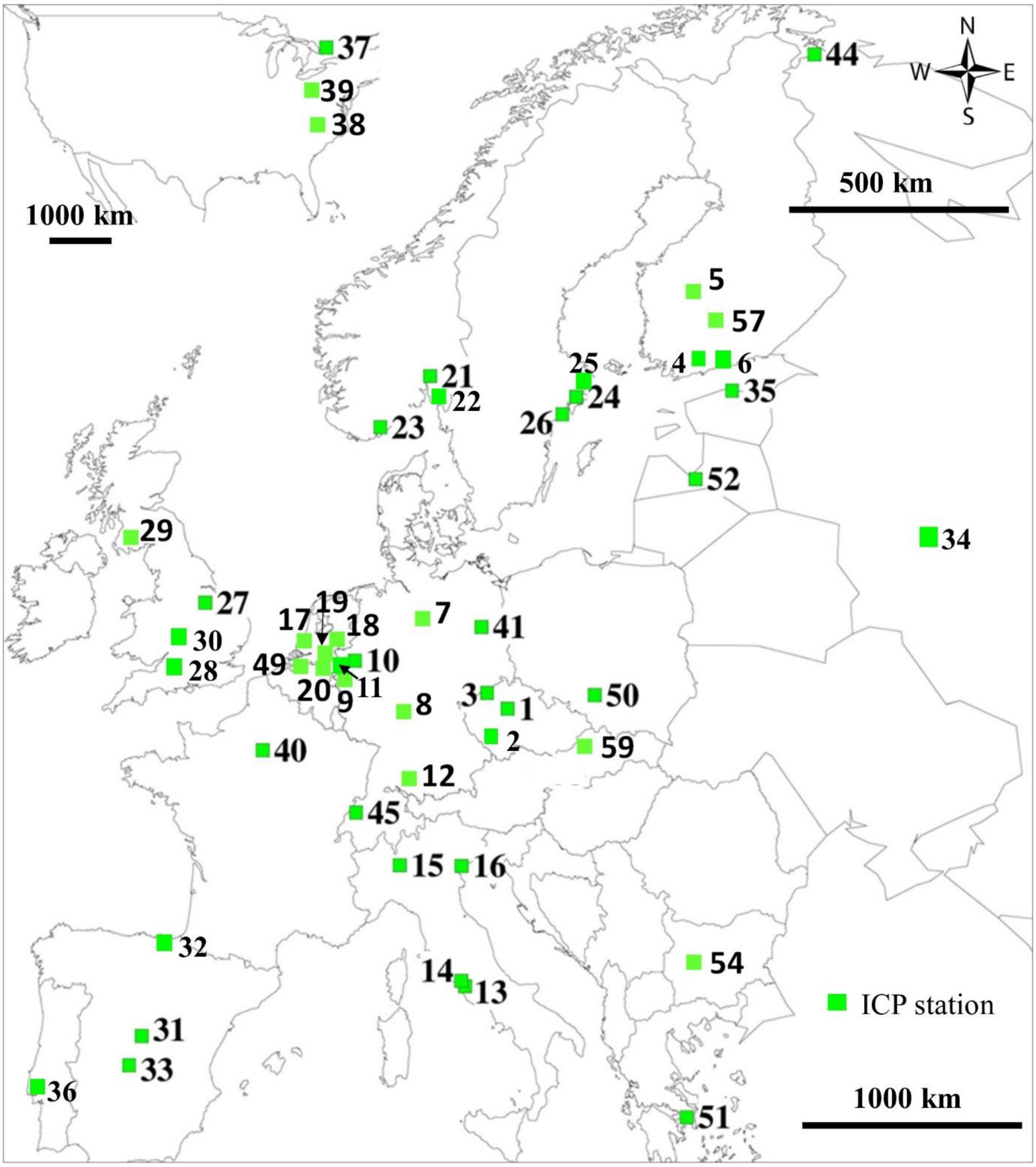

Figure 3: The ICP-materials exposure locations since 1987. The scale changes from south to north due to the map projection. (See Appendix for station names and measurement years)

The calculations were made with the zinc dose-response function for the SO_2 dominated situation (as information from recent exposures in ICP-materials indicate that the nitrate effect included in the multipollutant function (Tidblad, 2014) is uncertain (ICP, 2017)), and using the Portland limestone function for the multipollutant situation (Watt et al., 2009). Multi-pollutant dose response functions are also available from the ICP-materials programme for carbon steel, cast bronze and copper. Functions including chloride are also available (Sabbioni et al., 2010). Differently from the zinc function, the multi-pollutant functions for carbon steel and cast bronze include particulate exposure, measured as the concentration of particulates in air with average aerodynamic diameter smaller than 10 µm (PM10). PM10 has only been reported from the ICP stations in five years since 2002, for an average number of 9

stations per year. The copper function includes, besides SO_2, tropospheric ozone, O_3, which is a secondary photochemical pollutant. The sources for O_3 are complex with less immediate connection to anthropogenic emission reductions (Seinfeld & Pandis, 1998). The environmental parameters, which are included in the used zinc function (SO_2 and H^+(pH)) are, on the other hand, available from 19 years from an average number of 25 stations per year (Tidblad et al., 2014). The weathering steel function for the SO_2 dominated situation only includes the SO_2 pollution, whereas the zinc function includes the effect of acid rain in addition to the effect of SO_2. Zinc is a common construction material. The zinc function for the SO_2 dominated situation (1) was for these reasons selected to represent the metal corrosion in this work, together with the Portland limestone function.
The ICP, SO_2 dominated dose-response function for Zinc is given by (Tidblad, 2014):

$$ML = 1.4 \cdot [SO_2]^{0.22} \cdot exp\{0.018 \cdot RH + f(T)\} \cdot t^{0.85} + 0.029 \cdot Rain \cdot [H^+] \cdot t \qquad (1)$$

$$f(T) = 0.062 \cdot (T-10) \text{ when } T<10°C, \text{ otherwise } -0.021 \cdot (T-10)$$

The ICP, multi-pollutant dose-response function for Portland limestone is given by (Watt et al., 2009):

$$R = 4.0 + 0.0059 \cdot [SO_2] \cdot RH60 + 0.054 \cdot Rain \cdot [H^+] + 0.078 \cdot [HNO_3] \cdot RH60 + 0.0258 \cdot PM10 \qquad (2)$$

where $[HNO_3]$ can be approximated by (Kucera, 2005):

$$[HNO_3] = 516 \cdot e^{-3400/(T+273)} \cdot ([NO_2] \cdot [O_3] \cdot RH)^{0.5} \qquad (3)$$

where ML is mass loss (g/m^2) and R is the surface recession (µm). The remaining parameters are the annual averages of relative humidity (RH, %), temperature (T, °C), amount of precipitation (*Rain*, mm/year) and concentration of hydrogen ions in rain water ($[H^+]$, mg/l), the time (t, years), and finally the concentrations in air (µg/m^3) of sulfur dioxide, $[SO_2]$, nitric acid, $[HNO_3]$, particulate matter with average aerodynamic diameter smaller than 10 µm $[PM10]$, nitrogen dioxide, $[NO_2]$, and ozone, $[O_3]$. For zinc the calculation can be made with (1) to obtain as the result the recession (R, µm) instead of the mass loss (ML, µm), by dividing (1) by the density of zinc, equal to 7.14 g/cm^3 (Tidblad, 2014).

Kucera (2005) reports a near similar equation as (2) including a time dependence, derived from four years of exposure experiments:

$$R = 3.1 + (0.85 + 0.0059 \cdot [SO_2] \cdot RH60 + 0.054 \cdot Rain \cdot [H^+] + 0.078 \cdot [HNO_3] \cdot RH60 + 0.0258 \cdot PM10) \cdot t \qquad (4)$$

When the time dependence is included the weathering loss over a number of years can be calculated. When the tolerable[2] weathering depth (recession, R) before action (maintenance or replacement) and the environmental parameter values for the present situation and the background situation, or the background recession depth, are known, then the lifetimes, t, until maintenance or replacement can be calculated. The weathering cost due to air pollution

[2] The term "acceptable" is reserved for materials used in technical constructions while "tolerable" is used in connection with degradation of cultural heritage (Tidblad, 2014). The term "tolerable" is used in this paper for both.

can then be calculated by the "standard method" (Doytchinov, Spezzano, Screpanti, & Leggeri, 2013; Watt et al., 2009) from:

$$K_{p,r}= M\cdot P\cdot(1/t_{p,r} - 1/t_b), \tag{5}$$

and a maintenance cost saving due to pollution reduction would be given by:

$$\Delta C = K_p - K_r \tag{6}$$

Where K_p and K_r (Euro/year) are material weathering costs due to national or local air pollution in the present (*p*) or some reduced (*r*) air pollution situation, ΔC (Euro/year) is the maintenance cost saving that could be obtained by reducing the air pollution, M (m^2) is the area of stock at risk of a given type of material, P (Euro/m^2) is the maintenance costs per square meter of the material, and $t_{p,r}$ and t_b (year) are the «lifetimes» between conservation-restoration intervention in the present (p) or some reduced (*r*), and the background (*b*), pollution situations. The maintenance cost savings over a period of years could be calculated by multiplying by the number of years of interest.

In this work this "standard method" was used for zinc and Portland limestone, with modifications as described below. Calculations were made of the "absolute" atmospheric weathering costs due to air pollution over background levels (Eq. 5 and 7, Table 2[3], A1 and A3), and the savings in the weathering costs that could have been obtained by reduction in air pollution (Eq. 6 and 9, Table 3, A2 and A3, Figure 4 to Figure 6, Figure 10). The calculations were performed for a maintenance cost ($M\cdot P$), set to 100 Euro, giving results values representing % savings. Average European first year background corrosion rates for zinc, reported to be 0.45 µm, and for Portland limestone, reported to be 3.2 µm (Tidblad, 2014), and suggested tolerable corrosion depths (R) of 80 µm for an evenly corroded zinc monument surface and of 100 µm for a Portland limestone ornament (Kucera, 2005), were used in lifetime calculations, by (1) and (4). The average expected service lifetimes between maintenance were calculated for the ICP locations for each year of environmental measurement at the ICP stations, assuming constant future environments as in the measurement years (Figure 8). The lifetimes were calculated numerically for zinc, from (1), and analytically for Portland limestone, from (3-4), from the suggested corrosion depths before maintenance, of 80 µm and 100 µm. The service lifetimes at reduced pollution situations were calculated similarly (Figure 4, Figure 8 and Figure 9). It must be mentioned here that suggestions for corrosion depths before maintenance are highly uncertain for Portland limestone. Therefore, the following calculation of cost savings for Portland limestone avoids this approach (as explained below). When reading the results reported below for the lifetime before maintenance of Portland limestone ornament this uncertainty must be taken into account.

For zinc, the lifetime until maintenance in the background (t_b) was approximated from the measured environmental values for the rural ICP station in Toledo, Spain, in 2014. The measured first year annual corrosion was in that year 0.46 µm, close to the suggested average European first year background corrosion of 0.45 µm (Tidblad et al., 2014; Tidblad 2014). The lifetime until maintenance at a target recession of two times the background (= 0.9 µm), suggested for year 2050 (Tidblad 2014) was approximated from the measured environmental

[3] References to results-figures and tables are included in the Methods chapter to assist in the reading of where results from use of the equations is shown. The results-figures and tables are presented in the Results chapter.

values for the rural ICP station in Oslo, Norway, in 2000. The measured first year annual corrosion was in that year 0.896 µm, close to the suggested target of 0.9 µm (Tidblad et al., 2014). The background lifetime was estimated by adjusting the lifetime calculated for Toledo (2014), according to (1), by multiplying with "the first year Toledo (2014) to background recession rate" of 0.46/0.45. A background lifetime of 436 years, as compared to the calculated Toledo (2014) lifetime of 425 years, was then obtained. Similarly, the 2050 target lifetime was estimated by adjusting the lifetime calculated for Oslo (2000), according to (1), by multiplying with "the first year Oslo (2014) to target recession rate" of 0.896 /0.9. A target lifetime of 174 years, as compared to the Oslo (2000) lifetime of 175 years, was then obtained.

