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Title: Air pollution reduction due to the adoption of high efficiency
small scale pellet boilers characterized by low emissions

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Abstract: This study focuses on the environmental impact assessment of
three different high efficiency residential pellet boilers manufactured
by an Austrian company. A Life Cycle Analysis (LCA) and an Environmental
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boilers in place of outdated biomass boilers.

The SimaPro software (v. 8.05.13, Recipe Midpoint Method) was used for
the LCA and ELCC analysis while CALPUFF (v. 6.42) was used for air
quality simulations.

Boilers emission and efficiency factors operating in real life conditions
were used as input data for all environmental impact assessment analysis.
Results showed an interesting reduction of both the environmental impact
and pellet consumption cost (linked to the highest monetary value in the
ELCC analysis) associated to the most innovative boiler model among the
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end of life biomass boilers with high efficiency pellet boilers in EU
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is found for the short term scenario (2020) with respect to the baseline
scenario (2010). No significant differences in air quality were evidenced
for NO2 between baseline (2010) and replacement (2020) scenarios.

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UNIVERSITÀ
CATTOLICA
del Sacro Cuore

Brescia, 12th November, 2015

Dear Editor in Chief,
Prof. C.P. Mitchell,

Please find enclosed the electronic version of the manuscript:

**“Air pollution reduction due to the adoption of high efficiency
small scale pellet boilers characterized by low emissions ”**

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The manuscript is focused on the environmental impact assessment of three different high efficiency residential pellet boilers manufactured by an Austrian company. An integrated approach has been used. A Life Cycle Analysis (LCA) and an Environmental Life Cycle Costing (ELCC) analysis were performed, along with air quality modelling simulations for two EU case studies to evaluate CO, PM10, SO₂, NO₂ concentration reductions due to the substitution of the innovative boilers in place of outdated biomass boilers.

The SimaPro software (v. 8.05.13, Recipe Midpoint Method) was used for the LCA and ELCC analysis while CALPUFF (v. 6.42) was used for air quality simulations.

To our knowledge such an integrated study focused on small scale pellet boilers is not present in literature. Furthermore, most of LCA research available in literature



is only focused on specific phases of a pellet boiler lifecycle: forestry operations, pellet production and transport, pellet production and boiler use phase, pellet transport on long distances and boiler use phase. The advance of the present research in comparison to the state of the art consists in the identification of the environmental impact of all the different life cycle phases included in the system boundaries (pelletisation, boiler construction, boiler operation, boiler transports, boiler and ashes disposal) with respect to all the impact subcategories foreseen by the chosen life cycle impact assessment method (Recipe Midpoint Method – European Hierarchist version). In addition, input data coming from literature (i.e. energy mix, disposal data, pellet transport data) have been selected only considering the EU territorial framework so that our LCA analysis results could represent an average European case study (and not a global case study). Even ELCC analysis applied to small scale pellet boilers represents an innovative approach that has been performed along with LCA using the same software.

I kindly ask you to consider publishing the manuscript in the Journal *Biomass and Bioenergy*. We believe that the originality and the focus of our Research Paper well fits with the journal aims and scope, since it deals with “*environmental and economic aspects of biomass and bioenergy*”.

Hoping in your positive feedback,

best regards

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Highlights

- LCA was performed on three high efficiency small scale pellet boilers
- ELCC integrated LCA to evaluate the monetary values of different life cycle phases
- Experimental data of real boilers operation were used for LCA and ELCC analysis
- The substitution of old biomass systems with high tech pellet boilers was envisaged
- Air quality scenarios (timeline:2020) for two EU case studies were envisaged

Air pollution reduction due to the adoption of high efficiency small scale pellet boilers characterized by low emissions

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Abstract

This study focuses on the environmental impact assessment of three different high efficiency residential pellet boilers manufactured by an Austrian company. A Life Cycle Analysis (LCA) and an Environmental Life Cycle Costing (ELCC) analysis were performed, along with air quality modelling simulations for two EU case studies to evaluate CO, PM10, SO₂, NO₂ concentration reductions due to the substitution of the innovative boilers in place of outdated biomass boilers.

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Boilers emission and efficiency factors operating in real life conditions were used as input data for all environmental impact assessment analysis. Results showed an interesting reduction of both the environmental impact and pellet consumption cost (linked to the highest monetary value in the ELCC analysis) associated to the most innovative boiler model among the three envisaged. Furthermore, it emerged that air quality could be improved in the short term (2020) with the substitution of obsolete and end of life biomass boilers with high efficiency pellet boilers in EU areas where biomass is the main source of residential heating. A potential reduction of local CO, SO₂ and PM10 concentrations from 10% to 54% depending on the pollutant and on the specific case study considered is found for the short term scenario (2020) with respect to the baseline scenario (2010). No significant differences in air quality were evidenced for NO₂ between baseline (2010) and replacement (2020) scenarios.

Keywords

LCA, small scale pellet boilers, high efficiency, low emissions, air quality modelling, ELCC analysis

36

37 **List of Abbreviations**

38

39	BW 102	BioWin-2 pellet boiler 10kW
40	VA 60	VarioWin pellet boiler 6kW
41	VA 120	VarioWin pellet boiler 12kW
42	EU	European Union
43	FP7	Seventh Framework Programme
44	CO	Carbon Monoxide
45	CO ₂	Carbon Dioxide
46	NO _x	Nitrogen Dioxide
47	SO ₂	Sulphur Dioxide
48	LCA	Life Cycle Assessment
49	LCI	Life Cycle Inventory
50	LCIA	Life Cycle Impact Assessment
51	ELCC	Environmental Life Cycle Costing
52	EIA	Environmental Impact Assessment
53	H	Hierarchist
54	PM	Particulate Matter
55	PM ₁₀	Particulate Matter with an aerodynamic diameter below 10 µm
56	LC	Load Cycle
57	HHV	Higher Heating Value
58	LHV	Lower Heating Value
59	CC	Climate Change
60	OD	Ozone Depletion
61	TA	Terrestrial Acidification
62	FE	Freshwater Eutrophication
63	ME	Marine Eutrophication
64	HT	Human Toxicity
65	POF	Photochemical Oxidant Formation
66	PMF	Particulate Matter Formation
67	TET	Terrestrial Ecotoxicity
68	FET	Freshwater Ecotoxicity
69	MET	Marine Ecotoxicity
70	IR	Ionizing Radiation
71	ALO	Agricultural Land Occupation
72	ULO	Urban Land Occupation
73	NLT	Natural Land Transformation
74	WD	Water Depletion
75	MD	Metal Depletion
76	FD	Fossil Depletion

77 **1. Introduction**

78 This work focuses on the environmental impact assessment of three different high efficiency
79 residential pellet boilers. The boilers envisaged were tested (and one of them developed as a new
80 innovative product put on the market very recently) in the framework of the EU FP7 “BioMaxEff”
81 project [1].

(Cost efficient biomass boiler systems with maximum annual efficiency and lowest emissions) [1]. Actually, as the recent European policies encourage the use of renewable energies, biomass consumption for residential heating is growing at EU level [2]. Nonetheless, the environmental impact due to most of the outdated wood biomass combustion appliances adopted in residential heating at EU level today lead to high emissions of particulate matter [3,4], polycyclic aromatic hydrocarbons (PAHs) [5-7] and volatile organic compounds (VOCs) [8-10] if compared to a natural gas boiler [11]. With reference to pellet boilers in particular, emissions of organic compounds, including the ones ascribed as certain or suspected carcinogens by the International Agency for Research on Cancer [12], are not only due to the wood biomass combustion phase but even to other processes, like pellet production and storage [8-9,13-23]. Therefore, different research activities at EU level are focused on both the development and testing of innovative biomass boilers characterized by lower emissions and higher efficiencies with respect to the best available EU technologies and the analysis of their environmental impact along their life cycle, from the pelletisation phase till their final disposal [1,24].

This work presents an integrated analysis on three high efficiency pellet boilers aimed at the evaluation of their environmental and economic impact along their life cycle. Another aim of the present study is the estimation of the environmental benefits due to their short term diffusion in EU areas where at present wood biomass represents the main fuel used in residential heating appliances. The advance of the present research in comparison to the state of the art consists in the evaluation of the environmental impact of three innovative pellet boilers along their different life cycle phases, from the pelletisation process till their final disposal where most of the input data are real data provided by the manufacturer (i.e. energy consumptions, materials, disposal scenarios) and testing institutions (real efficiencies and emission factors). The life cycle analysis has been integrated with an Environmental Life Cycle Costing analysis (ELCC) in order to evaluate the weight percent of the most important costs linked to the boilers life cycle for the boiler manufacturer (pellet cost, R&D costs, boiler construction and transports costs). In addition, short term scenarios of environmental benefits on air quality due to the substitution of old and less efficient wood biomass boilers with the ones investigated in present study have been developed for two EU case studies (a mountain site in Italy and a rural site in Austria) where wood biomass represents one of the main fuels currently used for residential heating (29% in Italy and 38% in Austria).

2. Materials and methods

2.1. Boilers under investigation

115 In this study three different high efficiency small scale pellet boilers are investigated in order to
116 evaluate the air quality improvement potentials due to their installation and operation in EU areas
117 where wood biomass is presently the main source for residential heating.

118 All pellet boilers are manufactured by the Austrian company Windhager Zentralheizung GmbH.

119 The VarioWIN6 and VarioWIN12 boiler models (VA 60 and VA 120, with a nominal power of 6
120 kW and 12 kW respectively) consist of a steel body with a fully insulated cladding. A speed
121 controlled vacuum fan regulates the primary and secondary air supply. The stainless steel burner
122 provides an efficient combustion even for low power outputs. Different pellet feeding systems are
123 available for this boiler model: manual pellet loading, a pneumatic suction system or direct dosing
124 auger.

125 The BioWIN10 2 (BW 102) boiler consist of a steel body with a fully insulated cladding. The flue
126 gas temperature is measured directly at the exit of the combustion chamber. Its stainless steel
127 burner ensures low pellet consumption and high efficiency. The main feature of the BW 102 is a
128 new ignition element that is extremely durable, maintenance free, and ignites silently. More boilers
129 technical details are available in [25-26]. Quality labels such as the Blaue Engel [27] and the
130 Austrian Ecolabel [28] testify VA 60, VA 120 and BW 102 quality and environmental credentials.

131 All pellet boilers were tested in the laboratory according to two different test methods. The first
132 method consisted of a steady state test at nominal load according to EN 303-5 [29]. The second
133 method was a dynamic load cycle including stationary operation at different loads, as well as
134 transient operation, in order to reproduce the heating and domestic hot water demand of a single
135 family house. CO, SO₂, NO_x, and PM emission factors as well as boilers efficiencies were
136 determined with both test methods. The load cycle was developed as a laboratory test based on a
137 typical daily profile of heating and domestic hot water demand of a single family house. The
138 detailed characterization of the load cycle is given in [25,30]. Efficiency and emission factors
139 calculation along the load cycle test are thus representative of boilers real operation.

140 Table 1 presents the technical specifications, efficiency and emission factors resulting from load
141 cycle tests of the boilers investigated in the present study. An average emission factor for all
142 pollutants considered in the air quality modelling analysis was calculated to be used in the
143 development of the air quality maps as representative of a similar penetration on the market of the
144 three pellet boiler models in substitution of old and less efficient wood biomass combustion systems
145 for the two case studies envisaged.

146
147 *Approximate location of Table 1*
148

149 **2.2 LCIA and ELCC methodology**

150
151 The SimaPro software (version 8.05.13) was used to perform life cycle analysis since it is a
152 widespread and accredited LCA tool and its transparent life cycle inventory (LCI) data are regularly
153 updated [31,32]. It also includes different impact assessment methods and the most updated
154 Ecoinvent database libraries [33,34]. LCIA analysis has been performed according to ISO14040-
155 ISO14043 and ISO 14050 standards [35-39]. The ReCiPe midpoint (European Hierarchist version,
156 H) method was chosen as impact assessment method [40-41].

157 According to the ReCiPe midpoint method the environmental impact was quantified on 18 impact
158 subcategories (Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater
159 Eutrophication, Marine Eutrophication, Human Toxicity, Photochemical Oxidant Formation,
160 Particulate Matter Formation, Terrestrial Ecotoxicity, Freshwater Ecotoxicity, Marine Ecotoxicity,
161 Ionizing Radiation, Agricultural Land Occupation, Urban Land Occupation, Natural Land
162 Transformation, Water Depletion, Metal Depletion, Fossil Depletion). In this study we considered a
163 pelletisation process representative for the Central EU case. In particular, raw biomass comes from
164 saw dust (57%), wood shavings (15% hardwood and 15% softwood) and wood chips (13%). It is
165 thus important to underline that even according to the most updated Ecoinvent database (v. 3.1,
166 Allocation recycled content) the environmental impact of forestry residues use as raw biomass for
167 pellet production is overestimated since a weighed contribution due to the “forest impact” (that
168 takes into consideration forest planting, management and land use) is included in the calculations
169 [42]. Actually, at least at EU level, raw biomass for the pelletisation phase mainly comes from forestry
170 residues [43] so that activities like forests planting and land use contributions considered in the Ecoinvent
171 v.3.1 database tend to overestimate the real pelletisation phase contribution for our specific case study. In
172 the present work, as in [25], we assumed that forests are not intensively cultivated (thus excluding
173 plantation and irrigation operations) but are already existent. Nevertheless, forests pruning, wood
174 biomass transports and forest management activities like creation of paths/roads inside the forests
175 are included in our analysis.