A tolerable corrosion depth can be difficult to recommend for limestone (Grøntoft, 2017). All the calculations of cost savings for Portland limestone were therefore made for an undetermined service life time, represented by different recession amounts for different pollution scenarios in the first year of weathering according to the linear (with time) equation (3-4). Instead of calculating cost per year as for zinc, the costs were adjusted to represent the same, undetermined, time span (service life) as for one reference station and year, which was selected to be Prague (2005), by adjusting the calculated values according to the reference ($R_{ref,PL}$, Eq. 4-7) by (for further details see Grøntoft, 2017):

$$K_{p,r} = P\cdot [(R_{p,r} - R_b)/R_{ref,\,PL}] \qquad (7)$$

where R is the material corrosion recession (µm) and the subscripts represents the measured, "present" (p) and hypothetically reduced (r), air pollution and/or climate situations. For a suggested tolerable corrosion depth the cost per year for any station and year would simply be the calculated value for $K_{p,r}$ divided by lifetime in Prague (2005) as calculated by (4).

The maintenance cost savings for Portland limestone that could be obtained by reducing the air pollution, were then calculated by subtracting the maintenance cost in the hypothetical situation with reduced air pollution, or changed climate, from the measured ("present") air pollution situation for any year. This is, as the direct mathematical derivation from Grøntoft (2017), given by:

$$\Delta C(Euro) = K_p - K_r = P\cdot [(R_p - R_r)/R_{ref,\,PL}] \qquad (8)$$

$$\Delta C(\%) = (\Delta C(Euro) / P) \cdot 100 = [(R_p - R_r)/R_{ref,\,PL}] \cdot 100 \qquad (9)$$

where ΔC(Euro) and ΔC(%) are the cost savings due to the pollution reduction, in Euro and in % of the total maintenance cost[4].

When calculating the total maintenance cost and cost savings due to air pollution (7), a first year approach was used in this work for Portland limestone. It was assumed that the relative values for the weathering between different air pollution and climate situations, including the background value, were similar for the first and the later years of façade weathering, and given by Eq. (7). By using (7-9) rather than (5-6) for Portland limestone, the maintenance cost and savings (Euro or %) over the same undetermined working life, similar to the lifetime before maintenance for the reference, was calculated, rather than the cost saving per year.

[4] Differently from the "cost savings due to air pollution reduction as % of the total maintenance cost due to air pollution over background" reported in Grøntoft (2017).

This is only a matter of scale. That is, the costs and savings were compared for a longer, undetermined, working life time than one year. When calculating differences, that is the cost savings (8-9), for any number of years, the constant terms in the linear equations (2) and (4) and the background values (7), are subtracted and thus not influencing the result. When calculating the total maintenance cost for the longer working life time, the first year approach simplifies the calculation by only needing as input the background recession for the first year (Tidblad, 2014). A calculation of probable changes in lifetimes representing a reported 100 µm tolerable recession before maintenance of aged Portland limestone ornament (Kucera (2005) was still performed by (4).

Comparison was then made with suggested target values for the corrosion, for protecting materials in built structures and cultural heritage monuments, corresponding to 2.5 and 2 times the background corrosion rates, in 2020 and 2050, respectively, as presented in "Indicators and targets for air pollution effects" (WGE, 2009; Tidblad, 2014; Kucera, 2007). Comparison was made with the 2050 target for averages of all the ICP sites and years (Figure 7). For Portland limestone at the reference location of Prague (Figure 4), comparison was also made with the 2020 target level, the EU 2008 Air Quality Directive and with the effect of probable climate change. The EU 2008 Air Quality Directive (Guerreiro et al. 2013) determines annual average concentrations of: SO_2 = 20 µg/m^3 for vegetation, and for NO_2 = 40 µg/m^3 and PM10 = 40 µg/m^3, for protection of health. Annual average health limits are not given for SO_2.

The cost savings due to the hypothetical reduction in the air pollution are reported as positive. Where meeting a target would mean allowing increased pollution the cost changes for the target are reported as negative. The climate change effect is, for the sake of clear presentation in Figure 4, represented as a positive cost increase, and noted as such.

Drdácký et al. (2006) report total replacement costs for one square meter galvanized steel sheet to vary from 16 to 54 Euro, which could indicate the cost for zinc sheet., They report the cost for the total replacement of non-plastered irregular stone masonry of 200 mm thickness to be 578 Euro/m^2. Thus, a maintenance cost of 100 Euro/m^2 could be a possible realistic cost for maintenance of zinc sheet in 2017, considering price increase since 2006 and price variation depending on material and work characteristics. Most maintenance of limestone would, however, probably cost more. There would, in any case, be large variations in maintenance cost in Europe depending on type of construction and location. Therefore, the "maintenance cost due to air pollution over background" and "maintenance cost saving due to 50 % air pollution reduction" are presented in the more general units of %/year for zinc, and as % relative to the reference situation, Prague 2005, for Portland limestone.

These values can be recalculated to the unit Euro/year for any other maintenance intervention cost ($M{\cdot}P$). For zinc, by multiplying any reported value (of %/year) with $M{\cdot}P/100$. For Portland limestone, by dividing any reported value (%) by the service lifetime for Portland limestone in the reference situation in Prague 2005. For example of 27 years (Figure 8), representing in that case the suggested service time until a tolerable recession depth of 100 µm for Portland limestone ornament.

For Portland limestone, locations and years with higher pollution load than the reference (Prague 2005) (Tidblad et al., 2014) would have shorter service life between maintenance than the references and lower cost savings for that shorter period than reported (in Table A3 and Figure 6). Locations and years with lower pollution load than the reference would have longer service life between maintenance, than the reference, and higher total cost savings than reported in this paper, for that longer period.

The corrosion costs and lifetimes reported in this work only represent the effect of outdoor atmospheric chemical weathering. There are other reasons for maintenance investments for outdoor surfaces, both related to different wear mechanisms and other concerns. The savings on total maintenance cost which could be obtained by reducing air pollution and thus atmospheric weathering, should be weighed with the other reasons for maintenance investments in actual cases (Grøntoft, 2017).

3 Data

The calculations in this work were made for all the ICP stations and years with the needed environmental data, as input to (1, 3-4). The results reported in the Appendix tables thus represent the ICP stations' data availability (Tidblad et al., 2014). The tables also report the station classifications, as urban (U), industrial (I) or/and rural (R).

The environmental data were used to calculate time series estimates of maintenance costs, and savings (changes) due to reduction in air pollution and future expected climate change, and the service life time for zinc and Portland limestone, for the average of all the ICP stations and some individual stations (Prague and Kopisty in the Czech republic, and Toledo in Spain), by (1-9). The environmental data are reported in Tidblad et al. (2014). Mapping of maintenance costs and savings due to reduction in air pollution was performed for Portland limestone in the city of Oslo, Norway.

The environmental data values for the average of the ICP stations in 1987, 2005 and 2014, for the selected reference situation for Portland limestone (Prague 2005), for Prague in 2014, and for Oslo, Norway, applied in the mapping and measured at the Oslo ICP station from 2002 to 2014, are shown in Table 1. The years reported for the ICP data represent, in accordance with ICP reporting, annual average values from measurements which started in October that year, and so mostly cover the following year.

Table 1: Environmental parameter values (annual averages) used as input to the calculation of the maintenance costs and savings, as measured for the average of the ICP stations, for the Prague station used as reference for Portland limestone, and for Oslo from 2002-14 compared to the mapping results values for the ICP-Oslo station. n.a. = not available.

Parameter	ICP-mean 1987	ICP-mean 2005	ICP-mean 2014	ICP-Prague 1995	ICP-Prague 2005	ICP-Prague 2014	ICP-Oslo (mean 2002-14)	ICP-Oslo mapping value
SO_2 (µg/m^3)	22.3	9.3	5.1	31.5	11.1	4.6	2.1	3
H^+ (mg/l)	0.037	0.011	0.011	0.03	0.002	0.0018	0.012	0.01
NO_2 (µg/m^3)	33.4	21.0	21.6	24	40	38	28	28
O_3 (µg/m^3)	42.1	51.3	52.2	55	47	37	35	41
PM10 (µg/m^3)	n.a.	29.8	19.2	n.a.	20	22	n.a.	21
Precip. (mm)	816	677	677	550	491	414	828	635
RH (%)	76	73	74	80	74	73	75	74
T (°C)	9.9	9.7	11.0	7.7	9.3	11.0	7.1	7.6

The input values used for the calculation of the effect of anthropogenic climate change in Prague until the period 2081–2100, were a change in annual averages of temperature of +2.9°C and of rain amount of +2.5%. These values were derived as averages of values from a lowest scenario, RCP 2.6, and a highest scenario, RCP 8.5, as reported in mapping from the IPCC (2014).

The mapping for Oslo (Figure 10) was performed by applying available gridded data from the period 2000 – 2016. The air pollution load in Oslo has changed little since about year 2000. The mapping was therefore expected to be generally valid for Oslo for these years. The mapping was performed with gridded pollution and climate values with a resolution of one times one km, for an area of 22 km (west-east) times 18 km (north south) covering the main central Oslo urban area. The air pollution gridded values, for NO_2, O_3 and PM10, were obtained from emission-dispersion modeling adjusted to the values for the pollution measured at central traffic and urban background stations, according to the method in Slørdal, Walker & Solberg (2003). The ozone values were obtained from the values for NO_2 (µg/m^3) and sun radiation (*Sun*, annual number of sun hours) by using the empirical equation: $O_3 = (38 + 0.013 \cdot Sun) \cdot e^{(-0.022 + 0.000005 \cdot Sun) \cdot NO_2}$, where the annual average number of sun hours measured at the main Oslo meteorological station of Blindern in the three years from 2000 to 2002, of 1679 hours, was used (eKlima, 2017). The climate values used, of temperature, precipitation amount and relative humidity, were annual average values measured at the Oslo air quality measurement traffic station “Valle Hovin” in 2003. For acidity in precipitation, *pH*, the average value measured at the ICP-materials station in Oslo from 2002 to 2014 was used (Tidblad, 2014). Constant values for precipitation amount, relative humidity, acidity in precipitation and the concentration of SO_2, were used for the whole grid. The annual average temperature value from the Valle Hovin station was adjusted for each grid cell according to the topography, assuming a temperature change of 0.98 °C for each 100 m increase in altitude. Air quality reports from the municipality of Oslo (Luftkvalitet.info, 2018; “Luftkvaliteten i Oslo i 2016”, 2016; Lützenkirchen & Løseth, 2015) and data from the Oslo ICP-materials station (Tidblad et al., 2014) show variation, but no significant trends in Oslo after 2002, for the concentration of the air pollutants impacting on limestone (2), except a possible slight decrease in airborne particulate matter (PM10) since 2005. The averages and ranges of the input variables to the mapping were: Input variable (Average, Minimum, Maximum) = O_3 (50, 30, 56 µg/m^3), NO_2 (14, 4, 50 µg/m^3), SO_2 (3 µg/m^3), *PM10* (10, 5, 30 µg/m^3), *RH* (74%), T (7, 3, 8°C), *Prec* (635 mm), *pH* in precipitation (5).

4 Results

Results are presented below of the maintenance cost savings (and increase due to climate change) for zinc and Portland limestone surfaces due to given percentages reduction of noted pollutants, due to meeting suggested target levels for the air pollution, and due to future expected climate change calculated from (6) and (9) from the environmental parameter values given in the ICP database. For the “Portland limestone reference location, Prague” (Figure 4) the calculations were made with continuous reduction (0-100%), and for the averages of ICP stations (Figure 5 to Figure 9) and Oslo (Figure 10) with a 50% reduction, of all the air pollutants in (1) and (4), except O_3 for which the values were not changed. Thus, when below mentioning the reduction of “all pollutants” this does not include O_3. The results are presented for some single ICP-materials stations, and as averages for all the stations with available needed annual average environmental data measured at the stations.

Figure 4 shows results for the urban location of Prague, in 2005 (used as reference), and for the most recent measurement year in ICP-materials in 2014. The estimates are for the savings in maintenance cost for Portland limestone surfaces, that could be obtained from reduction of the noted single pollutants, and for simultaneous reduction of all the pollutants, compared to target levels and to the expected climate change effect until the period 2070-2100 (IPCC, 2014).The diagram also shows the respective change in lifetimes between maintenance at 100 µm recession. The diagram represents the first year, but also an undetermined lifetime due to the reported linearity of (2 to 4) (Watt et al., 2009).

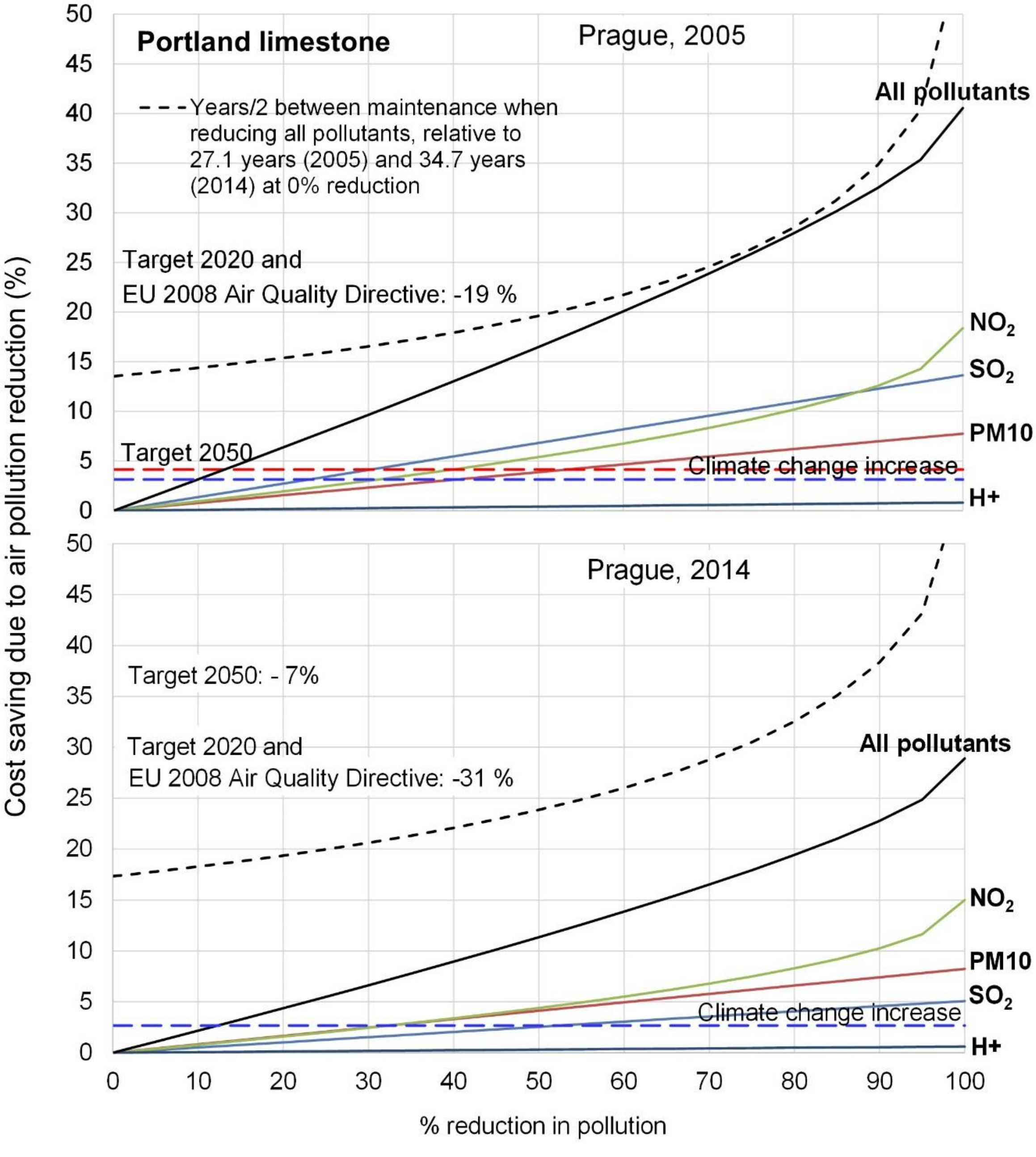

Figure 4: Increase in lifetime between maintenance and savings in maintenance cost for a Portland limestone surface that could have been obtained from reduction of the noted single pollutants and for simultaneous reduction of all the pollutants, for the urban ICP location of Prague in 2005 and 2014, compared to target levels and the expected climate change effect until the period 2070-2100.

Figure 4 shows how for Prague the situation for Portland limestone was improved in 2014 as compared to 2005, due mostly to a reduction in the concentration of SO_2 (Table 1), so that in 2014 all the targets, including the 2050 target, were met. For the other pollutants some variation, but no major differences, were observed when comparing 2005 and 2014. The cost saving from reducing all the pollutants with 50% was reduced from 16% in 2005 to 11% 2014. The expected increases in maintenance costs caused by atmospheric chemical weathering of Portland limestone in Prague, due to climate change, until the period 2070-2100, were calculated to be 2.5% from the 2005 environmental values and 1.9% from the 2014 values.

Figure 5 and Figure 6 show the calculated "%/year" (zinc) and "% over an undetermined lifetime" (Portland limestone) maintenance cost due to air pollution over the background level, and the average, and minimum and maximum, values for the cost saving due to a 50% reduction of all the impacting pollutants, according to (1) to (9). The results were calculated for every year for all the stations with available environmental data in the ICP-materials data base, and for the case of the 50% pollution reduction also for the stations noted as urban (U), industrial (I) and rural (R) (see Appendix). In Figure 5 (and Figure 7) one year, 1990, stand out with an unusually high maximum station value. This value represents the rural station no. 30, "Stoke Orchard" (see Appendix), where a very low pH in rain, of 3.18 *([H^+]* = 0.66 mg/l) was reported in this year (Tidblad et al., 2014). In Figure 6 the cost estimates for the reference station for Portland limestone, "Prague 2005" (Figure 4), are also shown.

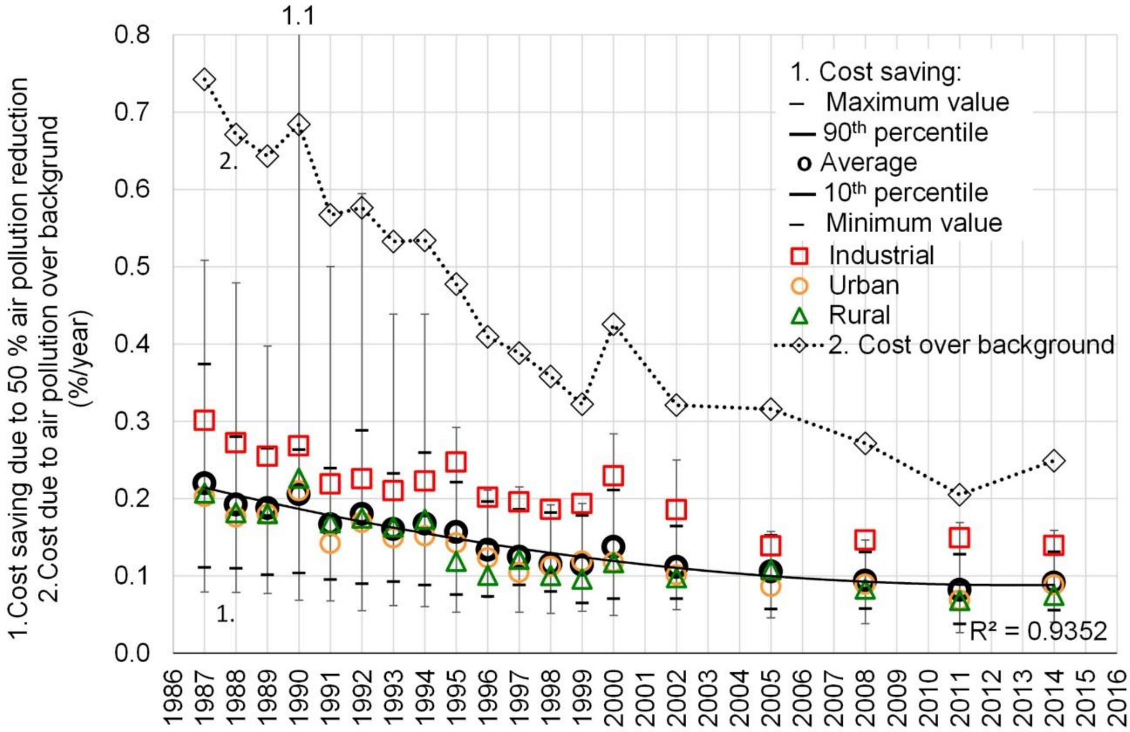

Figure 5: The calculated average zinc maintenance cost due to air pollution over the background level, and average, minimum and maximum, values for the maintenance cost saving due to a 50% reduction of the impacting pollutants (5-6) on all the ICP stations with available data, and for the sub-selections of stations noted as urban (U), industrial (I) and rural

(R) (cost savings), calculated for every year for all the stations with available environmental data (see Appendix).

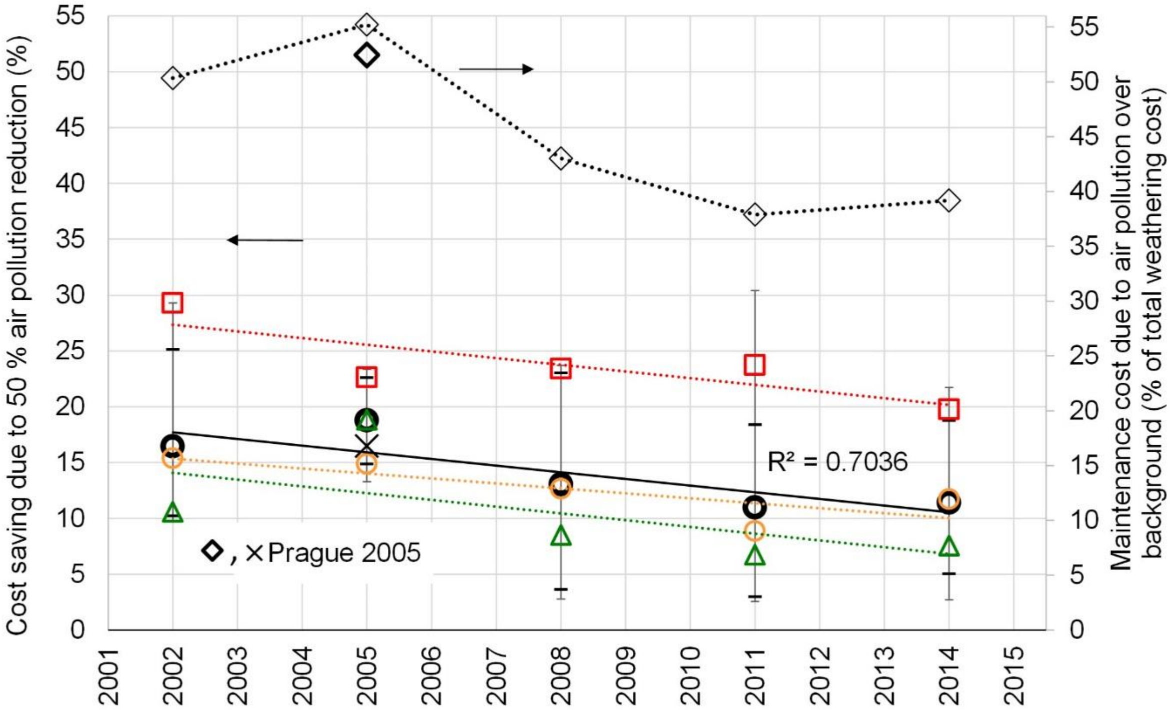

Figure 6: The calculated average Portland limestone maintenance cost due to air pollution over the background level, and average, minimum and maximum, values for the maintenance cost saving due to a 50% reduction of the impacting pollutants (7-9), for an undetermined lifetime, on all the ICP stations with available data, and for the sub-selections of stations noted as urban (U), industrial (I) and rural (R) (cost savings), calculated for every year for all the stations with available environmental data. (see Appendix).