176 1 MJ of useful heat was chosen as functional unit, in order to compare LCA results of boilers with
177 different nominal heat outputs. An average boiler lifetime of 20 years was assumed (personal
178 communication from boiler manufacturer).

179 ELCC (Environmental Life Cycle Costing) is a tool to evaluate the economic dimension of the
180 sustainability of a product or a process [44].

181 ELCC was developed by the Society of Environmental Toxicology and Chemistry (SETAC)
182 Working Group between 2002 and 2006 [45]. Aim of the Working Group was the creation of a
183 LCC methodology that could be consistently combined with LCA. ELCC has its own autonomy and

completeness, but results should be interpreted along with LCA results, since LCA represents the pillar of the environmental impact analysis and assessment of the sustainability of the products (boilers) envisaged. The economic and environmental impact analysis were both performed using the same software (SimaPro, v. 8.05.13) [32].

In our research ELCC analysis integrated LCA but considered only those cost items whose data were available, listed here below:

1. R&D costs;
2. Boiler Production costs;
3. Pellet cost;
4. Boiler transports cost.

System boundaries for ELCC result as a subset of the ones developed for LCA: actually, ELCC does not include a cost analysis of pellet production and boilers final disposal phases that could have been based on proxy and not actual data. The uncertainty of monetary values for pellet production is given by the fragmentation of local markets with reference to the costs of pellet production and the final pellet market price. Furthermore, individual European States show huge differences on the cost of final boiler disposal and on the sales prices of secondary materials arising from the recovery of the metals contained in the boiler. Therefore, ELCC analysis has been restricted to R&D, boiler production, boiler operation and transport costs.

Figure 1 shows the system boundaries for the LCA and ELCC analysis applied to the three pellet boiler types envisaged in our study. The following life cycle phases were considered:

- 1. Boiler construction:** electricity and heat come from the Austrian energy production mix for the boiler technologies locally manufactured [46,47]: materials have been provided by the manufacturer. Fossil fuels are used to carry raw materials before boiler construction. Metals recovery is considered as well as the land use given by the production plant facility [48,49]. The detailed LCI for boilers construction is reported in S1 (Tables S1.1, S1.2 and S1.3). About ELCC, the item Construction Costs includes materials, spare parts, the costs of personnel hours and the electricity used in this phase. On the basis of cost accounting principles Windhager, the boilers manufacturer, gave us the total personnel cost included in the creation or in the processing of the boilers main components. We included the use of energy within the Production Costs. The energy price used is the average price of European market in 2012 on the basis of Eurostat publications and statistics [50].
- 2. Pellet production:** average EU pellet production technologies are considered and the European energy mix is used as energy input data. LDPE is considered since 20% of

produced pellet is supposed to be sold in 15 kg bags [48]. Raw biomass transport from the field till the pelletising plant is included [49]. Input data related to pellet production are reported in S1 (Tables S1.4-S1.9);

3. Boiler transports: only boiler transports are considered in this phase. Transports from manufacturer to customer (100 km, [48]) and from customer to the final disposal site (100 km [48]) are included. Input data related to boiler transports are reported in S1 (Table S1.10). Transport costs were calculated summing up costs due to two different routes: from the boiler manufacturer site to the final customer and from the customer to the final disposal /recovery site at the end of the boiler life cycle. For the evaluation of transports cost, the same average travelling distances used for the LCA were assumed assuming the use of an EURO 4 diesel lorry (personal communication from boiler manufacturer), travelling about 30,000 km/year considering the delivering of all boilers sold in one year (personal communication from boiler manufacturer). We then calculated the total transport cost per kilometer adding two cost components, one of them proportional to distance due to fuel, tires and maintenance costs and the other one not proportional to distance, due to depreciation, personnel costs and vehicle tax [51]. An average overall cost of 1.7179 €/km (excluded Value Added Tax) was thus assumed [51]. Considering the specific boilers weight, we assumed a cost / km / kg delivered.

4. Boiler operation: load cycle efficiency and emission factors, representative of real operation conditions, were used for the three innovative pellet boiler types (see values reported in Table 1). Input data related to boilers operation are reported in S1 (Tables S1.11-S1.13). We considered the fuel (pellet) cost used during the overall boilers life cycle. Considering market price at EU level, its fluctuation depends on fossil fuels market price, since pellet production cost strictly depends on the raw biomass used whose market price was considered in our calculations [52]. We adopted the average EU discounting rate related to fuel price increase equal to 2,0% per year [53,54]. We assumed a constant discounting rate during all the boilers lifetime (20 years).

5. Boiler Disposal: on average metals are recovered up to 50% while the other 50% is sent to landfill, as part of the electronic components, all plastic, insulation and painting materials [55,56]. Ashes are sent to landfill and land farming activities [57]. Input data and SimaPro processes used for the boiler disposal phase are reported in S1 (Tables S1.14-S1.19). The disposal phase was not included in the ELCC analysis. Actually, it depends on the laws of individual European Member States. The boiler has a life cycle that is not associable to urban solid wastes (i.e. durable goods) management.

2.3 Air quality modelling methodology

In order to study the environmental benefits due to the substitution of the three innovative pellet boiler types in areas where biomass is the main fuel for residential heating, two EU case studies have been considered: the Municipality of Valdidentro (mountain site, IT, whose coordinates are: Lat 46°29'24''N Long 10°17'43''E) and Lunz am See (rural site, AT, whose coordinates are: Lat: 47°51'00''N; Long 15°03'00''E).

Different datasets were available for the two sites in relation to energy consumptions due to residential heating and wood biomass combustion systems presently installed.

In the following paragraphs we describe the input data of both case studies and the methodology used to evaluate the pollutants emission reduction due to the substitution of existing systems with more efficient pellet boilers in order to finally estimate the pollutants concentrations abatement for both case studies.

2.3.1 Case study of Valdidentro (IT)

The municipality of Valdidentro is located in the Province of Sondrio, in the Lombardy region (Italy); it is a mountain village located at an altitude of 1350 m above sea level and has approximately 4000 inhabitants.

Annual total emissions of Valdidentro municipality due to domestic heating of the pollutants considered were derived from the INEMAR database (Macro-sector 2 in CORINAIR classification, [58]); these emissions have been spatially spread on each residential dwelling, according to its volume. Subsequently, a temporal disaggregation was carried out to derive hourly emissions according to the heating requirements estimate based on hourly difference of indoor and ambient temperature and on the presence of house occupants [See Figures S1.2-S1.3].

The emission factors of existing wood-fired boilers in the Lombardy region have been calculated for the present case study (Valdidentro), starting from the emissions available in the INEMAR database for the macro sector 2 (non-residential combustion in CORINAIR classification) [59]. The same methodology, using the INEMAR database for the macro sector 2, has also been applied in [60] and [61]. INEMAR (Regional Air Emissions Inventory) is a regional atmospheric emissions database that estimates the overall yearly emissions of pollutants at municipal level for each activity of the CORINAIR classification according to the different fuels used. Thanks to the availability of both emissions and heat demand data associated to the residential macro-sector available in the SIRENA database (Regional Informative System for Environment and Energy, [62]), the average

288 emission factors of the existing wood boilers were obtained. Finally, with the use of the building
289 database provided by the Province of Sondrio, for each building the following input data were
290 provided:

- 291 ▪ coordinates;
- 292 ▪ height;
- 293 ▪ surface;
- 294 ▪ land use (residential, tertiary, ...).

295
296 The annual pollutants emissions for the municipality of Valdidentro were thus obtained from the
297 regional INEMAR database [59] for the year 2010 (Table S1.20). The following air quality
298 modelling simulations will be focused on macro-sector 2 emissions - residential sources according
299 to the CORINAIR classification.

300 Modelling simulations were performed in the main residential area of the town of Valdidentro with
301 a higher population density (See Figure S1.1)

302 This “central part” of the municipality includes the 92.6% of the total volume of residential
303 buildings of the town of Valdidentro, thus emissions were reduced appropriately to take this
304 assumption into account (Tables S1.21-S1.22). Macro-sector 2 emissions represent a significant
305 percentage (about 70%, Table S1.23) of the total emissions of the town of Valdidentro for all
306 considered pollutants, except for nitrogen dioxide (20%):

307 Total annual emissions of each considered pollutant ($E_b^y(p)$) were assigned to each building,
308 depending on its volume according to the following formula:

$$309 \quad E_b^y(p) = \frac{V_b}{\sum_{b=1}^n V_b} \cdot E_t^p$$

310 where:

- 311 - V_b is the weighted mean volume of a building b ;
- 312 - E_t^p is the total annual emission of the pollutant p from the specific macro-sector and the
313 activities that are considered.

314
315 The total annual emissions of each building, calculated with the formula above, were then spread on
316 each hour of the year thanks to a parameter dependent on the outside temperature (α_T^h) ; in this way
317 emissions (E_b^h) are calculated using the following formula:

318

$$E_b^h = E_b^y \cdot \alpha_T^h$$

The parameter α_T^h assumes non-zero values if, within a day, the following conditions are both true:

- The difference between the daily average temperature and the reference temperature of 12 ° is negative;
- The number of hours in a day having a temperature less than 12 °C is greater than 6.

If the two conditions are verified, the hourly parameter α_T^h is calculated by the following formula:

$$\alpha_T^h = \frac{|T_h - 12|}{\sum_{h=1}^{24} |T_h - 12|}$$

where T_h is the hourly temperature measured in the meteorological station of Valdidentro.

The trend of the indicator connected to the temperature during the year is represented in Figure 2a.

The graphs above show that α_T^h is higher in the colder months and lower during the warmer months, in line with the heating use. About 7000 hours have values different from zero meaning that the boilers are working for a great part of the year.

To obtain hourly emissions, a coefficient (α_p^h) that takes into account the presence of family components in the building during the day was used. The value of 1 corresponds to the presence in all the considered buildings while zero means no building occupation (during both a weekday and the weekend). Trends of the coefficient α_p^h depending on the time of the day are reported for weekdays and weekends in Supplemental Material S1 (Figures S1.2-S1.3).

After multiplying and normalizing the coefficient of presence (α_p^h) and the hourly temperature coefficient (α_T^h), an overall parameter of hourly indicator of temporal disaggregation is obtained ($\alpha_T^{h,b}$).

Hourly building emissions (E_b^h) are thus given by the following formula:

$$E_b^h(p) = \frac{V_b}{\sum_{b=1}^n V_b} \cdot E_b^y(p) \cdot \alpha_T^{h,b}$$

In the emissions disaggregation some assumptions were made, listed below:

- Only residential buildings with surface area greater than 50 m² were considered;

- Minimum height set equal to one floor building;
- Floor height set equal to three meters;
- Each chimney has been placed on the vertical line crossing the building's barycentre;;
- Chimney height set to 2 m above the maximum height of the building;;
- The flue gas velocity is a function of the stack diameter (linked to the boiler nominal power and thus to the building's heated volume) that is assumed variable to keep constant the concentration of pollutants in all the chimneys. ;
- Flue gas temperature set to 100 ° C.

Under these assumptions 1272 buildings (thus chimneys) were identified (Figure S1.1)

The resulting yearly emission maps (expressed in tons/year) for each pollutant were thus evaluated

Air quality modelling has been performed using the CALPUFF model v. 6.42 [63]. CALPUFF is a Lagrangian model, non-stationary Gaussian puff, multi-layer and multi-pollutant. It is recommended by U.S. Environmental Protection Agency (EPA) for the estimated impact of punctual as well as real and volumetric emission sources and in the case of medium-and long-range transport, both for relapse in the immediate neighborhood of sources with complex weather conditions. The CALPUFF model was used in this analysis to simulate the impact on air quality caused by residential heating in a complex terrain context considering two different scenarios: the baseline scenario (2010) and the 2020 replacement scenario, assuming the substitution of half of the presently installed biomass boilers with the three pellet boilers types envisaged by our study. A uniform market penetration of the three pellet boilers types was assumed, thus considering average emission factors for pollutants for all simulations. Representative air quality data (CO, NO₂, PM10 and SO₂ concentrations) and meteorological data (temperature, wind speed and direction, net solar radiation, precipitation) for the period 2007-2010 were acquired by the nearby monitoring station of ARPA (Regional Protection Agency for the Environment) Lombardia placed in the Municipality of Bormio. Meteorological data measured from the ARPA monitoring station were preprocessed through the model MICROMETEO [64] in order to build the CALPUFF model meteorological input; this pre-processor is useful for temporal interpolation of missing weather data and for the calculation of atmospheric turbulence parameters (wind class stability, friction velocity, mixing layer height). The simulation domain is rectangular (9.5 km x 3.5 km) with the South-West corner of the reference grid located at UTM coordinates E = 595.6 km, N = 5146.5 km, so that the urbanized areas are located at the center of the domain.

The CALPUFF model computed pollutants concentrations at ground level in 3360 receptors (100 m x 100 m resolution of simulation domain). The altitude above sea level of each point of the

computational grid was derived from the DTM (Digital Terrain Model) SRMT NASA-USGS (available on the NASA website [65]) with a spatial resolution of 90 m. All receptors were placed at a height of 2 meters above ground level. Air quality maps were then developed both for the baseline scenario (2010) and for the 2020 replacement scenario (2020) and are reported in Figures S2.9-S2.24.

2.3.2 Case study of Lunz am See (AT)

The municipality of Lunz am See is located in the district of Scheibbs, in Lower Austria; the mean altitude is 601 m above sea level and it has about 1800 inhabitants. The area under study is located in a hilly area with a maximum altitude above sea level equal to 728 m.