Figure 5 and Figure 6 show a decrease in the maintenance costs due to air pollution over the background level, for zinc and Portland limestone, over the ICP measurement years. For zinc the costs decreased with 68% from 1987, and 25 % from 2002-5, to 2008-14. A similar decrease of 26% is indicated for Portland limestone over five measurement years from 2002 to 2014, with relatively large variation between years (Table 2).

Table 2: Maintenance costs due to air pollution over the background level, relative to the total maintenance cost, for the average of the ICP-materials sites since 1987.

Site category	Start year	End year(s)	Start years	End year(s)	ΔCost, start to end (%)
Zinc (%/year)	1987	2008, 2011, 2014	0.74	0.24	-68
Zinc (%/year)	2002, 2005	2008, 2011, 2014	0.32	0.24	-25
P. limestone (%)	2002, 2005	2011, 2014	53	39	-26

Figure 5 and Figure 6, and Table 3, further show decrease in the average maintenance cost savings for zinc and Portland limestone surfaces that could be obtained by reducing the air pollution by 50%, according to (1) to (9), over all the ICP stations and measurement years.

This decrease corresponds with a decrease in the average concentration of the air pollutants, especially SO_2, towards a lower and more constant value in the later years when approaching year 2014 (Table 1). From 1987 to 2008-14 the potential savings per maintenance investment decreased with 59% for zinc, from about 0.2% (0.22%) per year to about 0.1% (0.09%) per year (Figure 5, Table 3). From 2002-5 to 2008-14 the decrease was 18 % for zinc and was indicated to be the double of this, 36%, for Portland limestone, sinking from about 18% to about 11% (2011-14) (Figure 6, Table 3).

Table 3: Maintenance cost savings for zinc and Portland limestone surfaces due to 50% air pollution reduction, at ICP-materials locations. Averages for all stations and years.

Site category	Start year(s)	End years	Cost saving in start year(s) (%/year)	Cost saving in end year(s) (%/year)	ΔCost saving, start to end (%)
		Zinc			
Rural	1987	2008, 2011, 2014	0.21	0.08	-62
Urban	1987	2008, 2011, 2014	0.20	0.08	-60
Industrial	1988	2008, 2011, 2014	0.30	0.14	-53
All stations	1987	2008, 2011, 2014	0.22	0.09	-59
Rural	2002, 2005	2008, 2011, 2014	0.10	0.08	-20
Urban	2002, 2005	2008, 2011, 2014	0.09	0.08	-11
Industrial	2002, 2005	2008, 2011, 2014	0.17	0.14	-18
All stations	2002, 2005	2008, 2011, 2014	0.11	0.09	-18
		Portland limestone (%)			
Rural	2005	2011, 2014	14.7	7.2	-51
Urban	2002, 2005	2011, 2014	15.1	10.3	-32
Industrial	2002, 2005	2011, 2014	26.0	21.7	-16
All stations	2002, 2005	2011, 2014	17.6	11.2	-36

The values for the cost savings were always found to be larger for the industrial stations than for the urban and rural stations. For zinc the cost savings for the urban stations were found to be slightly larger than for the rural stations in the years except 1987-1994, 1997, 2000 and 2005. For Portland limestone the cost savings for the urban stations were found to be larger than for the rural stations for four of five years (except 2005). For both zinc and Portland limestone the decrease in cost savings over the years was largest for the rural stations then urban stations, from 1987 for zinc and from 2002-5 for Portland limestone. There was larger variation between years for the industrial stations and the ranking of the decrease between the urban and industrial stations was less clear for zinc (Table 3).

Figure 7 compares the calculated average values for the maintenance cost savings at 50% air pollution reduction (as also given in Figure 6) with suggested target values for the corrosion recession in year 2050, corresponding to a first year recession of 0.9 µm (= 6.4 g/m^2) for zinc and 6.4 µm for Portland limestone, which is equal to two times the first year background recession (Kucera, 2007; Tidblad, 2014). To illustrate application for single stations Figure 7 also shows the respective values for maintenance cost savings and the 2050 target for an industrial station with relatively high air pollution, Kopisty, and the urban station, Prague (which was used as reference in the calculations for Portland limestone), both in the Czech republic, and for a rural station with relatively low air pollution, Toledo, in Spain (see Appendix).

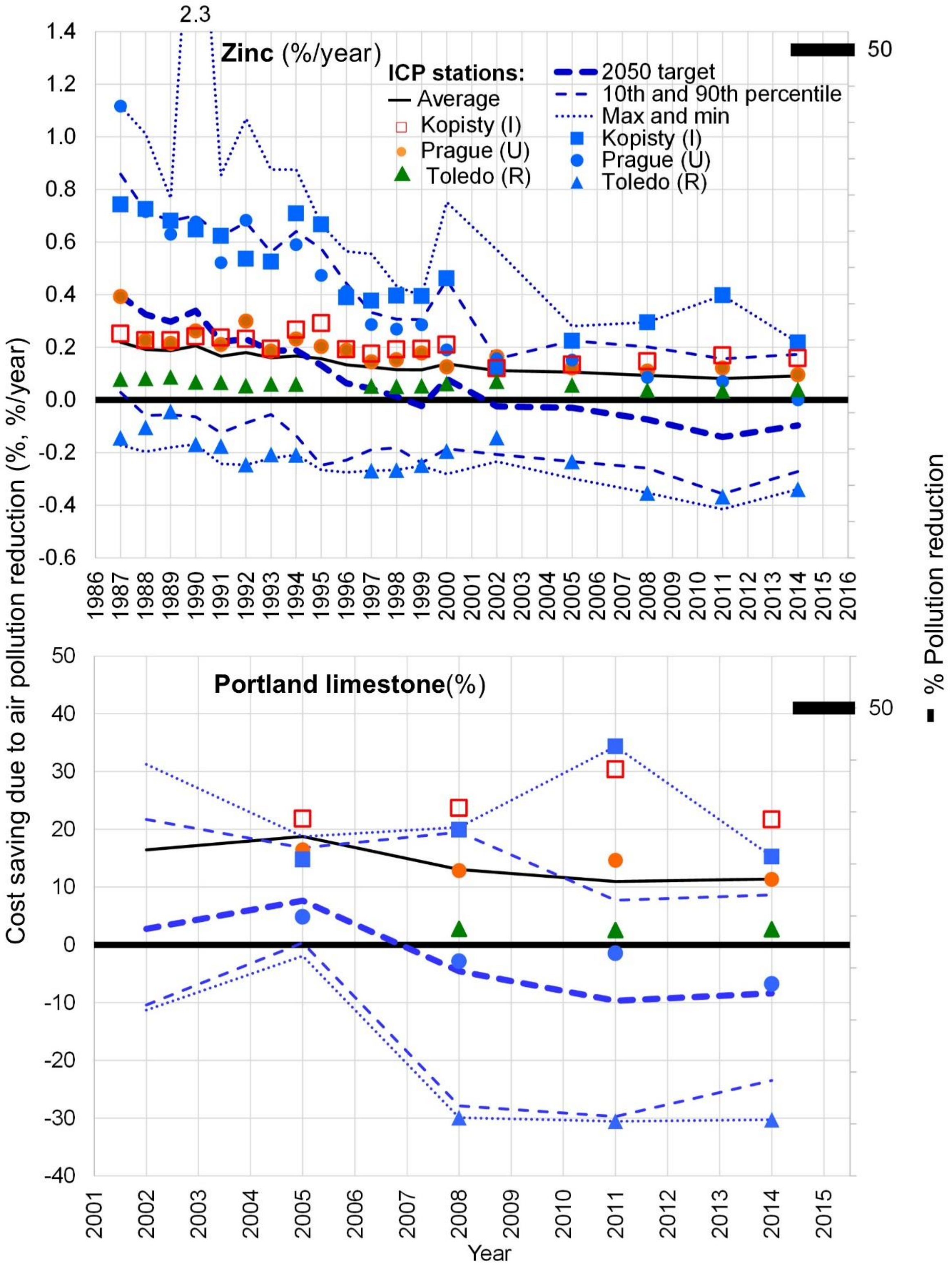

Figure 7: Comparison between the calculated average values for all the ICP locations and for three selected stations, for the maintenance cost saving (1-9) due to 50% air pollution reduction (as also given in Figure 6), and suggested target values in year 2050 of two times the background recession. The selected ICP stations are the industrial station in Kopisty (I) and the urban ("Portland limestone reference") station Prague (U), both in the Czech Republic, and the rural station Toledo (R) in Spain. The thick horizontal black line on the right axis shows the selected calculated amount (%) of pollution reduction. The needed

environmental measurement values for the calculation for zinc were not available in Toledo in 1995 and 1996, and for Portland limestone for none the three included separate ICP stations in 2002 and also not for Toledo in 2005 (see Appendix).

Due to the complexity of Figure 7, the data for the target were not simply added to Figure 6, and some additional guidance to the interpretation of Figure 7 will be given. With no (zero %) pollution reduction the calculated average cost savings in Figure 6 and Figure 7 would be zero in all cases and every year. On reducing the air pollution the average cost savings would increase until, at 50% reduction, the values given in Figure 6 and Figure 7 were obtained. At 100% reduction the savings would be at the maximum that could be calculated for zinc (1) and for Portland limestone, representing all the pollutant terms (except O_3) after the constant value of 4 in (2). The same calculations could alternatively be made for reductions of any single or some combination of air pollutants (SO_2, H^+ and NO_2, HNO_3), for some other reduction level (%) through the years (then the 50% reduction of all pollutants used in Figure 6 and Figure 7), or showing the cost savings over the range of possible reduction of the pollutants (0-100 %) (as in Figure 4). Figure 7 compares the possible average maintenance cost saving for the ICP stations and for a single selected industrial, urban and rural station, due to 50% air pollution reduction, and due to meeting the 2050 target (blue lines) of 2 times the background corrosion for every year, and includes 10^{th} and 90^{th} percentile, and maximum and minimum values for the stations, for the target. As the target for the corrosion recession (or lifetime) is always a constant value, the cost saving from meeting the target was higher in the first phase of the programme, from 1987, when the air pollution was higher and has decreased as the air pollution has decreased. Similar or higher values in Figure 7, for the cost savings due to 50% air pollution reduction at the ICP stations, as for meeting the target, indicates that the target will be met by the 50% air pollution reduction. A zero value for the blue line of the target (a crossing of the x axis) indicates that the target was reached – at the measured values for the air pollution. The blue lines for the minimum, 10^{th} and 90^{th} percentile and maximum values for the target are interpreted similarly. Thus, Figure 7 indicates that for zinc a 50% reduction in the air pollution would, for the average of all the stations and years, have been sufficient to reach the 2050 target from 1995 and that from 2002 this target was reached at the measured values for the air pollution. Before 1995 a larger pollution reduction (then 50%) would have been needed to reach the target, whereas from 1995 to 2002 a smaller reduction (then 50%) would have been needed. For Portland limestone Figure 7 indicates that for the period with transgression of the 2050 target, before 2007, a pollution reduction less than 50% would have been sufficient to reach the target. In the period between, from 2007 to 2014 the 2050 target was reached, at the measured values for the air pollution.

The values given for the three singles stations are interpreted similarly. When the (blue) target markers (cost saving at target) are below the x-axis the 2050 target was reached for that station, at the measured values for the air pollution. When the (blue) target markers are above the x-axis and the ICP station marker is positioned on or above the target marker, this indicates that the maintenance cost saving due to 50% air pollution reduction would be equal to or higher than the target in that year, and thus sufficient to reach the target. Thus, for zinc the 2050 target was reached in all years in Toledo. However, a 50% pollution reduction would not have be sufficient to reach the target in Kopisty in any year (1987-2014) except 2002, and in Prague the target would only have been reached by this measure in 2002 and from 2008 (2008-2014). For Portland limestone the 2050 target was reached in all three measurement years in Toledo (2008-2014) and also in these three years, but not in 2005, in Prague. In Kopisty, 50% pollution reduction would have been sufficient to reach the 2050 target in three of four of the measurement years, only in year 2011 more than 50% pollution reduction would have been needed to reach the target.

In the dynamic version of the diagrams (Figure 7) any target can be compared with any pollution reduction for any selection of stations, or single station, to determine if the target was reached or how much pollution reduction had been needed to reach the target. Any air pollution scenario could be used similarly to predict how future reduction situations could meet targets.

Figure 8 shows the calculated indicative average lifetimes before maintenance of zinc monument surfaces since 1987, and of Portland limestone ornament surfaces since 2002, for the locations of the ICP-materials stations, at the measured air pollution situation and for a situation with hypothetical 50% simultaneous reduction in the impacting air pollution at the stations, according to (1) and (3-4). The calculations were based on suggested tolerable corrosion depths before maintenance of 80 µm for a plain zinc surface and 100 µm for an aged Portland limestone ornament (Kucera, 2005). For Portland limestone the figure also shows the values calculated for the "reference station" Prague, as in Figure 4, at 0% and 50% reduction of all pollutants

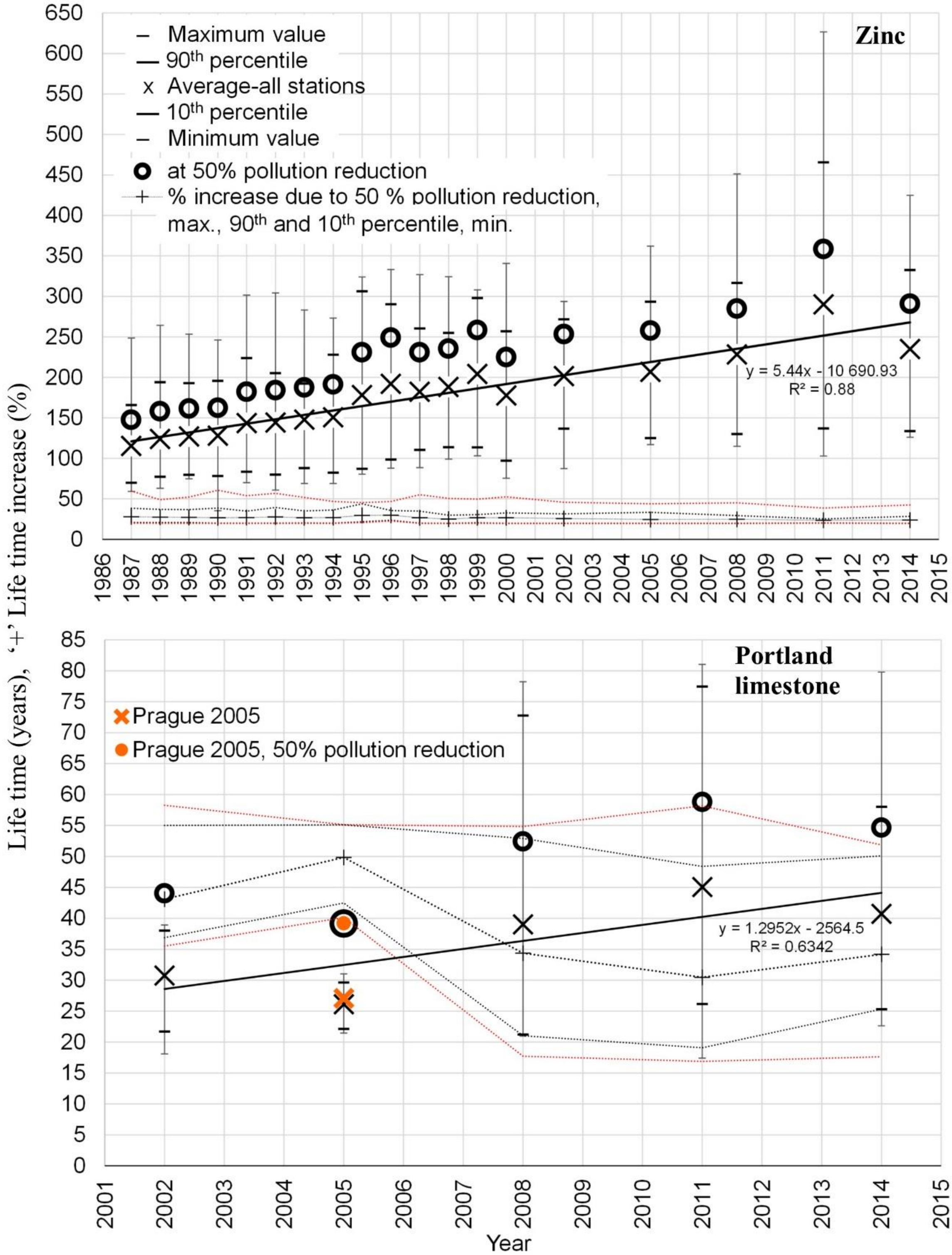

Figure 8: Indicative average lifetimes (years) before recommended maintenance of zinc and Portland limestone surfaces, and increase in lifetimes (%, and "years"), due to 50% simultaneous reduction in the impacting pollutants, according to (1) and (3-4), for the ICP-materials stations since 1987 (zinc) and 2002 (Portland limestone). The calculations used tolerable recession before maintenance of 80 µm for zinc surfaces and 100 µm for Portland limestone ornament. The "% increase in lifetimes" are the difference between the lifetimes at 50% pollution reduction and the average values for all the stations, given in the figure.

The result in Figure 8 indicates an increase in lifetime before maintenance (as evaluated from the linear regression values in the figure), as an average for the ICP stations, clearly for zinc from 1987 to 2014, from 118 to 265 years = 125%, and from 2002 to 2014, from 200 to 265 years = 33%, and tentatively for Portland limestone from 2002 to 2014, from 28 to 44 years = 55%. The additional increase due to a hypothetical 50% reduction in the corroding air pollution, was indicated to be about 26% for zinc, decreasing from 28% in 1987 to 24% in 2014, and about 38% for Portland limestone, varying between 30% and 50% in the measurement years from 2002 to 2014. For the zinc service life times of 118 (1987) and 265 (2014) years, the cost savings, as calculated from Table 3, would be 26% and 24%. A comparison of total savings should however be made for the same service time. A reasonable approximation seems to be that for a service time of 100 years (~118 years) there would be a reduction in the average all stations' cost savings from about 20% in 1987 to about 10% in 2014 (Table 3).

Figure 9 shows the average calculated percent increase in lifetime between maintenance (%) at the ICP stations for zinc and Portland limestone, over the years from 1987 (zinc) and from 2002 (Portland limestone), to 2014, due to increasing simultaneous reduction of all the impacting air pollutants (%), according to (1) and (3-4). The calculations were for the suggested tolerable corrosion depths before maintenance of 80 µm for a plain zinc surface and 100 µm for an aged Portland limestone ornament.

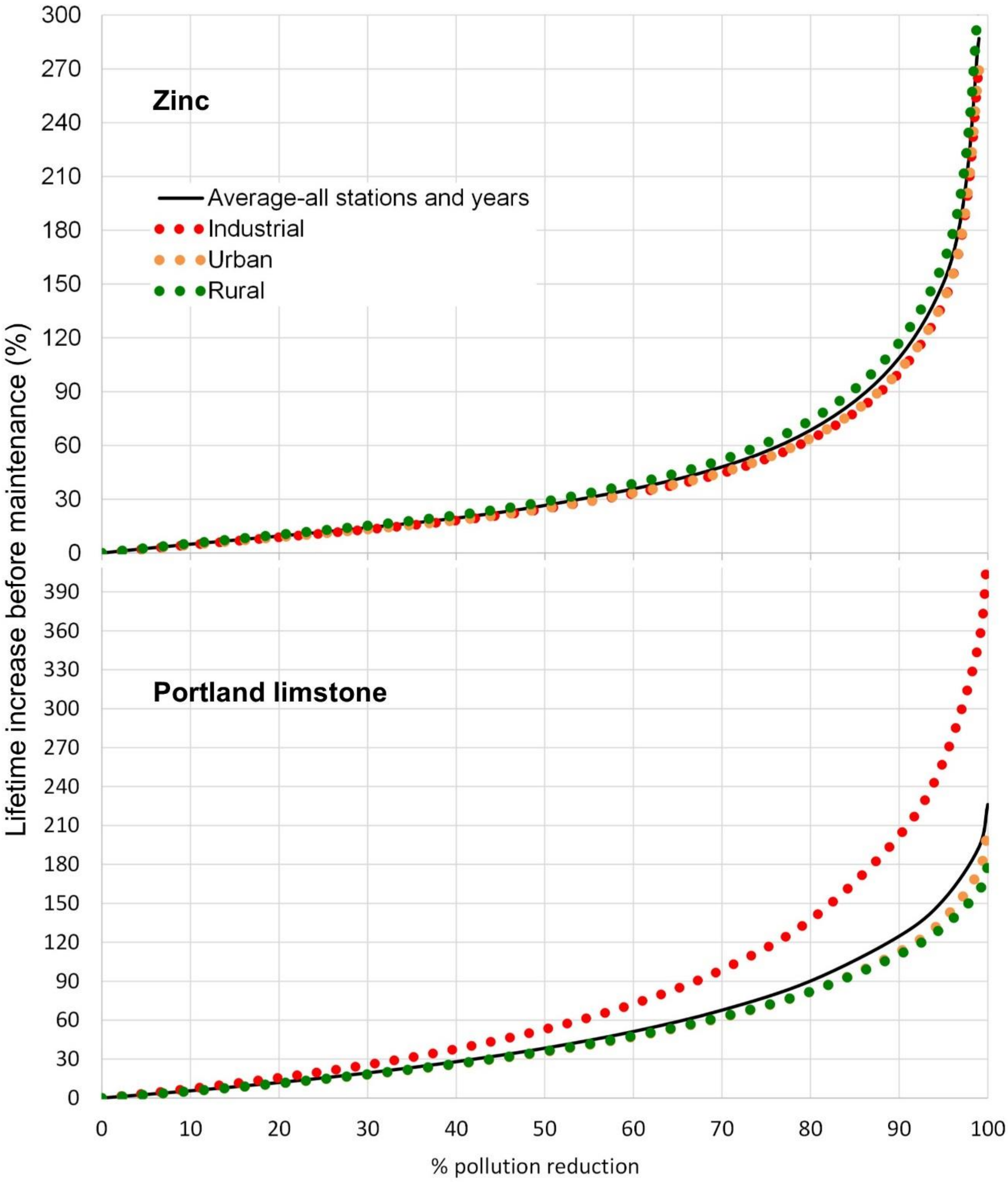

Figure 9: Calculated average percent increase in lifetime for zinc and Portland limestone over the years from 1987 (zinc) and 2002 (Portland limestone), to 2014, at the locations of the ICP stations, and for the selections of industrial, urban and rural stations, due to increasing simultaneous percentages reduction of all the impacting pollutants. For tolerable corrosion depths before maintenance of 80 µm for a plain zinc surface and 100 µm for an aged Portland limestone.