As a detailed emissions database (seen for the Italian case study) was not available, the average emission factors of biomass boilers in Lunz am See were obtained considering the average emission factors of the European biomass boilers used for domestic heating [47]. Thanks to the topographic database Corine Land Cover, available on the European Environmental Agency website [66], the location of the urbanized areas was identified (continuous urban fabric category), considered as sources of residential heating emissions (Figure S1.4).

Total pollutants emissions were obtained from the municipal emission inventory for the year 2010 (Table S1.24). Emissions due to residential sources (belonging to Macro-sector 2 in the Italian Emissions Inventory) were ascribed to Macro-sector 7 according to the Lower Austria Emissions Inventory [not public data supplied by Amt der NÖ Landesregierung, Abteilung Umwelttechnik for the year 2009].

Even for this case study residential emissions cover a great part of municipal emissions except for NO₂ (20%) (Table S1.25).

The urbanized area was divided into squared cells having a 100 m side length.

Total annual emissions of each considered pollutant (E_b^y) were assigned to each cell of the simulation domain, as follows:

$$E_b^y(p) = \frac{A_b}{\sum_{b=1}^N A_b} \cdot E_T^p$$

where:

- A_b is the urbanized area of cell b ;
- $b = 1, \dots, N$;
- E_T^p are the total annual emissions of pollutant p of the macro-sector considered.

419 The total annual emissions of each cell, calculated with the formula above, were then spread on
420 each hour of the year using a parameter dependent on the outside temperature (α_T^h) (as already
421 described in par. 2.3.1); in this way emissions (E_b^h) are thus calculated according to the following
422 formula:

423

424

425

$$E_b^h = E_b^y \cdot \alpha_T^h$$

426 The trend of the indicator connected to the temperature during the year in Lunz am See is
427 represented in Figure 2b.

428 Figure 2b shows that α_T^h is higher in the colder months and lower during the warmer months, in
429 line with heating use. About 5000 hours present values different from zero meaning that the boilers
430 are working for more than half of the year.

431 As already described in par. 2.3.1, even for this case study the coefficient of presence (α_p^h) was
432 calculated. As for the previous case study, trends of the coefficient α_p^h are reported for weekdays
433 and weekends in Supplemental Material S1 (Figures S1.5-S1.6).

434 It is assumed that:

- 435 • total municipal emissions were spread on a grid square mesh (100 m side length) on
436 urbanized areas identified by the Corine Land Cover database;
- 437 • emissions per unit area are uniform;
- 438 • Emissions height was set equal to 20 meters above ground level (12 meters of stack height
439 and 8 meters of vertical thermal force due to the exit temperature of the flue gas).

440 The resulting yearly emission maps (expressed in tons/year) for each pollutant were thus evaluated
441 and are reported in details in Supplemental Material S2 (Figures S2.5-S2.8).

442 Representative air quality data (CO, NO₂, PM10 and SO₂ concentrations) and meteorological data
443 (temperature, wind speed and direction, precipitation) for the year 2008 for this case study have
444 been acquired by a local monitoring station placed in the Municipality of Lunz am See (air quality
445 data) and 100 km far away (meteorological data). Global radiation data and daily cloud cover data
446 were obtained, respectively, from the World Radiation Data Centre (WRDC) and National Oceanic
447 and Atmospheric Administration (NOAA) websites [67-68].

448 Meteorological data were preprocessed through the Micrometeo model [64] in order to build
449 CALPUFF model meteorological input.

450 The simulation domain is made up of squared cells (7 km x 7 km), the South-West corner of the
451 reference grid located at UTM coordinates E = 499.0 km, N = 5297.2 km, so that the urbanized
452 areas are located at the center of the domain.

453 The CALPUFF model computed pollutants concentrations at ground level in 4900 receptors (100 m
454 x 100 m resolution of simulation domain). At each point of the computational grid its altitude above
455 sea level was derived from the DTM (Digital Terrain Model) SRMT NASA-USGS [65] with a
456 spatial resolution of 90 m. All receptors were placed at a height of 2 meters above ground level. Air
457 quality maps were then developed both for the baseline scenario (2010) and for the 2020
458 replacement scenario (2020) and are reported in Figures S2.25-S2.40.

459 460 **3. Results and discussion** 461

462 **3.1 LCA and ELCC analysis results and discussion**

463 In the following results of Life Cycle Analysis and ELCC analysis of three high efficiency pellet
464 boiler types are presented.

465

466 3.1.1. Environmental impact of different pellet boilers types through life cycle analysis

467 Figure 3 presents the comparison of LCA results for the 3 pellet boiler types according to the
468 ReCiPe Midpoint method and its specific subcategories (16 subcategories over 18 since impacts on
469 OD and WD are negligible). Figure 3a evidences that, apart from the only exception given by the
470 ALO subcategory, BW 102 presents the lowest environmental impact on all subcategories with
471 respect to the other 2 boilers (VA 120 and VA 60 models). With respect to the VA 60 model (which
472 presents on average the highest environmental impact), the biggest reduction by BW 102
473 environmental impact with respect to the other two boiler technologies is given by the ALO and
474 NLT subcategories (-94% and -45% respectively, mainly due to the reduction of pellet consumption
475 during the whole life cycle). Interesting further reductions (in the range 10%-20%) are given by the
476 FD, CC, PMF, FET and MET subcategories. Other categories that present not negligible impact
477 reductions (in the range from 3% to 8%) are given by the TA, HT, TET and IR subcategories.
478 Results in absolute values are reported in Figure 3a while percent impact reductions (with respect to
479 VA 60, whose impacts are set to 100%) are shown in Figure 3b. Both Figure 3a and 3b show, on
480 average, an intermediate environmental impact associated to VA 120 with respect to BW 102 and
481 VA 60 boiler models. According to some specific ReCiPe Midpoint subcategories (TA, ME, POF,
482 FET, MET and MD) VW 120 presents a higher environmental burden compared to VA 60.

483

Approximate location of Figure 3

The absolute values for environmental impacts of the BW 102, VA 60 and VA 120 pellet boilers according to the specific ReCiPe Midpoint subcategories are reported in Table 2.

Approximate location of Table 2

3.1.2 Environmental Life Cycle Costing Analysis applied to the pellet boilers

Table 3 summarizes the results of the Environmental LCC analysis applied to the 3 pellet boilers types envisaged according to the major cost categories: R&D, Construction or production costs, transport costs and pellet consumption costs. R&D costs were calculated as 17% of the boiler value. For this reason, BW 102 R&D costs are slightly higher with respect to costs associated to VA 60 and VA 120 boiler models (+0,5% and +0,6% respectively) since BW 102 presents the highest value among the boilers envisaged.

Even with reference to production costs, the lowest can be ascribed to VA 60 followed by VA 120 boiler models since BW 102 shows the highest weight, mainly given by metal components. Transport costs in the ELCC analysis are negligible. Finally, pellet consumption cost is the most relevant in ELCC analysis and was calculated over the whole boiler lifetime (i.e. 20 years, as for LCA).

An annual increase of pellet price by 2% was assumed on long term bases (20 years). [54]. Average pellet consumption data of the boilers tested in the BioMaxEff Project [1] were considered. The BW 102 model presents the lowest pellet consumption costs (-16% with respect to the VA 60 boiler model, reference case of LCA) showing as ELCC analysis final result a lower overall monetary value by 9% of BW 102 with respect to VA 60. Despite of a higher investment cost, the adoption of the BW 102 boiler will bring economic savings to end users due to lower operational costs compared to VA 60 and VA 120 boiler models.

Approximate location of Table 3

3.2 Air quality modelling results

Table 4 reports CO, NO₂, PM₁₀ and SO₂ yearly municipal emissions due to residential heating for Valdidentro (IT) and Lunz am See (AT) case studies with baseline (2010) and replacement scenario (2020). The emissions percentage difference for the 2 scenarios is also reported. With reference to

the case study of Valdidentro, the reduction of CO and primary PM10 emissions amounts to about 11% for the 2020 scenario with respect to the baseline scenario while for SO₂ emissions are reduced by 9%. A negligible increase of NO₂ emissions (+0,1%) is foreseen from 2010 to 2020. With reference to the case study of Lunz am See, the reduction of CO, SO₂ and primary PM10 emissions amounts to about 23% for the 2020 scenario with respect to the baseline scenario while for SO₂ emissions are reduced by 9%. A reduction by 7% of NO₂ emissions is foreseen from 2010 to 2020 for the Austrian case study.

Approximate location of Table 4

Figure 4 reports air quality modelling results for NO₂ and PM10 associated to the case study of Valdidentro (Figures 4a, 4b, 4c, 4d) and Lunz am See (Figures 4e, 4f, 4g, 4h). In particular, the contribution to NO₂ and PM10 atmospheric concentrations (in terms of absolute values, expressed in µg/m³) due to residential heating was evaluated both for the baseline scenario (year 2010) and for year 2020. Similar figures for CO and SO₂ are reported in Supplemental Material S2 (CO: Figures S2.9-S2.10 Valdidentro, Figures S2.25-S2.26 Lunz am See; SO₂: Figures S2.19-S2.24 Valdidentro, Figures S2.35-S2.40 Lunz am See).

Considering the Italian case study, Figure 4b shows that, with respect to the baseline scenario (Figure 4a), the substitution of half of the already installed wood biomass boilers with the VA 60, VA 120 and BW 102 boiler models (considering the same penetration on the market and thus the average emission factors given in Table 1) would lead to similar contributions to NO₂ atmospheric concentrations (in the range 0,30-2,03 µg/m³) over the urbanized area of the Municipality of Valdidentro. Instead, with reference to PM10 concentrations, Figure 4d evidences relevant reductions of atmospheric PM concentrations (up to about 10% with the operation of high efficiency pellet boilers with respect to the base scenario (Figure 4c) with contributions to air quality in the range 0,40-2,17 µg/m³).

An important reduction of primary PM10 emissions could thus be gained using high efficiency pellet boilers , also confirmed in [69] where the increase of PM10 emissions due to the spread of old biomass combustion technologies from 1990 to 2010 in the Marche Region (Italy) is shown. Considering the Austrian case study, Figure 4f shows that with respect to the baseline scenario (Figure 4e) the substitution of half of the already installed wood biomass boilers with the VA 60, VA 120 and BW 102 boiler models would lead to a reduction of primary NO₂ atmospheric concentrations up to 7% over the Municipality of Lunz am See. With reference to PM10 concentrations, Figure 4h evidences even more relevant reductions of atmospheric concentrations

550 (up to about 54%) installing high efficiency pellet boilers compared to the base scenario (Figure 4g,
551 range 0,12-0,36 $\mu\text{g}/\text{m}^3$).

552 Considering the air quality maps related to the other two pollutants (i.e. CO and SO₂) and reported
553 extensively in S2 (CO: Figures S2.9-S2.10 Valdidentro, Figures S2.25-S2.26 Lunz am See; SO₂:
554 Figures S2.19-S2.24 Valdidentro, Figures S2.35-S2.40 Lunz am See) a reduction of their ground
555 level concentrations up to 11% and 9% respectively according to the replacement scenario (2020)
556 with respect to the baseline scenario of Valdidentro is foreseen. Similar trends are foreseen for the
557 Austrian case study (Lunz am See) presenting a reduction of CO and SO₂ atmospheric
558 concentrations up to 23% and 22% respectively, with respect to the baseline scenario.

559

560 *Approximate location of Figure 4*

561

562 **4. Conclusions**

563 The present study shows air quality improvement potential in two EU regions if old existing
564 biomass heating systems are replaced by high tech pellet boilers.

565 In particular, the reduction of the contribution of wood biomass combustion systems to the local
566 concentrations of primary PM₁₀, NO₂, CO and SO₂ was quantified with respect to a baseline
567 scenario (year 2010) and a short term scenario (timeline: 2020) where the latter foresees the
568 implementation of high efficiency pellet boilers in substitution of half of the presently installed
569 wood biomass combustion systems used for residential heating.

570 Results showed that air quality could be improved in the short term (timeline: 2020) with the
571 substitution of obsolete and end of life biomass boilers with high efficiency pellet boilers in EU
572 areas where biomass represents the main primary source for residential heating. In particular, for the
573 case study of Valdidentro (IT), the maximum percentage reduction in terms of annual pollutants
574 concentration with respect to the baseline scenario (characterized by old biomass combustion
575 technologies) amounts to -12,07% for primary PM₁₀, -9,09% for SO₂ and -11,57% for CO.

576 For the case study of Lunz am See, the maximum percentage reduction in terms of annual pollutants
577 concentration with respect to the baseline scenario (characterized by old biomass combustion
578 technologies) amounts to -23,31% for primary PM₁₀, -23,7% for SO₂ and -23,19% for CO.

579 No relevant differences in residential heating contributions to air quality were evidenced for NO₂
580 for the baseline (2010) and replacement (2020) scenarios. The comparison of life cycle analysis
581 results of the three high efficiency boiler models even evidenced interesting impacts reduction on
582 almost all ReCiPe Midpoint subcategories (starting from a 2% reduction considering the TA
583 subcategory by up to 94% associated to the ALO subcategory) for one specific pellet boiler (BW

102) with respect to the boiler assumed as reference (VA 60). The BW 102 pellet boiler even showed an overall 9% costs reduction (calculated as the sum of boiler construction, pellet consumption, R&D and boiler transports costs) with respect to the VA 60 boiler model, assumed as reference presenting on average higher impacts with respect to LCA subcategories and a higher overall monetary value.