The averages over all the years, of the "% increase due to 50% pollution reduction" given in Figure 8, are shown at 50% pollution reduction in Figure 9. For zinc, the lifetime expectancy increases near linearly up to 70-80% pollution reduction, where the increase in lifetime between maintenance would be about 50%. With even more pollution reduction the lifetime is expected to increase sharply (Figure 9). The life time expectancy increases slightly more for the rural, than urban and industrial stations. The expected increase in lifetime between maintenance of Portland limestone due to the air pollution reduction was calculated to be higher than for zinc, especially at the industrial stations with more than 100% lifetime increase, but also for the urban and rural stations with about 75% lifetime increase, at 70-80% pollution reduction. For higher, than 70-80%, pollution reduction the lifetime of Portland limestone is expected to increase sharply, but less so than for zinc.

Figure 10 shows the mapping performed, of the % savings in maintenance cost for Portland limestone facades, which could be obtained by 50% reduction in the impacting air pollution, resulting in reduced atmospheric chemical weathering, for Oslo, Norway.

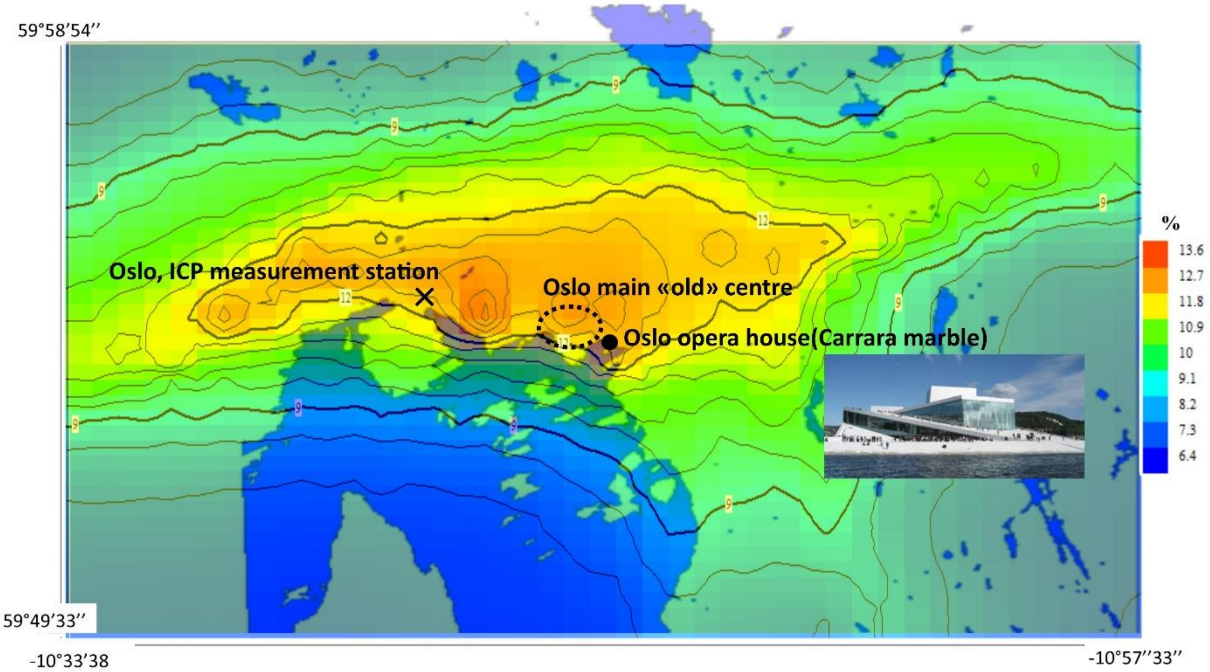

Figure 10: Expected % cost savings in maintenance of Portland limestone facades in Oslo, Norway, due to atmospheric chemical weathering, which could be obtained by 50% reduction in impacting air pollution. The locations of the ICP measurement station in Oslo, the main old city center with many lime plaster facades, and the new (2008) Oslo opera built from marble, are shown.

Simple validation of the mapping was performed by comparison of the mapping results with the values for the average of the calculated % cost saving, according to (3-4), for the years 2002, 2005, 2008 and 2014, for the ICP station in Oslo, for which the location is shown on the map. The PM10 value was not measured at this ICP station, therefore the same PM10 value as that applied in the mapping for this location, of 21.3 $\mu g/m^3$, was used in the validation (Table 1). This value is about 50% of the present values at traffic stations in Oslo (Lützenkirchen & Løseth, 2015). The ICP station is an urban background station (Figure 1) and it is expected that the concentration is lower than at the traffic stations. The measured input environmental values to the calculation of the cost savings for the ICP location in Oslo, and the values used in the mapping are compared in Table 1.

The value for the possible maintenance cost saving for the location of the Oslo ICP station, obtained from the mapping, was 12.4%, as compared to a value of 12.6% calculated from the ICP station measurement values, giving reasonable confidence to the mapping results.
The mapping shows the level and major differences in the possible maintenance cost savings for Portland limestone that could be obtained by reducing the air pollution in the city.

5. Discussion

The calculations of corrosion cost savings due to pollution reduction and of lifetimes between maintenance, for zinc and Portland limestone surfaces, performed in this work, are presented as trends over recent years for a selection of European, and three North American, stations with different environments. The values are not presented as "European averages", as this would need explanation about representation, which is not provided in this work. The industrial (8 sites) are underrepresented in comparison to the urban (23) and rural (21) sites. The distinguishing between these three categories was made in ICP-materials to assess differences in environmental exposures and corrosion, depending on main site characteristics. The long time series, since 1987, give important information about trends in the corrosion costs. The air pollution in rural locations is, generally, less affected by single pollution sources and more affected by long range transport and dispersion over large areas. The values measured over the years at single urban stations can be more affected by changes in emissions around the stations, for example due to change in traffic patterns, which could be unrelated to general trends in the pollution situation in cities. However, most of the ICP urban stations were located in a distance from traffic in the "urban background" and the exposure would, generally, come from emissions from a larger area of the city, and not mainly from one local road. The corrosion and calculated cost values for the few industrial stations, is expected to depend more on the selection of the sites. Similar trends of reduction of maintenance costs were calculated from the environmental measurements at the ICP stations, although with significant variation between years and between the three categories of stations (Figure 5 and Figure 6).
Clearly, minimum and maximum values can depend on the selection of locations. The North American sites were included to fully represent the work in ICP-materials. Whereas the zinc corrosion on two North American stations (37 and 38, Appendix) were in the range of the European stations, the zinc corrosion on the remaining North American station (39, Appendix), located in an industrial area, was usually the highest of all the stations. With few industrial stations among the ICP stations it was still considered useful to include this station, based also on the evaluation that a similar European station with high pollution could well have been found.

As can be seen from the tables in the Appendix, there was a significant change of stations in the ICP network in 1995, most clearly affecting the smaller number of industrial stations, among which only two stations, Kopisty (3) and Bottrop (10), were continuing to do measurements after 1995, then with measurements also in a few years at a third new station in Katowice (50). The deviation in1995 and some larger variation in results after 1995 for the industrial stations, seen in Figure 5, is probably related to this change to fewer stations.

The calculation of maintenance cost savings due to pollution reduction was made for hypothetical future periods of years with the same air pollution situation as for the measurement years. This should be a reasonable procedure for assessment of changes over time. It would, however, as long as pollution values are decreasing, exaggerate to some extent the future expected integrated corrosion from any one year. Thus, for the period with a continuous sinking trend in the pollution at the ICP stations, from 1987 until about 2010, the future cost savings would probably be somewhat lower than reported in Figure 5, Figure 6 and Table A1 to A3. Future cost savings from the present (2014) would also be lower than reported if the decrease in the air pollution continuous. This possible error is somewhat reduced for zinc due to the higher corrosion rate in the initial years ($t^{0.85}$ in Eq. 1), and is generally more uncertain for Portland limestone due to the larger variation between fewer measurement years.

Climate change will over the coming century most probably have the opposite effect, as that of pollution reduction, by increasing the corrosion and maintenance costs. For the Portland limestone "reference station", Prague, this probable increase in corrosion costs was, however, calculated to be considerably less than the saving that could be obtained by 50% pollution reduction, representing about 15% of this saving (14.5% in 2005 and 16.9% in 2014, Figure 4).

The reduction in the possible cost savings for maintenance that could be obtained by reducing air pollution, for Portland limestone in Prague from 2005 to 2014, were mainly due to reduced concentration of SO_2 (Table 1) and consequent reduced weathering rates. The concentrations and thus possible costs savings by reducing other impacting air pollutants showed little change during these years (2005-14) (Table 1, Figure 4). This reflects the considerably larger relative reduction of SO_2 than NO_x emissions in Europe during these years (Guerreiro, González & de Leeuw, 2017). This may be due to continuing reduction in emissions from coal burning, especially in coal areas like southern Poland and the Czech Republic, but less change in fuel use and traffic emissions, which are the main source for NO_2. Thus, in the present multi-pollutant situation, some more of the focus should probably be moved to the nitrogen oxides (NO_x), and PM10 (2), with its inclusion in cost benefit analysis in relation to reduction measures.

Corrosion cost evaluations, like in Figure 4 for Prague, were performed for all the ICP stations and could easily be performed by the method here described for any other locations with the necessary available environmental input data. To exemplify the usefulness of such modelling, without further discussing results that are not here reported, some general evaluations can be given. For the ICP sites the present (2014) costs due to SO_2 exposure was higher in the industrial locations, whereas corrosion costs due to NO_2 exposure was typically higher in the urban locations, like Prague, with expected substantial traffic emissions. The corrosion cost due to high acidity (low pH) was, relatively to the impact of other air pollutants, higher in Northern Europe. This may be due to some continuing long range transport and deposition of acidic air pollution (Aas, Hjellbrekke, Hole & Tørseth, 2017), and probably the low local alkalinity and thus neutralization potential of northern soils and dust.

The sharp increase in the station-average lifetime for zinc, and partly Portland limestone, at higher than 80% pollution reduction (Figure 9), indicates that the presence of relatively small remaining amounts of pollution (especially SO_2 and H^+) may significantly increase corrosion and reduce the lifetime of the surfaces. It should be considered, though, that the uncertainty in the dose-response functions (1 and 3) may be higher for low pollution values which would be a small part of their statistical basis.

6. Conclusion

It was found that the average increase in the theoretical lifetime before maintenance due to atmospheric chemical weathering at the ICP-locations, was for zinc surfaces about 125% (from 118 to 265 years) over the period from 1987 until 2014, and for Portland limestone about 38 % (from 36 to 50 years) over the period from 2002 until 2014. The average increase in lifetime between the maintenance due to 50% pollution reduction was found to be 26% for zinc surfaces (1987-2014) representing maintenance cost savings sinking from about 20% in 1987 to 10% in 2014, and 36% for Portland limestone (2002-2014) representing cost savings over these years of about 14% (sinking from 18 to 11%) (Figure 8, Table 3). This would have been very significant savings considering the total use of zinc and Portland limestone as construction and façade materials.

One should consider that the cost savings due to reduced air pollution, weathering and corrosion of other materials and metals may be at a comparable level. Based on the reported results, it seems a reasonable suggestion that for material surfaces exposed outdoor in Europe, a hypothetical 50% reduction in air pollution from present levels, would give an average overall increase in near future lifetimes between maintenance, carried out due to atmospheric chemical weathering, of about 25%, and savings in maintenance cost of about 10%. The importance of atmospheric chemical weathering relative to other factors influencing the timing of refurbishment, renovation and maintenance interventions on outdoor material surfaces and façades, will however vary. Estimations of the realized increase in lifetime and cost savings, due to reduction in air pollution, could be made by adjusting the above reported values according to the assessed relative importance of the atmospheric chemical weathering for any intervention.

Acknowledgements

The work could only be performed on the basis of the 30 years of field work, analysis and reporting by the partners in the International Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments (ICP-materials) started in 1985, initiated in order to provide a scientific basis for new protocols and regulations developed within the Convention on Long-range Transboundary Air Pollution under the United Nations Economic Commission for Europe (UNECE). I strongly want to thank all past and present ICP partners for their invaluable work over these many years, which today make assessments like those reported here possible. The work was performed with support from the Norwegian Environment Agency, to NILU-Norwegian Institute for Air Research as partner in ICP-materials, and from NILU.

References

Aas, W., Hjellbrekke, A., Hole, L. & Tørseth, K. (2017). Deposition of major inorganic compounds in Norway, 2007- 2011. Statlig program for forurensningsovervåking Rapportnr. 1136/2012.

Doytchinov, S., Spezzano, P., Screpanti, A., & Leggeri, G. (2013). UNECE International co-operative programme on effects on materials, including historic and cultural monuments. Report No 73 Pilot study on inventory and condition of stock of materials at risk at United Nations Educational, Scientific and Cultural Organization (UNESCO) cultural heritage sites. Part III Economic evaluation, Italian National agency for new technologies, Energy and

sustainable economic development (ENEA), Rome, Italy, 2013. [Available at: http://www.corr-institute.se/icp-materials (Accessed Dec. 2017)]
Drdácký, M., Sližková, Z., Langhammer, P., Yates, T., Swabey, A., Doytchinov, S. & Grøntoft, T. (2006). "Estimation of cost for conservation/renovation works for materials and elements considering regional diversities", EU project, CULT-STRAT (SSPI-CT-2004-501609), Deliverable no. 10. [Available at: http://www.corr-institute.se/cultstrat, (Accessed Jan, 2014)].
EEA. (2017). European Environment Agency, Sulphur Dioxide (SO_2): annual mean concentrations in Europe, EEA, AirBase v.8 & AQ e-Reporting. [Available at: http://www.eea.europa.eu/themes/air/interactive/so2 (Accessed Dec. 2017)]
eKlima.(2017). Norwegian Meteorological Institute - eKlima. [Available at: http://sharki.oslo.dnmi.no/portal/page?_pageid=73,39035,73_39049&_dad=portal&_schema=PORTAL (Accessed 10th July 2017)]
Graedel, T.E. & Leygraf, C. (2000). Atmospheric Corrosion, Electrochemical Society Series, John Wiley & Sons Inc., New York.
Grøntoft, T. (2017). Conservation-restoration costs for limestone façades due to air pollution in Krakow, Poland, meeting European target values and expected climate change. Sustainable Cities and Society 29, 169–177.
Grøntoft, T. & Ferm, M. (2017) International co-operative programme on materials, including historic and cultural monuments. Trend exposure programme 2014-2015. Environmental data report. October 2014 to October 2015. UN/ECE International co-operative programme on effects on materials, including historic and cultural monuments. Report no. 81 (NILU report 19/2017) [Available at: http://www.corr-institute.se/icp-materials (Accessed Dec. 2017)]
Grøntoft, T. (2011). "Climate change impact on building surfaces and façades", International Journal of Climate Change Strategies and Management, Vol. 3 Iss: 4, pp.374 – 385.
Guerreiro, C., González, A., & de Leeuw, F. (2017). Air quality in Europe — 2017 report. EEA report No 13. [Available at: https://www.eea.europa.eu/publications/air-quality-in-europe-2017 (Accessed Dec. 2017)]
Guerreiro, C., de Leeuw, F. and Foltescu, V., 2013. Air quality in Europe — 2013 report. EEA Report No 9. [Available at: https://www.eea.europa.eu/publications/air-quality-in-europe-2013 (Accessed Dec. 2017)]
ICP. (2018). http://www.corr-institute.se/ICP-Materials/ (Accessed Jan. 2018)
ICP. (2017). Oral communication within ICP-materials.
IPCC. (2014). Climate Change 2014, Synthesis Report, Summary for Policymakers.
Kreislova, K & Knotkova, D. (2017) The Results of 45 Years of Atmospheric Corrosion Study in the Czech Republic. Materials (Basel). 2017 Apr; 10(4): 394. Published online 2017 Apr 7. doi:10.3390/ma10040394. [Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5506999/ (Accessed Dec. 2017)]
Kucera, V. (2005). EU project Multi Assess. Deliverable 0.2, Publishable Final report. [Available at: http://www.corr-institute.se/MULTI-ASSESS/ (Accessed Jan. 2018)]
Kucera, V. (2007). EU project CultStrat. Publishable Final Activity Report [Available at: http://www.corr-institute.se/cultstrat/web/page.aspx (Accessed Jan. 2018)]
Kucera, V., Tidblad, J., Kreislova, K., Knotkova, D., Faller, M., Reiss, D., Snethlage, R., Yates, T., Henriksen, J., Schreiner, M., Melcher, M., Ferm, M., Lefèvre R-A. & Kobus, J. (2007) UN/ECE ICP Materials Dose-response Functions for the Multi-pollutant Situation Water Air Soil Pollution: Focus. (2007). 7:249–258. DOI 10.1007/s11267-006-9080-z. [Available at: https://link.springer.com/article/10.1007/s11267-006-9080-z (Accessed Jan. 2018)]

Luftkvalitet.info. (2018). http://www.luftkvalitet.info/Libraries/Rapporter/oslo_historisk.sflb.ashx (Accessed Jan. 2018) (In Norwegian)

Luftkvaliteten i Oslo i 2016. (2016). – En oppsummering. Oslo kommune, Bymiljøetaten. [Available at: http://www.luftkvalitet.info/Libraries/Rapporter/Luftkvaliteten_i_Oslo_i_2016_-_en_oppsummering.sflb.ashx (Accessed Dec. 2017) (In Norwegian)]

Lützenkirchen, S. & Løseth, Å. (2015). The air quality in Oslo - Report for the year 2015, Report no.: 16/08293-2, City of Oslo, Agency for Urban Environment. [Available at: http://www.luftkvalitet.info/Libraries/Rapporter/Oslo_%c3%a5rsrapport_2015.sflb.ashx (Accessed 10 July 2017) (In Norwegian – English abstract)]

Sabbioni, Brimblecombe & Cassar (Eds.). (2010). "The Atlas of Climate Change Impact on European Cultural Heritage: Scientific Analysis and Management Strategies" Anthem Environmental Studies." Anthem Press.

Seinfeld, J. H. and Pandis, S.P. (1998) Atmospheric chemistry and physics. From air pollution to climate change. John Wiley & Sons, Inc. New York.

Slørdal, L.H., Walker, S.E. & Solberg, S. (2003). "The urban air dispersion model EPISODE applied in AirQUIS2003. Technical description", Norwegian Institute for Air Research, NILU, TR 12/03, Kjeller, Norway.

Tidblad, J. (2014). ICP Mapping manual chapter 4 (draft). Revised 2014-05-19 from initial text by V. Kucera. [Available at: http://www.corr-institute.se/icp-materials/web/page.aspx?refid=19 (Accessed Dec. 2017)]

Tidblad J., Kreislová K., Faller M., De la Fuente D., Yates T., Verney-Carron A., Grøntoft T., Gordon A. & Hans U. (2017). ICP-materials Trends in Corrosion, Soiling and Air Pollution (1987–2014). Materials 2017, 10(8), 969; doi:10.3390/ma10080969 (registering DOI)

Tidblad, J., Grøntoft, T., Kreislova, K., Faller, M., De la Fuente, D., Yates T. & Verney-Carron, A. (2014). International co-operative programme on materials, including historic and cultural monuments (ICP-materials). Trends in pollution, corrosion and soiling 1987-2012. Report no. 76. [Available at: http://www.corr-institute.se/icp-materials (Accessed Dec. 2017)]

Watt, J. Tidblad, J., Kucera, V. and Hamilton, R. (Ed.). (2009). The Effects of Air Pollution on Cultural Heritage, Springer, USA.

WGE. (2009). Review of air pollution effects. Indicators and targets for air pollution effects. Report by the Extended Bureau of the Working Group on Effects. Report to the 28th session of the Working Group on Effects, UN-ECE Convention on Long range Transboundary Air Pollution, Working Group on Effects, Geneva, Switzerland. ECE/EB.AIR/WG.1/2009/16. 12 p. [Available at: https://www.unece.org/fileadmin/DAM/env/documents/2009/EB/wge/ece.eb.air.wg.1.2009.16.e.pdf (Accessed Dec. 2017)]

Appendix

Table A1: The calculated zinc maintenance cost due to air pollution over background (%/year) according to (5). Negative values shows maintenance costs below background values. The cells with reported values represent the data availability for the ICP stations and measurement years. The values for the measured environmental variables used as input to the calculations are, for the years from 1987 until 2011, reported in Tidblad et al. (2014), and for 2014 be reported in Grøntoft & Ferm (2017). (U) = Urban, (I) = Industrial, (R) = Rural.