ELCC analysis results thus identified the main contributions due to pellet consumption (from 70% to 83%) and the boiler production phase (from 14% to 18%) in the definition of the overall boilers monetary value. The high monetary value associated to these two ELCC phases underlines the critical points to be investigated in order to improve the boilers eco-efficiency. The here presented results thus evidence a very promising solution in the short term to improve air quality in critical areas where biomass combustion plays a dominant role in air pollution.

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Boilers parameters	BW 102	VA 120	VA 60	AVE values
CO EF (kg/TJ)	276.32	220.98	435.18	310.83
NO _x (kg/TJ)	85.20	82.81	67.30	78.44
PM10 (kg/TJ)	18.10	25.95	25.27	23.11
SO ₂ (kg/TJ)	3.05	2.84	3.05	2.98
Efficiency (%)	81.12	79.41	73.14	77.89

Table 1: Emission factors (expressed in g/GJ) and efficiency (%) of BW 102, VA 60 and VA 120 boiler models and average values (used for the air quality modelling analysis).

Impact category	Unit	BW 102	VA 120	VA 60
CC	kg CO2 eq	9.36E-03	1.02E-02	1.05E-02
OD	kg CFC-11 eq	9.38E-10	1.05E-09	1.09E-09
TA	kg SO2 eq	9.30E-05	9.56E-05	8.85E-05
FE	kg P eq	6.03E-06	6.12E-06	6.29E-06
ME	kg N eq	9.58E-06	1.07E-05	1.04E-05
HT	kg 1,4-DB eq	8.82E-03	8.68E-03	8.76E-03
POF	kg NMVOC	1.39E-04	1.38E-04	1.34E-04
PMF	kg PM10 eq	5.44E-05	6.33E-05	5.96E-05
TET	kg 1,4-DB eq	6.54E-06	6.80E-06	7.00E-06
FET	kg 1,4-DB eq	2.47E-04	2.73E-04	2.66E-04
MET	kg 1,4-DB eq	2.50E-04	2.73E-04	2.67E-04
IR	kBq U235 eq	2.95E-03	3.36E-03	3.54E-03
ALO	m2a	6.75E-03	7.80E-03	8.27E-03
ULO	m2a	1.13E-03	1.31E-03	1.39E-03
NLT	m2	1.83E-06	2.08E-06	2.18E-06
WD	m3	-2.00E-04	-1.70E-04	-1.60E-04
MD	kg Fe eq	2.00E-03	2.04E-03	1.94E-03
FD	kg oil eq	2.49E-03	2.75E-03	2.86E-03

Table 2: LCA results for BW 102, VA 60 and VA 120 boiler models as environmental impacts on 16 ReCiPe Midpoint subcategories (impacts on WD and OD are negligible) expressed in their own specific units.

Model	Materials	R&D	Pellet	Transports	Total
BW 102	17.67	3.00	70.10	0.24	91.01
VA 120	15.05	2.39	74.22	0.15	91.80
VA 60	13.91	2.49	83.45	0.14	100.00

Table 3: ELCC analysis results for BW 102, VA 120 and VA 60 boiler models with respect to VA 60 boiler model, taken as reference boiler, where the cost items considered (associated to boiler production, R&D, pellet consumption and boiler transports) are expressed as percentage with respect to the overall boiler monetary value.

VALDIDENTRO				
Pollutant (tons/year)	CO	NO _x	PM10	SO ₂
Baseline scenario	117.60	10.50	12.70	6.50
Replacement 2020	104.90	10.50	11.20	6.00
% difference 2020/baseline	-10.90	0.40	-11.30	-8.40
LUNZ AM SEE				
Pollutant (tons/year)	CO	NO _x	PM10	SO ₂
baseline scenario 2010	173.50	6.10	3.9.	3.60
replacement 2020	134.30	5.70	3.00	2.80
% difference 2020/baseline	-22.60	-7.10	-22.70	-23.20

Table 4: CO, NO_x, PM10 and SO₂ yearly municipal emissions due to residential heating for Valdidentro (IT) and Lunz am See (AT) case studies according to the baseline scenario (2010), and the replacement scenario (2020). The emissions percentage difference for the 2 scenarios is also reported.

Figure captions

Figure 1: LCA and ELCC system boundaries (with reference to the life cycle phases considered).

Figure 2: Hourly temperature coefficient α_T^h for the case studies of Valdidentro (Figure 2a) and Lunz am See (Figure 2b)

Figure 3: LCA results according to the ReCiPe Midpoint method for BW 102, VA 60 and VA 120 boiler models. The environmental impact has been evaluated both in absolute values (Figure 3a) and as percentage reduction (or increase) with respect to VA 60 boiler model (Figure 3b) according to specific 16 subcategories (since contributions due to WD and OD are negligible).

Figure 4: Air quality modelling results representing the contribution of primary PM10 and NO₂ residential sector emissions to air quality in Valdidentro (Figures 4a and 4c) and Lunz am See (Figures 4e and 4g) according to the baseline scenario (2010) with respect to the contribution according to the 2020 scenario (Figures 4b and 4d for Valdidentro and Figures 4f and 4h for Lunz am See respectively).

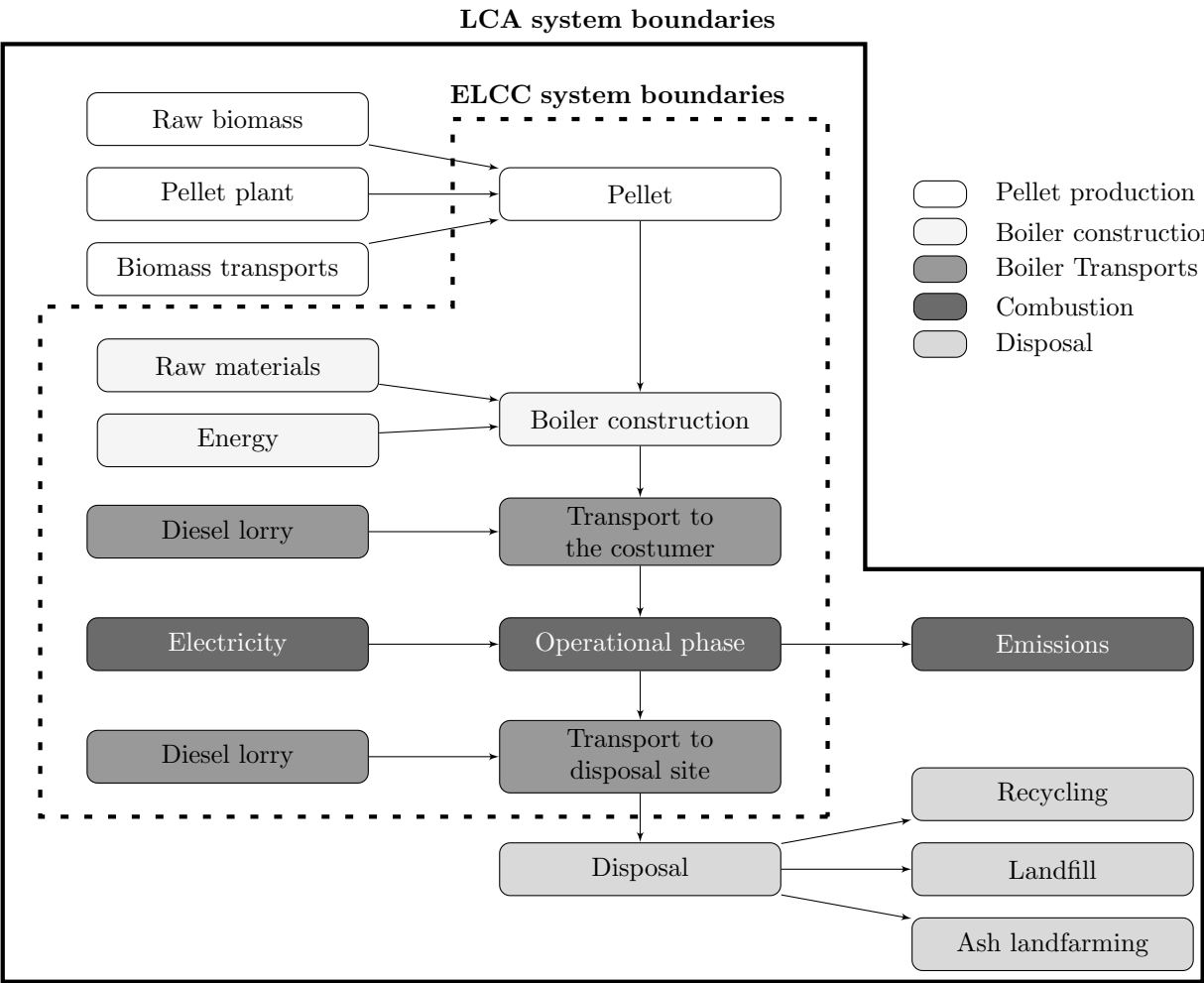


Figure 1

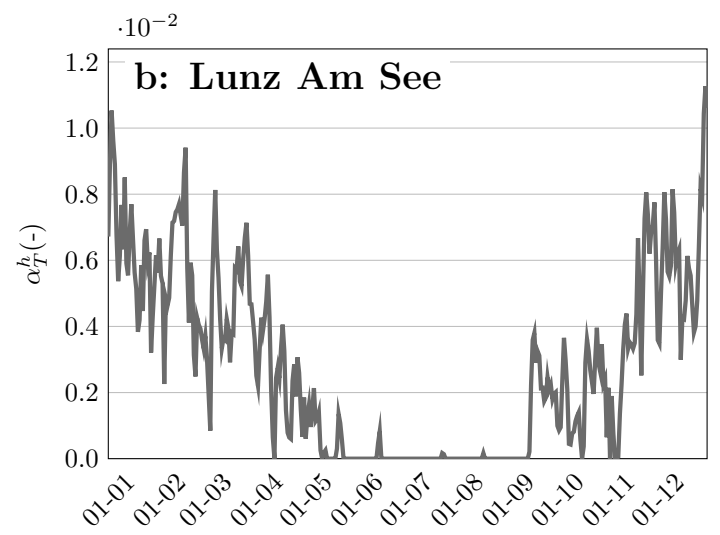
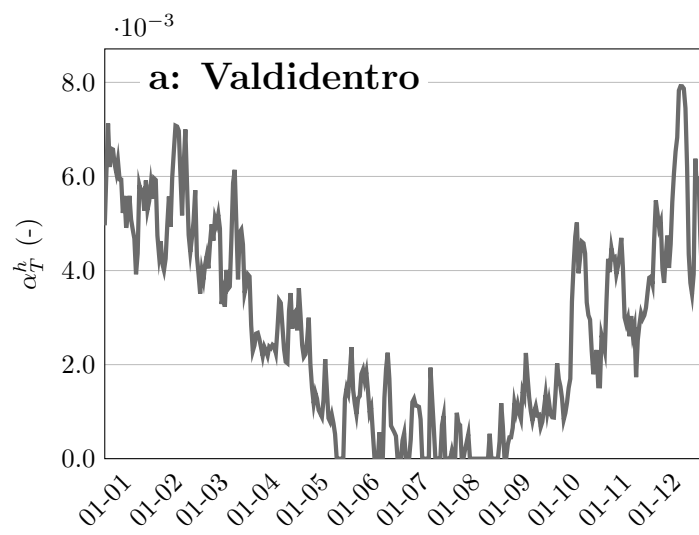