Station Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2002	2005	2008	2011	2014
1 Prague (U)	1.46	1.06	0.98	1.02	0.87	1.03	0.88	0.94	0.82	0.76	0.63	0.61	0.63	0.54	0.50	0.50	0.43	0.42	0.35
2 Kaspersky Hory (R)	1.21	0.60	0.77	0.78	1.20	1.41	0.49	0.60											
3 Kopisty (I)	1.09	1.07	1.03	0.99	0.97	0.88	0.87	1.05	1.01	0.74	0.72	0.74	0.74	0.81	0.46	0.57	0.64	0.74	0.56
4 Espoo (U)	0.65	0.57	0.62		0.35	0.28	0.38	0.35											
5 Ahtäri (R)	0.34	0.34	0.22	0.18	0.15	0.13	0.12	0.16	0.10	0.07	0.13	0.14	0.10	0.16	0.14				
6 Helsinki-Vallila (I)	0.66	0.65	0.73	0.70	0.47	0.36	0.35	0.34											
7 Waldhof-Langenbrügge (R)	0.84	0.77	0.73	0.72	0.59	0.65	0.67	0.51	0.46	0.42	0.39	0.26	0.24	0.38	0.27				
8 Aschaffenburg (U)	0.74	0.61	0.59	0.52	0.45	0.44	0.40												
9 Langenfeld-Reusrath (R)	0.88	0.88	0.88	0.95	0.78	0.79	0.79	0.76			0.62	0.48		0.51	0.43				
10 Bottrop (I)	1.02	1.00	0.98	1.16	0.98	1.01	0.97	1.02	0.90	0.91	0.90	0.78		0.80	0.73	0.63	0.64	0.51	0.55
11 Essen-Leithe (R)	0.96	0.90	0.90	0.92	0.80	0.89	0.83	0.79											
12 Garmisch-Partenkirchen (R)	0.61	0.72	0.52	0.46	0.42	0.34	0.33												
13 Rome (U)	0.58	0.56	0.54	0.51	0.10	0.24	0.37	0.24											
14 Casaccia (R)	0.40	0.42	0.37	0.36	0.33	0.38	0.37	0.38											0.14
15 Milan (U)	1.20	1.21	1.03	0.79	0.91	0.73	0.82	0.74									0.23		
16 Venice (U)	0.66	0.80	0.69	0.66	0.80	0.67	0.53	0.49									0.40		
17 Vlaardingen (I)	1.23	1.10	1.05	1.07	1.06	1.10	0.99	0.97											
18 Eibergen (R)	0.68	0.60	0.56	0.54	0.56	0.57	0.53	0.71											
19 Vredepeel (R)	0.70	0.63	0.62	0.59	0.62	0.61	0.62	0.50											
20 Wijnandsrade (R)	0.78	0.70	0.58	0.74	0.69	0.65	0.63	0.53											
21 Oslo (U)	0.59	0.46	0.46	0.40	0.42	0.29	0.30	0.23			0.30	0.44	0.36	0.34	0.23		0.19	0.10	0.31
22 Borregard (I)	1.36	1.02	0.91	0.78	0.86	0.74	0.70	0.86											
23 Birkenes (R)	0.83	0.50	0.54	0.46	0.43	0.30	0.43	0.33	0.34	0.22	0.31	0.33	0.31	0.39	0.24	0.27	0.08	0.11	0.18
24 Stockholm south (U)	0.68	0.50	0.46	0.39	0.38	0.39	0.30	0.33		0.25	0.26	0.34	0.27	0.32	0.22	0.22	0.12	0.13	0.27
25 Stockholm Centre (U)	0.71	0.61	0.49	0.29	0.33	0.36	0.30	0.30											
26 Aspvreten (R)	0.44	0.29	0.29	0.32	0.27	0.26	0.30	0.25	0.21	0.19	0.18	0.19	0.17	0.33	0.12	0.17	0.14	0.13	0.09
27 Lincoln Cathedral (U)	0.80	0.95	0.82	1.00	0.97	0.81	0.60	0.59											
28 Wells Cathedral (U)	0.64	0.45	0.55	0.56	0.60	1.08	0.48	0.44											
29 Clatteringshaws Loch (R)			0.83																
30 Stoke Orchard (R)	0.93	0.74	1.11	2.60	0.58	0.68	1.22	1.22											
31 Madrid (U)	0.44	0.25	0.28	0.24	0.24	0.31	0.35	0.30			0.32	0.17	0.12	0.06	0.11	0.05	0.09	-0.07	0.02
32 Bilbao (UI)	0.82	0.75	0.73	0.67	0.48	0.51	0.45	0.37											
33 Toledo (R)	0.20	0.24	0.30	0.18	0.17	0.10	0.14	0.14			0.08	0.08	0.10	0.15	0.20	0.11	-0.01	-0.02	0.01
34 Moscow (U)	0.39	0.59	0.53	0.49	0.53	0.48	0.34	0.34				0.45			0.18				
35 Lahemaa (R)	0.17	0.15	0.17		0.16	0.16	0.16	0.16	0.08	0.13		0.22	0.24	0.25	0.20	0.40	0.31		0.18
36 Lisbon (U)	0.29	0.27	0.21	0.28	0.43	0.31	0.28	0.19			0.33	0.38			0.30				
37 Dorset (R)	0.47	0.42	0.45	0.49	0.32	0.44	0.36	0.48	0.38		0.43				0.28				
38 Research Triangle Park (R)	0.61	0.74	0.52	0.55	0.51	0.49	0.51	0.61											
39 Steubenville (I)	1.14	1.36	1.08	1.27	0.81	1.02	1.09	1.00											
40 Paris (U)											0.42	0.37	0.48	0.49	0.41	0.38	0.24	0.16	0.19
41 Berlin (U)																			0.31
44 Svanvik (R)												0.22	0.24	0.16	0.15		0.21	0.16	0.20
45 Chaumont (R)											0.20	0.23	0.18	0.20	0.17	0.19	0.13	0.09	0.09
49 Antwerpen (U)													0.66	0.66	0.46				
50 Katowice (I)														1.10	0.92				0.51
51 Athens (U)																			0.21
52 Riga (U)																	0.30		
54 Sofia (U)																	0.49		
57 Hämeenlinna (UR)																			0.15
59 Zilina (U)																			0.42

Table A2: The maintenance cost savings (%/year) for zinc surfaces exposed outdoors, due to hypothetical 50% reduction in air pollution from the measured values for the reported stations and years, according to (6). The cells with reported values represent the data availability for the ICP stations and measurement years. The values for the measured environmental variables used as input to the calculations are, for the years from 1987 until 2011, reported in Tidblad et al. (2014), and for 2014 be reported in Grøntoft & Ferm (2017). (U) = Urban, (I) = Industrial, (R) = Rural.

Station Yeaı	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2002	2005	2008	2011	2014
1 Prague (U)	0.39	0.23	0.22	0.26	0.21	0.30	0.19	0.23	0.20	0.19	0.14	0.15	0.18	0.13	0.16	0.12	0.11	0.12	0.10
2 Kaspersky Hory (R)	0.46	0.18	0.22	0.26	0.50	0.59	0.14	0.20											
3 Kopisty (I)	0.25	0.23	0.23	0.24	0.24	0.23	0.19	0.27	0.29	0.19	0.18	0.19	0.19	0.21	0.12	0.13	0.15	0.17	0.16
4 Espoo (U)	0.22	0.19	0.19		0.14	0.12	0.15	0.14											
5 Ähtäri (R)	0.14	0.13	0.11	0.10	0.10	0.08	0.09	0.10	0.08	0.07	0.09	0.09	0.08	0.09	0.09				
6 Helsinki-Vallila (I)	0.20	0.20	0.23	0.22	0.15	0.13	0.13	0.11											
7 Waldhof-Langenbrügge (R)	0.24	0.20	0.19	0.19	0.16	0.19	0.19	0.15	0.13	0.13	0.12	0.09	0.09	0.12	0.09				
8 Aschaffenburg (U)	0.17	0.17	0.19	0.14	0.11	0.13	0.12												
9 Langenfeld-Reusrath (R)	0.23	0.22	0.23	0.24	0.20	0.20	0.20	0.21			0.16	0.12		0.15	0.11				
10 Bottrop (I)	0.25	0.24	0.23	0.29	0.23	0.23	0.23	0.26	0.20	0.21	0.21	0.18		0.19	0.19	0.14	0.15	0.13	0.14
11 Essen-Leithe (R)	0.23	0.22	0.24	0.23	0.20	0.22	0.20	0.21											
12 Garmisch-Partenkirchen (R)	0.17	0.19	0.16	0.15	0.12	0.10	0.11												
13 Rome (U)	0.16	0.15	0.14	0.14	0.08	0.10	0.12	0.08											
14 Casaccia (R)	0.12	0.13	0.10	0.11	0.10	0.11	0.12	0.11											0.06
15 Milan (U)	0.37	0.30	0.29	0.21	0.22	0.20	0.27	0.24									0.10		
16 Venice (U)	0.16	0.18	0.16	0.15	0.17	0.15	0.13	0.12									0.11		
17 Vlaardingen (I)	0.31	0.27	0.26	0.25	0.24	0.28	0.24	0.24											
18 Eibergen (R)	0.16	0.14	0.14	0.13	0.14	0.14	0.13	0.22											
19 Vredepeel (R)	0.16	0.15	0.14	0.14	0.16	0.14	0.15	0.13											
20 Wijnandsrade (R)	0.20	0.18	0.15	0.17	0.16	0.16	0.15	0.13											
21 Oslo (U)	0.20	0.14	0.15	0.12	0.13	0.10	0.11	0.09			0.09	0.15	0.14	0.13	0.11		0.07	0.07	0.10
22 Borregard (I)	0.51	0.32	0.27	0.23	0.26	0.22	0.21	0.25											
23 Birkenes (R)	0.40	0.24	0.26	0.22	0.21	0.17	0.23	0.18	0.18	0.14	0.19	0.19	0.18	0.21	0.15	0.15	0.09	0.09	0.12
24 Stockholm south (U)	0.20	0.16	0.15	0.14	0.13	0.15	0.11	0.12		0.11	0.10	0.11	0.10	0.11	0.08	0.08	0.06	0.06	0.13
25 Stockholm Centre (U)	0.20	0.18	0.15	0.12	0.12	0.15	0.11	0.11											
26 Aspvreten (R)	0.17	0.12	0.11	0.13	0.11	0.12	0.13	0.11	0.09	0.09	0.09	0.09	0.09	0.15	0.07	0.09	0.08	0.07	0.06
27 Lincoln Cathedral (U)	0.18	0.24	0.21	0.22	0.22	0.19	0.14	0.17											
28 Wells Cathedral (U)	0.15	0.11	0.13	0.13	0.14	0.43	0.12	0.13											
29 Clatteringshaws Loch (R)			0.23																
30 Stoke Orchard (R)	0.28	0.25	0.40	1.07	0.16	0.20	0.44	0.44											
31 Madrid (U)	0.11	0.08	0.09	0.08	0.08	0.09	0.10	0.09			0.09	0.07	0.06	0.05	0.06	0.05	0.05	0.03	0.04
32 Bilbao (UI)	0.22	0.17	0.19	0.17	0.14	0.15	0.12	0.11											
33 Toledo (R)	0.08	0.08	0.09	0.07	0.07	0.06	0.06	0.06			0.05	0.05	0.05	0.06	0.07	0.06	0.04	0.04	0.04
34 Moscow (U)	0.10	0.15	0.13	0.12	0.13	0.12	0.09	0.09				0.11			0.07				
35 Lahemaa (R)	0.09	0.10	0.09		0.09	0.09	0.09	0.09	0.05	0.07		0.09	0.10	0.11	0.09	0.16	0.12		0.08
36 Lisbon (U)	0.09	0.09	0.08	0.09	0.11	0.09	0.09	0.07			0.09	0.10			0.09				
37 Dorset (R)	0.21	0.19	0.20	0.21	0.16	0.21	0.18	0.21	0.18		0.18				0.15				
38 Research Triangle Park (R)	0.22	0.30	0.20	0.21	0.17	0.18	0.19	0.23											
39 Steubenville (I)	0.37	0.48	0.37	0.48	0.27	0.34	0.34	0.31											
40 Paris (U)											0.11	0.10	0.13	0.13	0.11	0.10	0.08	0.07	0.08
41 Berlin (U)																			0.09
44 Svanvik (R)												0.09	0.09	0.07	0.07		0.10	0.08	0.09
45 Chaumont (R)											0.09	0.10	0.08	0.09	0.08	0.09	0.07	0.06	0.06
49 Antwerpen (U)													0.16	0.18	0.13				
50 Katowice (I)														0.28	0.25				0.12
51 Athens (U)																			0.07
52 Riga (U)																	0.09		
54 Sofia (U)																	0.12		
57 Hämeenlinna (UR)																			0.08
59 Zilina (U)																			0.11

Table A3: The maintenance cost for Portland limestone surfaces exposed outdoors due to air pollution over background as % of total weathering cost (Eq. 7), and maintenance cost savings (%), due to 50% air pollution reduction from the pollution values, for the reported stations and years, over an undetermined lifetime (years) (Eq. 9). The cells with reported values represent the data availability for the ICP stations and measurement years. The values for the measured environmental variables used as input to the calculations are, for the years from 2002 until 2011, reported in Tidblad (2014), and for 2014 be reported in Grøntoft & Ferm (2017). (U) = Urban, (I) = Industrial, (R) = Rural.

Maintenance cost:	Due to air pollution over background (% of total weathering cost)					Saving due to 50 % air pollution reduction (%)				
Station Year	**2002**	**2005**	**2008**	**2011**	**2014**	**2002**	**2005**	**2008**	**2011**	**2014**
1 Prague (U)		52	45	46	41		16	13	15	11
3 Kopisty (I)		62	68	82	63		22	24	30	22
7 Waldhof-Langenbrügge (R)	39					11				
10 Bottrop (I)	79	66	68	52	58	29	23	23	17	19
14 Casaccia (R)					33					8
21 Oslo (U)	47		41	38	44	15		11	10	13
23 Birkenes (R)		50	37	35	41		18	12	11	14
24 Stockholm south (U)				31	54				7	18
26 Aspvreten (R)				28	25				6	5
31 Madrid (U)			18	18	23			3	3	5
33 Toledo (R)			18	17	17			3	3	3
35 Lahemaa (R)		54	37		29		20	11		7
40 Paris (U)		46	39				13	11		
41 Berlin (U)					50					14
44 Svanvik (R)					33					10
45 Chaumont (R)	36		34	31	28	10		8	7	6
50 Katowice (I)					54					19
51 Athens (U)					31					9
52 Riga (U)			50					15		
54 Sofia (U)			63					23		