Figure 2

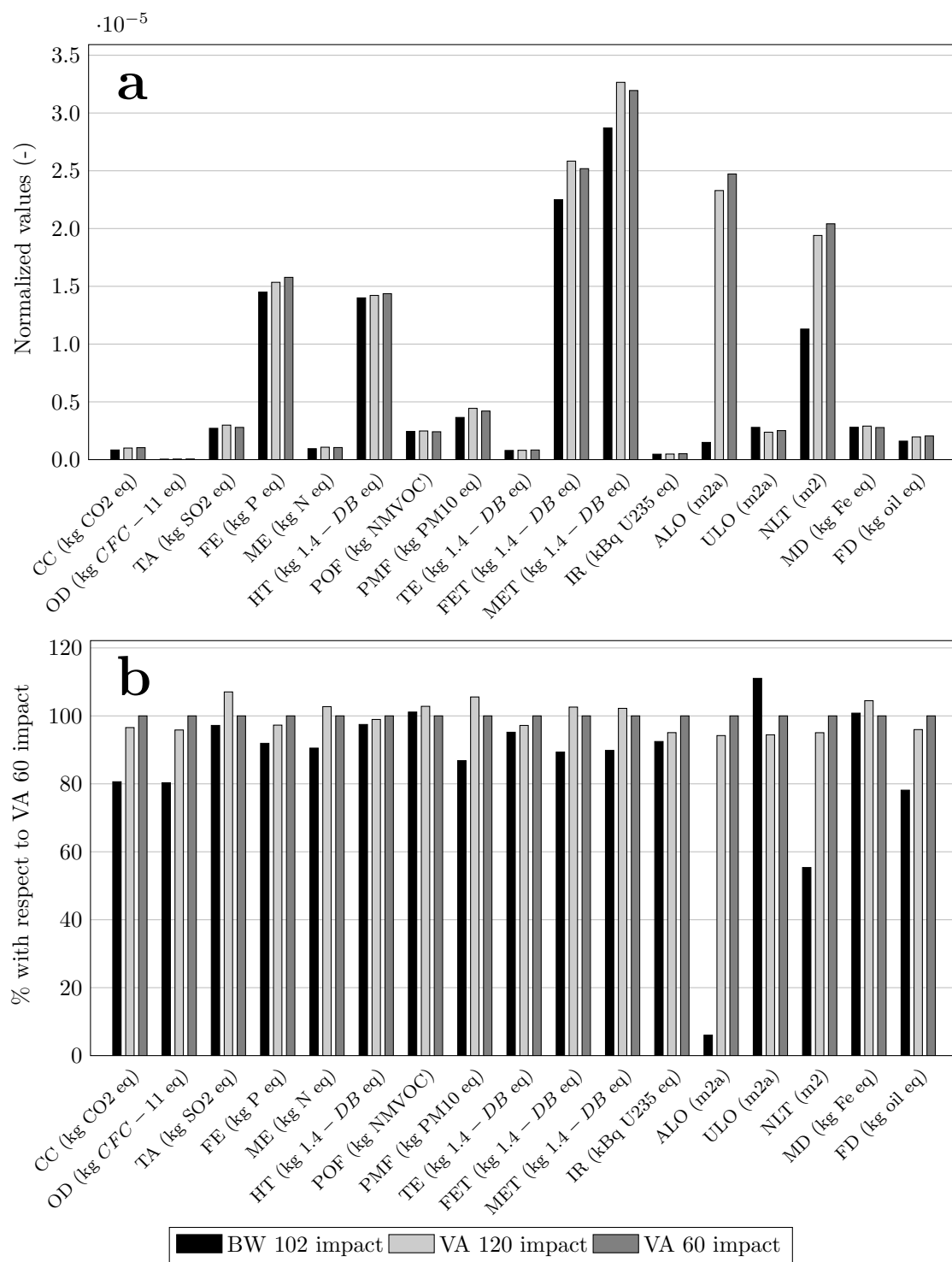


Figure 3

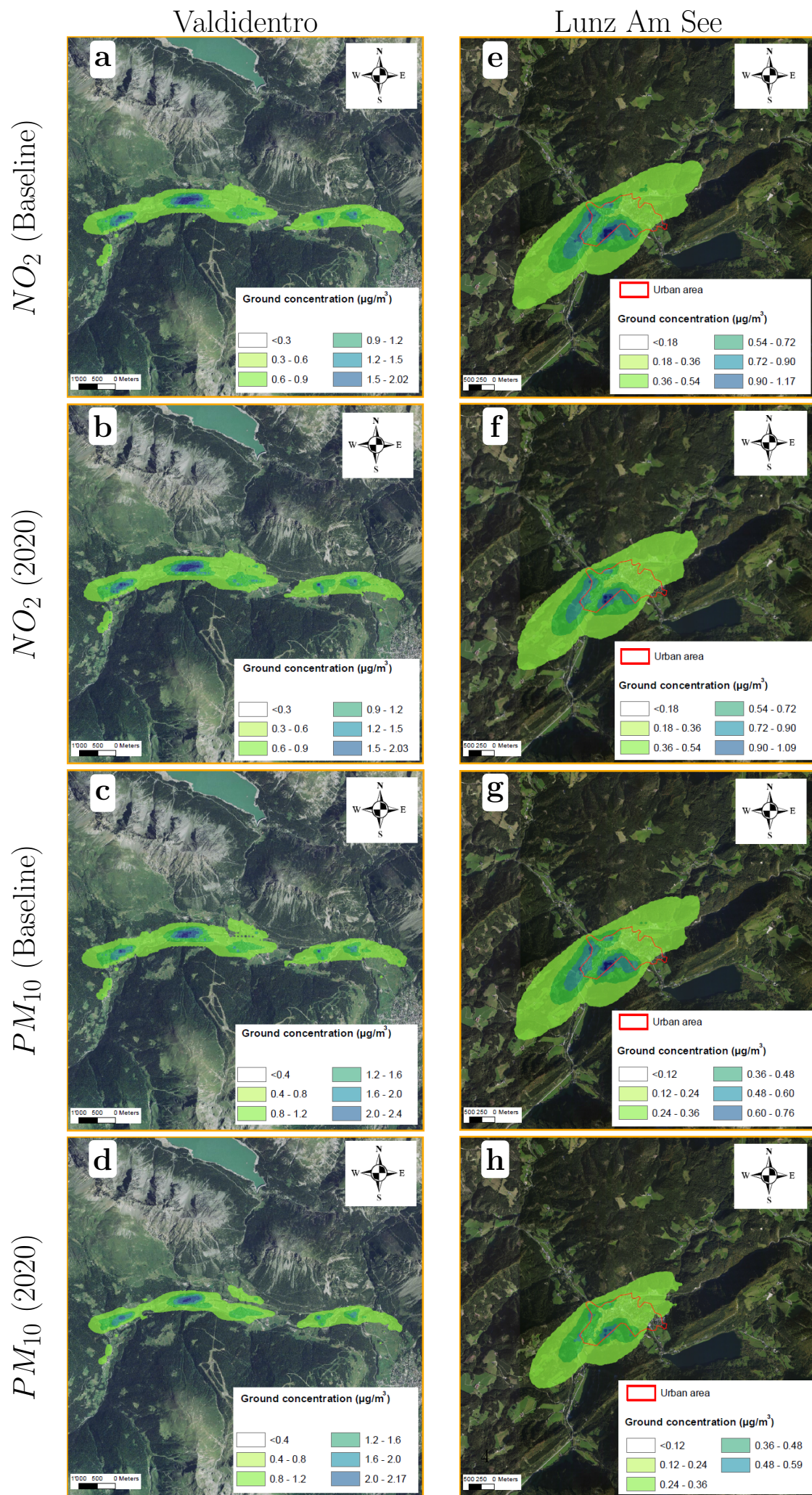


Figure 4

**Supplementary material related to LCI, load cycle method and pellet data
(S1)**

	Material	SimaPro Process	Quantity	Unit
Energy in production	Electricity in production	Electricity, medium voltage, Austrian market	381,99	kWh
	Heat in production	Heat, district or industrial, natural gas heat production, natural gas, at boiler condensing modulating >100kW	179,76	kWh
Insulation	Glass fibre	Glass fibre production RER	0,44	kg
	Rock wool	Glass wool mat RER	3,43	kg
	Vermiculite	Expanded vermiculite	8,22	kg
Metals	Brass	Brass production RER	0,04	kg
	Iron burner	Cast iron production RER	25,37	kg
	Steel pipes	Drawing of pipes steel RER	22,82	kg
	Galvanized steel	Galvanized steel sheet at plant RNA	76,26	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel production RER	120,98	kg
	Low alloyed steel	Steel, low alloyed, steel production converter RER	46,39	kg
	Mild unalloyed steel	Steel, unalloyed (RER) steel production, converter, unalloyed	75,46	kg
Electronics	Cables	Cable, unspecified, production GLO	3,90	kg
	Clamps	Electric connector, wire clamp production GLO	0,34	kg
	Thermostat and user interface	Electronics for control units	1,45	kg
Plastics	Handles	Nylon 6-6 RER production	0,67	kg
	Gaskets	Polyethylene low density granulate production mix at plant RER	0,01	kg
	Gaskets	Polyvinylchloride production, bulk polymerization	3,01	kg
	Sealing	Silicone product, production rest of the world	0,15	kg
	Gaskets	Synthetic rubber, RER production	0,03	kg
Packaging	Packaging film	Packaging film low density LDPE production	0,28	kg
	Installation manuals	Printed paper offset RER	0,09	kg
	Cardboard box	Corrugated board production	1,61	kg
	Warning stickers	Polyester resin, unsaturated	0,02	kg
Painting	White coating	Alkyd paint whitout solvent white 60% H2O	0,50	kg
	Coating	Coating powder	1,29	kg
Boiler weight			286,00	kg
Metals to recycling process			106,73	kg

S1.1: BW 102 LCI production phase (1 piece of boiler)

	Material	SimaPro Process	Quantity	Unit
Energy in production	Electricity in production	Electricity, medium voltage, Austrian market	381,99	kWh
	Heat in production	Heat, district or industrial, natural gas heat production, natural gas, at boiler condensing modulating >100kW	179,76	kWh
Insulation	Vermiculite	Expanded vermiculite	2,560	kg
	Glass fibre	Glass fibre production RER	0,517	kg
	Rock wool	Rock wool production, RER	0,810	kg
Metals	Brass	Brass production RER	0,659	kg
	Copper	Copper, production primary RER	0,010	kg
	Iron burner	Cast iron production RER	29,514	kg
	Steel pipes	Drawing of pipes steel RER	1,974	kg
	Galvanized steel	Galvanized steel sheet at plant	22,639	kg
	Lead	Lead, market for lead	0,280	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel production RER	117,761	kg
	Low alloyed steel	Steel, low alloyed, steel production converter RER	55,417	kg
	Mild unalloyed steel	Steel, unalloyed (RER) steel production, converter, unalloyed	41,096	kg
Electronics	Cables	Cable, unspecified, production GLO	1,594	kg
	Electrical circuits	Capacitor, auxiliaries and energy use	0,300	kg
	Clamps	Electric connector, wire clamp production GLO	0,430	kg
	Thermostat and user interface	Electronics for control units	1,880	kg
	Electrical circuits	Inductor, auxiliaries and energy use	0,150	kg
	Electrical circuits	Printed wiring board production, for surface mounting, Pb free surface GLO	0,250	kg
	Electrical circuits	Resistor, wirewound	0,160	kg
Plastics	Handles	Nylon 6-6 RER production	0,880	kg
	Gaskets	Polyethylene low density granulate production mix at plant RER	0,030	kg
	Gaskets	Polyvinylchloride production, bulk polymerization	0,000	kg
	Sealing	Silicone product, production RER	0,605	kg
	Gaskets	Synthetic rubber, RER production	0,291	kg
Packaging	Packaging film	Packaging film low density LDPE production	1,044	kg
	Installation manuals	Printed paper offset	0,636	kg
	Warning stickers	Polyester resin, unsaturated	0,032	kg
Painting	White coating	Alkyd paint whitout solvent white 60% H2O	0,300	kg
	Coating	Coating powder	0,585	kg
Lubrificant oil	Lubrificant oil	Lubricating oil RER production	0,022	kg
Boiler weight			176,000	kg
Metals to recycling process			106,525	kg

S1.2: VA 120 LCI production phase (1 piece of boiler)

Material		SimaPro Process	Quantity	Unit
Energy in production	Electricity in production	Electricity, medium voltage, Austrian market	381,99	kWh
	Heat in production	Heat, district or industrial, natural gas heat production, natural gas, at boiler condensing modulating >100kW	179,76	kWh
Insulation	Vermiculite	Expanded vermiculite	2,560	kg
	Glass fibre	Glass fibre production RER	0,721	kg
	Glass wool	Glass wool mat, production	0,590	kg
	Rock wool	Rock wool production, RER	0,810	kg
	Ceramics	Sanitary ceramics RER production	0,000	kg
Metals	Brass	Brass production RER	0,299	kg
	Iron burner	Cast iron production RER	14,988	kg
	Steel pipes	Drawing of pipes steel RER	1,985	kg
	Galvanized steel	Galvanized steel sheet at plant RNA	35,285	kg
	Lead	Lead, market for lead GLO	0,280	kg
	Stainless steel	Steel, Chromium steel 18/8, converter steel production RER	114,399	kg
	Low alloyed steel	Steel, low alloyed, steel production converter RER	52,256	kg
	Mild unalloyed steel	Steel, unalloyed (RER) steel production, converter, unalloyed	32,324	kg
Electronics	Cables	Cable, unspecified, production GLO	1,607	kg
	Electrical circuits	Capacitor, auxiliaries and energy use	0,150	kg
	Clamps	Electric connector, wire clamp production GLO	0,250	kg
	Thermostat and user interface	Electronics for control units	2,389	kg
	Electrical circuits	Inductor, auxiliaries and energy use	0,060	kg
	Electrical circuits	Printed wiring board production, for surface mounting, Pb free surface GLO	0,250	kg
	Electrical circuits	Resistor, wirewound	0,080	kg
Plastics	Handles	Nylon 6-6 RER production	0,430	kg
	Gaskets	Polyethylene low density granulate production mix at plant RER	0,045	kg
	Gaskets	Polyvinylchloride production, bulk polymerization	0,002	kg
	Sealing	Silicone product, production RER	1,004	kg
	Gaskets	Synthetic rubber, RER production	0,281	kg
Packaging	Packaging film	Packaging film low density LDPE production	0,040	kg
	Installation manuals	Printed paper offset RER	0,446	kg
	Warning stickers	Polyester resin, unsaturated	0,083	kg
Painting	White coating	Alkyd paint whitout solvent white 60% H2O	0,300	kg
	Coating	Coating powder	0,386	kg
Lubrificant oil	Lubrificant oil	Lubricating oil RER production	0,073	kg
Boiler weight			170,000	kg
Metals to recycling process			94,812	kg

S1.3: VA 60 LCI production phase (1 piece of boiler)

Input	SimaPro Process	Quantity	Unit
Water	Water, unspecified natural origin, RER	3,00E-05	m3
Pellet plant and equipment	Pointing device, optical mouse, with cable {GLO} market for	8,00E-09	p
	Computer, desktop, without screen {GLO} market for	8,00E-09	p
	Dust collector, multicyclone {GLO} market for	1,00E-09	p
	Dust collector, electrostatic precipitator, for industrial use {GLO} market for	1,00E-09	p
	Lubricating oil {GLO} market for	8,40E-05	kg
	Packaging film, low density polyethylene {GLO} market for	2,28E-03	kg
	Keyboard {GLO} market for	8,00E-09	p
	Display, liquid crystal, 17 inches {GLO} market for	1,60E-08	p
	Wood pellet factory {GLO} market for	4,00E-10	p
Wood	Shaving, hardwood, measured as dry mass {BIOMAXEFF} market for	1,50E-01	kg
	Shaving, softwood, measured as dry mass {GLO BIOMAXEFF} market for	1,50E-01	kg
	Wood chips, wet, measured as dry mass {RER BIOMAXEFF} market for	1,30E-01	kg
	Saw dust, wet, measured as dry mass {GLO BIOMAXEFF} market for	5,70E-01	kg
Binding materials	Maize starch {GLO} market for	5,00E-03	kg
Heat	Heat, central or small-scale, other than natural gas {CH} heat production, wood pellet, at furnace 300kW, state-of-the-art 2014	1,12E-01	MJ
European electricity mix	Electricity, medium voltage {SK} market for	7,29E-04	kWh
	Electricity, medium voltage {BA} market for	2,51E-04	kWh
	Electricity, medium voltage {PL} market for	3,72E-03	kWh
	Electricity, medium voltage {IE} market for	7,53E-04	kWh
	Electricity, medium voltage {AT} market for	1,75E-03	kWh
	Electricity, medium voltage {DE} market for	1,55E-02	kWh
	Electricity, medium voltage {BG} market for	8,98E-04	kWh
	Electricity, medium voltage {SE} market for	3,85E-03	kWh
	Electricity, medium voltage {ES} market for	7,69E-03	kWh
	Electricity, medium voltage {NO} market for	3,34E-03	kWh
	Electricity, medium voltage {FR} market for	1,33E-02	kWh
	Electricity, medium voltage {RO} market for	1,45E-03	kWh
	Electricity, medium voltage {HU} market for	1,10E-03	kWh
	Electricity, medium voltage {MK} market for	2,18E-04	kWh
	Electricity, medium voltage {SI} market for	3,70E-04	kWh
	Electricity, medium voltage {FI} market for	2,37E-03	kWh
	Electricity, medium voltage {GR} market for	1,70E-03	kWh
	Electricity, medium voltage {PT} market for	1,44E-03	kWh
	Electricity, medium voltage {HR} market for	4,81E-04	kWh
	Electricity, medium voltage {UA} market for	4,43E-03	kWh
	Electricity, medium voltage {RS} market for	8,65E-04	kWh
	Electricity, medium voltage {LU} market for	1,84E-04	kWh
	Electricity, medium voltage {IT} market for	9,19E-03	kWh
	Electricity, medium voltage {BE} market for	2,47E-03	kWh
	Electricity, medium voltage {CH} market for	1,71E-03	kWh
	Electricity, medium voltage {CZ} market for	1,74E-03	kWh
	Electricity, medium voltage {NL} market for	3,30E-03	kWh
	Electricity, medium voltage {GB} market for	1,02E-02	kWh
	Electricity, medium voltage {DK} market for	1,03E-03	kWh
Water to air	Water/m3	4,50E-06	m3
Water to water	Water, RER	2,55E-05	m3
Waste mineral oil	Waste mineral oil {GLO} market for	8,40E-05	kg

Table S1.4: Wood pellet LCI, Functional Unit 1 kg.

Input	SimaPro process	Quantity	Unit
Transports	Transport, freight, lorry, unspecified, market for	0,036	tkm
Hardwood beam shaving, air dried	Shaving, hardwood, measured as dry mass, planing, beam, hardwood, air dried	0,002	kg
Hardwood beam shaving, kiln dreid	Shaving, hardwood, measured as dry mass, planing, beam, hardwood, kiln dried	0,241	kg
Hardwood board shaving, air dried	Shaving, hardwood, measured as dry mass, planing, board, hardwood, air dried	0,504	kg
Hardwood board shaving, kiln dried	Shaving, hardwood, measured as dry mass, planing, board, hardwood, kiln dried	0,252	kg

Table S1.5: Hardwood shaving LCI, Functional Unit 1 kg.

Input	SimaPro process	Quantity	Unit
Transports	Transport, freight, lorry, unspecified market for	0,036	tkm
Softwood beam shaving, air dried	Shaving, softwood, measured as dry mass planing, beam, softwood, air dried	0,160	kg
Softwood beam shaving, kiln dreid	Shaving, softwood, measured as dry mass planing, beam, softwood, kiln dried	0,135	kg
Softwood board shaving, air dried	Shaving, softwood, measured as dry mass planing, board, softwood, air dried	0,338	kg
Softwood board shaving, kiln dried	Shaving, softwood, measured as dry mass planing, board, softwood, kiln dried	0,367	kg

Table S1.6: Softwood shaving LCI, Functional Unit 1 kg.

Input	SimaPro process	Quantity	Unit
Transports	Transport, freight, lorry, unspecified market for	0,036	tkm
Hardwood saw dust	Saw dust, wet, measured as dry mass sawing, hardwood	0,037	kg
Softwood saw dust	Saw dust, wet, measured as dry mass sawing, softwood	0,963	kg

Table S1.7: Saw dust LCI, Functional Unit 1 kg.

Input	SimaPro Process	Quantity	Unit
Transports	Transport, freight, lorry, unspecified {GLO} market for	0,021	tkm
Swiss hardwood chips from sawmill	Wood chips, wet, measured as dry mass {CH} wood chips production, hardwood, at sawmill	0,001	kg
Swiss softwood chips from sawmill	Wood chips, wet, measured as dry mass {CH} wood chips production, softwood, at sawmill	0,016	kg
German hardwood chips from beech forestry	Wood chips, wet, measured as dry mass {DE} hardwood forestry, beech, sustainable forest management	0,126	kg
Swedish hardwood chips from birch forestry	Wood chips, wet, measured as dry mass {SE} hardwood forestry, birch, sustainable forest management	0,367	kg
Swiss hardwood chips from mixed species forestry	Wood chips, wet, measured as dry mass {CH} hardwood forestry, mixed species, sustainable forest management	0,050	kg
German hardwood chips from oak forestry	Wood chips, wet, measured as dry mass {DE} hardwood forestry, oak, sustainable forest management	0,025	kg
Swiss softwood chips from mixed specied forestry	Wood chips, wet, measured as dry mass {CH} softwood forestry, mixed species, sustainable forest management	0,014	kg
German softwood chips from pine forestry	Wood chips, wet, measured as dry mass {DE} softwood forestry, pine, sustainable forest management	0,039	kg
Swedish softwood chips from pine forestry	Wood chips, wet, measured as dry mass {SE} softwood forestry, pine, sustainable forest management	0,144	kg
German softwood chips from spruce forestry	Wood chips, wet, measured as dry mass {DE} softwood forestry, spruce, sustainable forest management	0,062	kg
Swedish softwood chips from spruce forestry	Wood chips, wet, measured as dry mass {SE} softwood forestry, spruce, sustainable forest management	0,156	kg

Table S1.8: Wood chips LCI, Functional Unit 1 kg.

Parameter	Unit	Lab tests pellet data	Testing standard	Literature data [1]
Moisture	w-% (w.b.)	8,10	EN 14774-1[2]	10
C	w-% (d.b.)	50,01	EN 15104 [3]	50
H	w-% (d.b.)	6,18	EN 15104 [3]	6
O	w-% (d.b.)	43,37	by difference	44
N	w-% (d.b.)	0,06	EN 15104 [3]	0,08
S	w-% (d.b.)	< 0,01	EN 15289 [4]	0,01
Cl	w-% (d.b.)	< 0,01	EN 15289 [4]	< 0,001
Ash content	w-% (d.b.)	0,38	EN 14775 [5]	0,1-1
HHV	MJ/kg (d.b.)	20,20	EN 14918 [6]	N.A.
LHV	MJ/kg (d.b.)	18,85	EN 14918 [6]	18,5

Table S1.9: Quality labels and chemical and physical properties of the pellet used for lab tests compared to average pellet data used for LCA (column “Literature data”); w-% = weight percent, w.b. = wet bases, d.b.= dry bases.

Transports	SimaPro Process	Distance	Unit
From manufacturer to costumer	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER} transport, freight, lorry 3.5-7.5 metric ton, EURO4	100	km
From customer to final disposal	Transport, freight, lorry 3.5-7.5 metric ton, EURO4 {RER} transport, freight, lorry 3.5-7.5 metric ton, EURO4	100	km

Table S1.10: BW 102, VA 120 and VA 60 LCI transports data, Functional unit 1 piece

Input	SimaPro process	Quantity	Unit
Electricity	Electricity, low voltage {AT} market for	3,16E-03	kWh
Emissions to air	Dinitrogen monoxide	3,66E-06	kg
	Lead	3,05E-08	kg
	Sulfur dioxide	3,05E-06	kg
	Phosphorus	3,66E-07	kg
	Fluorine	6,10E-08	kg
	Acetaldehyde	7,44E-08	kg
	Potassium	2,85E-05	kg
	Benzene, ethyl-	3,66E-08	kg
	Particulates, < 2.5 um	1,81E-05	kg
	Magnesium	4,39E-07	kg
	Chlorine	2,20E-07	kg
	Ammonia	2,11E-06	kg
	Formaldehyde	1,59E-07	kg
	Hydrocarbons, aliphatic, alkanes, unspecified	1,11E-06	kg
	PAH, polycyclic aromatic hydrocarbons	1,35E-08	kg
	Nickel	7,32E-09	kg
	Copper	2,68E-08	kg
	Calcium	7,14E-06	kg
	Mercury	3,66E-10	kg
	Toluene	3,66E-07	kg
	NM VOC, non-methane volatile organic compounds, unspecified origin	2,81E-06	kg
	Chromium VI	4,88E-11	kg
	Zinc	3,66E-07	kg
	Manganese	2,07E-07	kg
	Arsenic	1,22E-09	kg
	Cadmium	8,54E-10	kg
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3,78E-14	kg
	Hydrocarbons, aliphatic, unsaturated	3,78E-06	kg
	Phenol, pentachloro-	9,88E-12	kg
	Chromium	4,83E-09	kg
	Benzo(a)pyrene	6,10E-10	kg
	Carbon monoxide, biogenic	2,76E-04	kg
	Carbon dioxide, biogenic	1,18E-01	kg
	Benzene	1,11E-06	kg
	Methane, biogenic	4,88E-07	kg
	Bromine	7,32E-08	kg
	Benzene, hexachloro-	8,78E-15	kg
	Sodium	1,59E-06	kg
	m-Xylene	1,46E-07	kg
	Nitrogen oxides	8,52E-05	kg

Table S1.11: BW 102 operational phase emissions. Functional Unit 1 MJ.

Input	SimaPro process	Quantity	Unity
Electricity	Electricity, low voltage {AT} market for	3,16E-03	kWh
Emissions to air	Methane, biogenic	4,88E-07	kg
	m-Xylene	1,46E-07	kg
	Nitrogen oxides	8,28E-05	kg
	Chromium VI	4,88E-11	kg
	Sulfur dioxide	2,84E-06	kg
	Nickel	7,32E-09	kg
	Hydrocarbons, aliphatic, alkanes, unspecified	1,11E-06	kg
	Particulates, < 2.5 um	2,60E-05	kg
	Benzene	1,11E-06	kg
	Carbon dioxide, biogenic	1,18E-01	kg
	Lead	3,05E-08	kg
	Acetaldehyde	7,44E-08	kg
	Phenol, pentachloro-	9,88E-12	kg
	Hydrocarbons, aliphatic, unsaturated	3,78E-06	kg
	Ammonia	2,11E-06	kg
	Manganese	2,07E-07	kg
	Toluene	3,66E-07	kg
	Dinitrogen monoxide	3,66E-06	kg
	Formaldehyde	1,59E-07	kg
	Magnesium	4,39E-07	kg
	Bromine	7,32E-08	kg
	Benzo(a)pyrene	6,10E-10	kg
	Sodium	1,59E-06	kg
	Zinc	3,66E-07	kg
	Chlorine	2,20E-07	kg
	NMVOC, non-methane volatile organic compounds, unspecified origin	2,81E-06	kg
	Copper	2,68E-08	kg
	Arsenic	1,22E-09	kg
	PAH, polycyclic aromatic hydrocarbons	1,35E-08	kg
	Fluorine	6,10E-08	kg
	Potassium	2,85E-05	kg
	Benzene, hexachloro-	8,78E-15	kg
	Chromium	4,83E-09	kg
	Cadmium	8,54E-10	kg
	Mercury	3,66E-10	kg
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3,78E-14	kg
	Carbon monoxide, biogenic	2,21E-04	kg
	Benzene, ethyl-	3,66E-08	kg
	Phosphorus	3,66E-07	kg
	Calcium	7,14E-06	kg

Table S1.12: VA 120 operational phase emissions. Functional Unit 1 MJ.

Input	SimaPro Process	Quantity	Unit
Electricity	Electricity, low voltage {AT} market for	3,16E-03	kWh
Emissions to air	Methane, biogenic	4,88E-07	kg
	m-Xylene	1,46E-07	kg
	Nitrogen oxides	6,73E-05	kg
	Chromium VI	4,88E-11	kg
	Sulfur dioxide	3,05E-06	kg
	Nickel	7,32E-09	kg
	Hydrocarbons, aliphatic, alkanes, unspecified	1,11E-06	kg
	Particulates, < 2.5 um	2,53E-05	kg
	Benzene	1,11E-06	kg
	Carbon dioxide, biogenic	1,18E-01	kg
	Lead	3,05E-08	kg
	Acetaldehyde	7,44E-08	kg
	Phenol, pentachloro-	9,88E-12	kg
	Hydrocarbons, aliphatic, unsaturated	3,78E-06	kg
	Ammonia	2,11E-06	kg
	Manganese	2,07E-07	kg
	Toluene	3,66E-07	kg
	Dinitrogen monoxide	3,66E-06	kg
	Formaldehyde	1,59E-07	kg
	Magnesium	4,39E-07	kg
	Bromine	7,32E-08	kg
	Benzo(a)pyrene	6,10E-10	kg
	Sodium	1,59E-06	kg
	Zinc	3,66E-07	kg
	Chlorine	2,20E-07	kg
	NM VOC, non-methane volatile organic compounds, unspecified origin	2,81E-06	kg
	Copper	2,68E-08	kg
	Arsenic	1,22E-09	kg
	PAH, polycyclic aromatic hydrocarbons	1,35E-08	kg
	Fluorine	6,10E-08	kg
	Potassium	2,85E-05	kg
	Benzene, hexachloro-	8,78E-15	kg
	Chromium	4,83E-09	kg
	Cadmium	8,54E-10	kg
	Mercury	3,66E-10	kg
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3,78E-14	kg
	Carbon monoxide, biogenic	4,35E-04	kg
	Benzene, ethyl-	3,66E-08	kg
	Phosphorus	3,66E-07	kg
	Calcium	7,14E-06	kg

Table S1.13: VA 60 operational phase emissions. Functional Unit 1 MJ.

	Material	SimaPro Process	Quantity	Unit
Insulation	Rock wool	Waste mineral wool, for final disposal {CH} treatment of waste mineral wool, inert material landfill	30,44	% assembly weight
	Glass fibre, vermiculite	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100	% remaining materials
Metals	Steel	Steel and iron (waste treatment) {GLO} recycling of steel and iron	10,72	% assembly weight
	Ferro metals	Steel and iron (waste treatment) {GLO} recycling of steel and iron	40,19	% assembly weight
	Remaining metals	Scrap steel {CH} treatment of, inert material landfill	50,00	% remaining materials
		Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	50,00	% remaining materials
Electronics	Thermostat	Electronics scrap from control units {GLO} market for	23,53	% assembly weight
	Cables	Used cable {GLO} treatment of	67,79	% assembly weight
	Wiring, clamps	Waste electric wiring {CH} treatment of, collection for final disposal	8,29	% assembly weight
	Remaining materials	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100,00	% remaining materials
Plastics	Gaskets	Waste polyethylene {GLO} market for	0,26	% assembly weight
	Gaskets	Waste polyvinylchloride {GLO} market for	75,98	% assembly weight
	Handles, sealings	Waste plastic, mixture {GLO} market for	100,00	% remaining materials
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	85,11	% assembly weight
	Packaging film	Waste plastic, mixture {GLO} market for	100	% remaining materials
Painting	Paint	Waste paint on metal {CH} treatment of, collection for final disposal	100,00	% assembly weight
Boiler weight			286	kg

Table S1.14: BW 102 LCI disposal data.

Material	SimaPro Process	Quantity	Unit
Wood ashes to landfarming	Wood ash mixture, pure {CH} treatment of, landfarming	0,00015	kg/MJ
Wood ashes to landfill	Wood ash mixture, pure {CH} treatment of, sanitary landfill	0,00015	kg/MJ

Table S1.15: BW 102 ashes disposal, Functional unit 1 MJ

	Material	SimaPro Process	Quantity	Unit
Insulation	Rock wool	Waste mineral wool, for final disposal {CH} treatment of waste mineral wool, inert material landfill	20,84	% assembly weight
	Glass fibre, vermiculite	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100,00	% remaining materials
Metals	Steel	Steel and iron (waste treatment) {GLO} recycling of steel and iron	40,05	% assembly weight
	Ferro metals	Steel and iron (waste treatment) {GLO} recycling of steel and iron	18,06	% assembly weight
	Remaining metals	Scrap steel {CH} treatment of, inert material landfill	50,00	% remaining materials
		Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	50,00	% remaining materials
Electronics	Thermostat	Electronics scrap from control units {GLO} market for	53,74	% assembly weight
	Cables	Used cable {GLO} treatment of	32,83	% assembly weight
	Wiring, clamps	Waste electric wiring {CH} treatment of, collection for final disposal	5,35	% assembly weight
	Wiring boards	Used printed wiring boards	5,15	% assembly weight
	Remaining materials	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100,00	% remaining materials
Plastics	Gaskets	Waste polyethylene {GLO} market for	1,66	% assembly weight
	Gaskets	Waste polyvinylchloride {GLO} market for	0,01	% assembly weight
	Handles, sealings	Waste plastic, mixture {GLO} market for	100,00	% remaining materials
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	37,15	% assembly weight
	Packaging film	Waste plastic, mixture {GLO} market for	100,00	% remaining materials
Painting	Paint	Waste paint on metal {CH} treatment of, collection for final disposal	100,00	% assembly weight
Boiler weight			176,00	kg

Table S1.16: VA 120 H/P LCI disposal data.

Material	SimaPro process	Quantity	Unit
Wood ashes to landfarming	Wood ash mixture, pure {CH} treatment of, landfarming	0,00016	kg/MJ
Wood ashes to landfill	Wood ash mixture, pure {CH} treatment of, sanitary landfill	0,00016	kg/MJ

Table S1.17: VW 120 ashes disposal, Functional unit 1 MJ

	Material	SimaPro Process	Quantity	Unit
Insulation	Rock wool	Waste mineral wool, for final disposal {CH} treatment of waste mineral wool, inert material landfill	17,305	% assembly weight
	Glass fibre, vermiculite	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100,000	% remaining materials
Metals	Steel	Steel and iron (waste treatment) {GLO} recycling of steel and iron	44,470	% assembly weight
	Ferro metals	Steel and iron (waste treatment) {GLO} recycling of steel and iron	9,482	% assembly weight
	Remaining metals	Scrap steel {CH} treatment of, inert material landfill	50,000	% remaining materials
		Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	50,000	% remaining materials
Electronics	Thermostat	Electronics scrap from control units {GLO} market for	54,720	% assembly weight
	Cables	Used cable {GLO} treatment of	31,639	% assembly weight
	Wiring, clamps	Waste electric wiring {CH} treatment of, collection for final disposal	4,923	% assembly weight
	Wiring boards	Used printed wiring boards	4,923	% assembly weight
	Remaining materials	Inert waste, for final disposal {CH} treatment of inert waste, inert material landfill	100,000	% remaining materials
Plastics	Gaskets	Waste polyethylene {GLO} market for	1,437	% assembly weight
	Gaskets	Waste polyvinylchloride {GLO} market for	0,002	% assembly weight
	Handles, sealings	Waste plastic, mixture {GLO} market for	100,000	% remaining materials
Packaging	Instruction manuals, cardboard box	Paper (waste treatment) {GLO} recycling of paper	43,788	% assembly weight
	Packaging film	Waste plastic, mixture {GLO} market for	100,000	% remaining materials
Painting	Paint	Waste paint on metal {CH} treatment of, collection for final disposal	100,000	% assembly weight
Boiler weight			170,000	kg

Table S1.18: VA 60 DDA LCI disposal data.

Material	SimaPro process	Quantity	Unit
Wood ashes to landfarming	Wood ash mixture, pure {CH} treatment of, landfarming	0,00017	kg/MJ
Wood ashes to landfill	Wood ash mixture, pure {CH} treatment of, sanitary landfill	0,00017	kg/MJ

Table S1.19: VA 60 ashes disposal, Functional unit 1 MJ

Italian case study: Valdidentro municipality

	Emissions [tons/year]			
	PM ₁₀	CO	SO ₂	NO _x
LPG	0.004	0.18	0.004	0.93
Oil	0.65	2.61	6.11	6.5
Wood and similar	12.0	114	0.40	3.0
Total	12.6	118	6.5	10.4

Table S1.20: Valdidentro yearly emissions, Macrosector 2 per fuel for year 2010.

	Emissions [tons/year]			
	PM ₁₀	CO	SO ₂	NO _x
LPG	0.003	0.17	0.004	0.86
Oil	0.60	2.4	5.6	6.0
Wood and similar	11.1	106.3	0.37	2.8
Total	11.7	108	6.0	9.7

Table S1.21: Simulated emissions of Valdidentro municipality (2010).

	PM ₁₀	CO	SO ₂	NO _x
LPG	89.9%	89.8%	89.7%	89.8%
Oil	74.6%	74.6%	74.6%	74.6%
Wood and similar	88.5%	89.4%	90.9%	91.6%
Total	87.6%	89.0%	75.4%	80.1%

Table S1.22: Macro-sector 2 emissions compared to the total emissions of the town of Valdidentro.

	PM ₁₀	CO	SO ₂	NO _x
Percentage of total emissions	71.0%	70.6%	71.5%	20.4%

Table S1.23: Percentage of emissions considered compared to the total emissions of Valdidentro municipality.

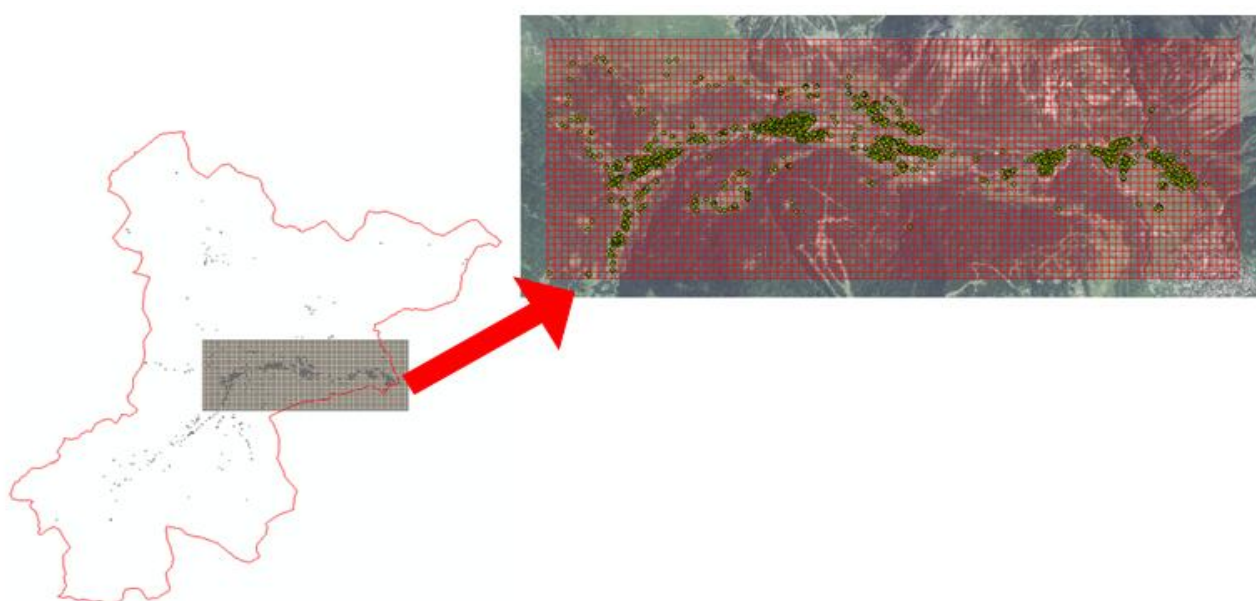


Figure S1.1: Valdidentro municipality with focus on residential area

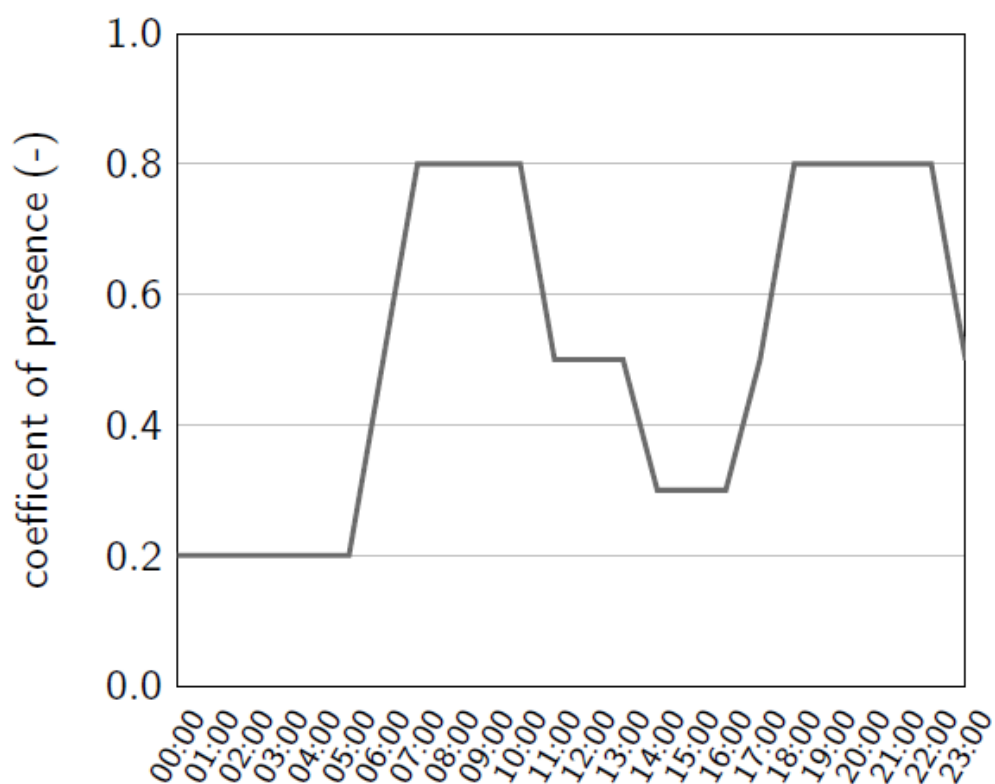


Figure S1.2: Coefficient of presence during weekdays for Valldidentro municipality

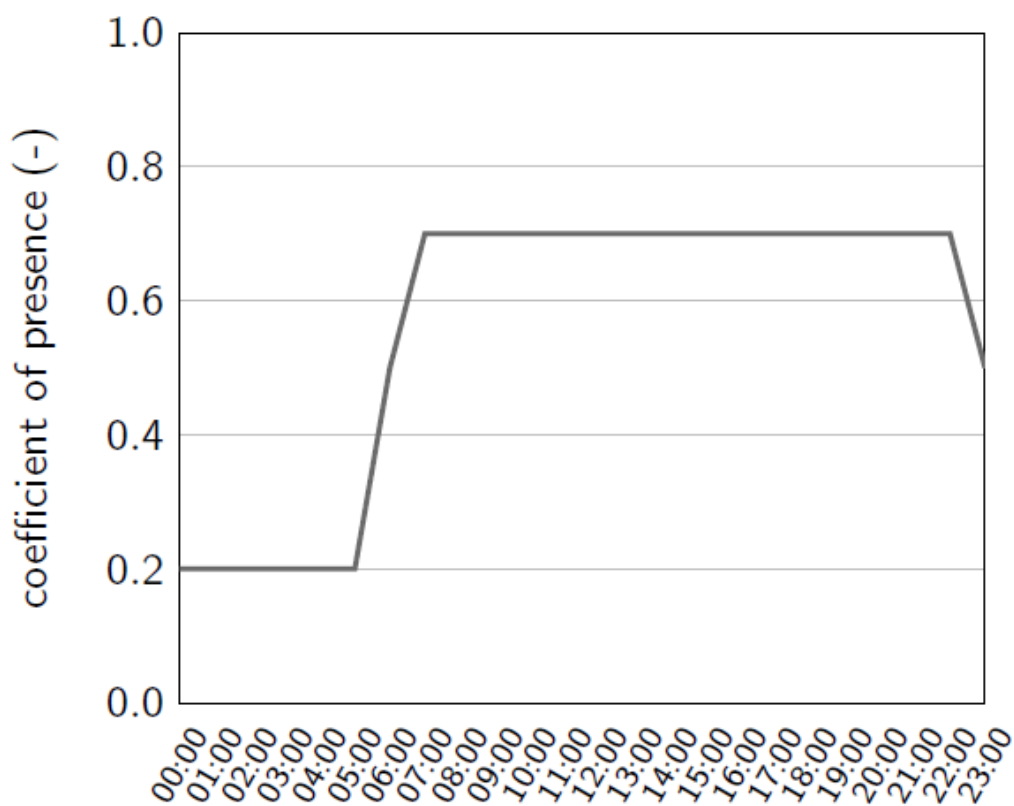


Figure S1.3: Coefficient of presence during weekends for Valldidentro municipality

Austrian case study: Lunz am See municipality



Figure S1.4: Localization of the urban area of Lunz am See municipality.

	Emissions [tons/year]			
	PM ₁₀	CO	SO ₂	NO _x
Lunz am See	3.96	173.58	3.61	6.11

Table S1.24: Total yearly emissions of Lunz am See (2010).

	PM ₁₀	CO	SO ₂	NO _x
Lunz am See	66%	88%	70%	21%

Table S1.25: Emissions of the macro-sector 7 compared to the total emissions.

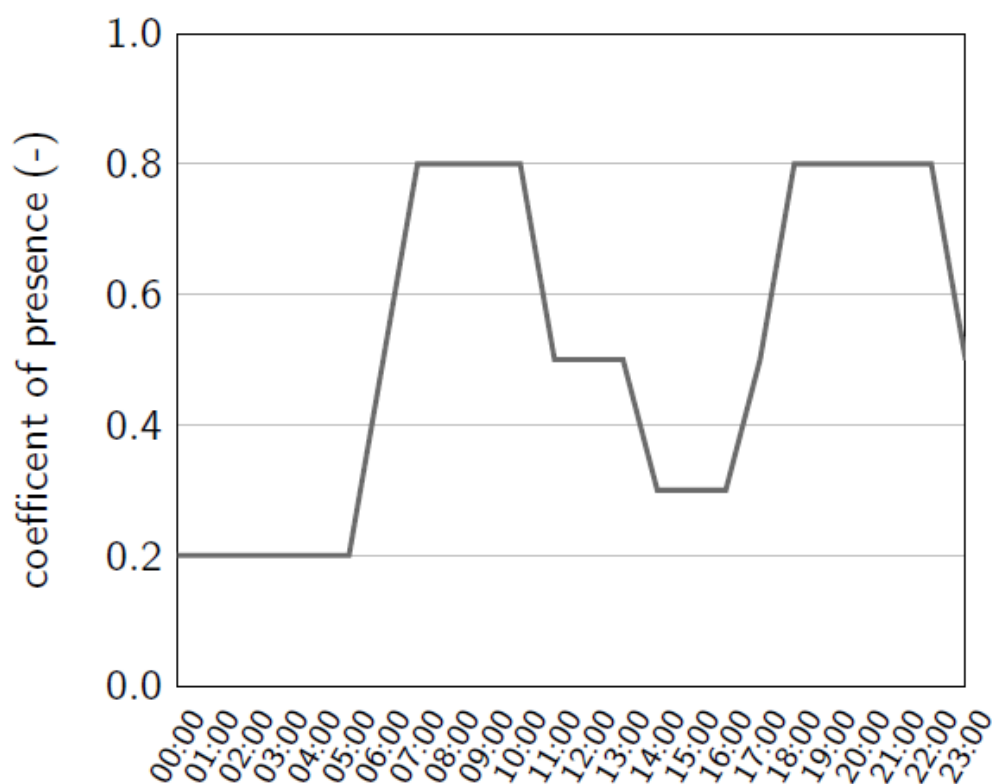


Figure S1.5: Coefficient of presence during weekdays for Lunz am See municipality

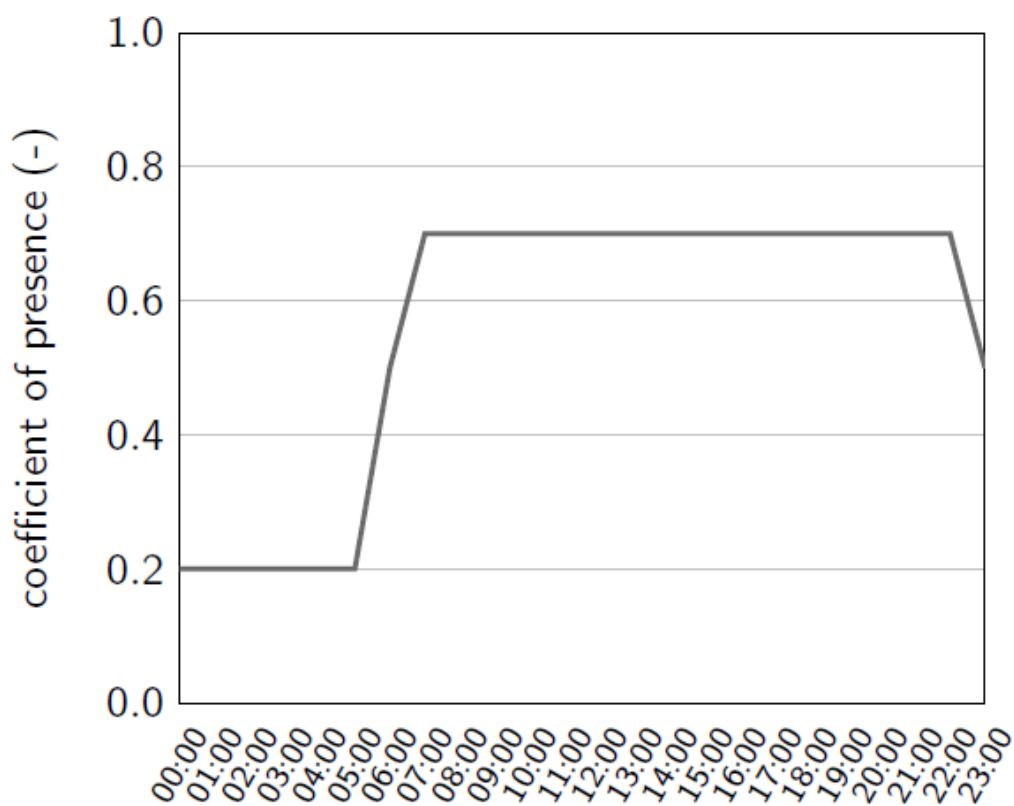


Figure S1.6: Coefficient of presence during weekend for Lunz am See municipality

References

- [1] Nussbaumer T, *Technische Energienutzung von Biomasse*. Thermochemische Verfahren: Verbrennung, Vergasung, Pyrolyse. Unterlagen zur Vorlesung an der ETH Zürich, Wintersemester 2000/01.
- [2] EN 14774-1 Determination of moisture content - Oven dry method Part 1: Total moisture- Reference method. (2010).
- [3] EN 15104 Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen – Instrumental methods. (2011).
- [4] EN 15289 Solid biofuels - Determination of total content of sulfur and chlorine. (2011).
- [5] EN 14775 Solid biofuels - Determination of ash content. (2009).
- [6] EN 14918 Solid biofuels - Determination of calorific value. (2010).

Supplementary material with CO, SO₂, PM₁₀ and NO₂ emission and concentration maps

Case studies of Valdidentro (IT) and Lunz am See (AT) Municipalities

(S2)

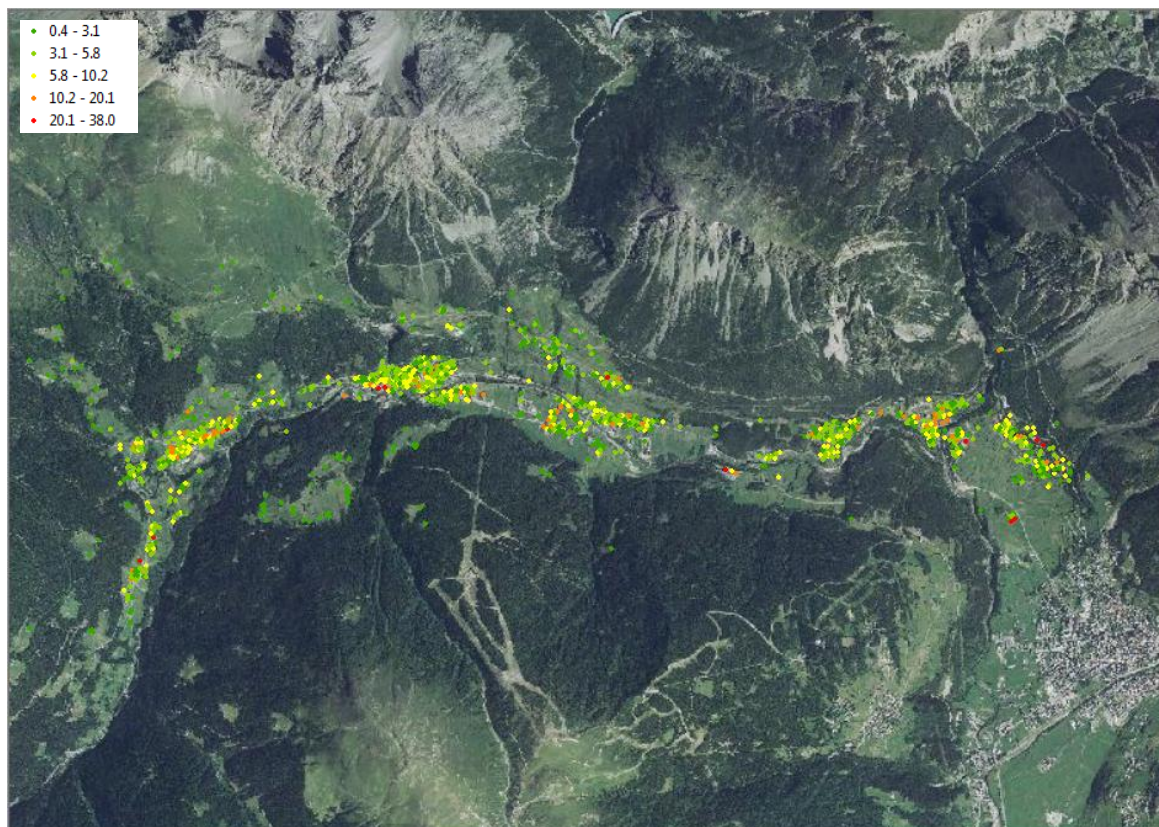


Figure S2.1: Valdidentro SO₂ emissions map (2010).

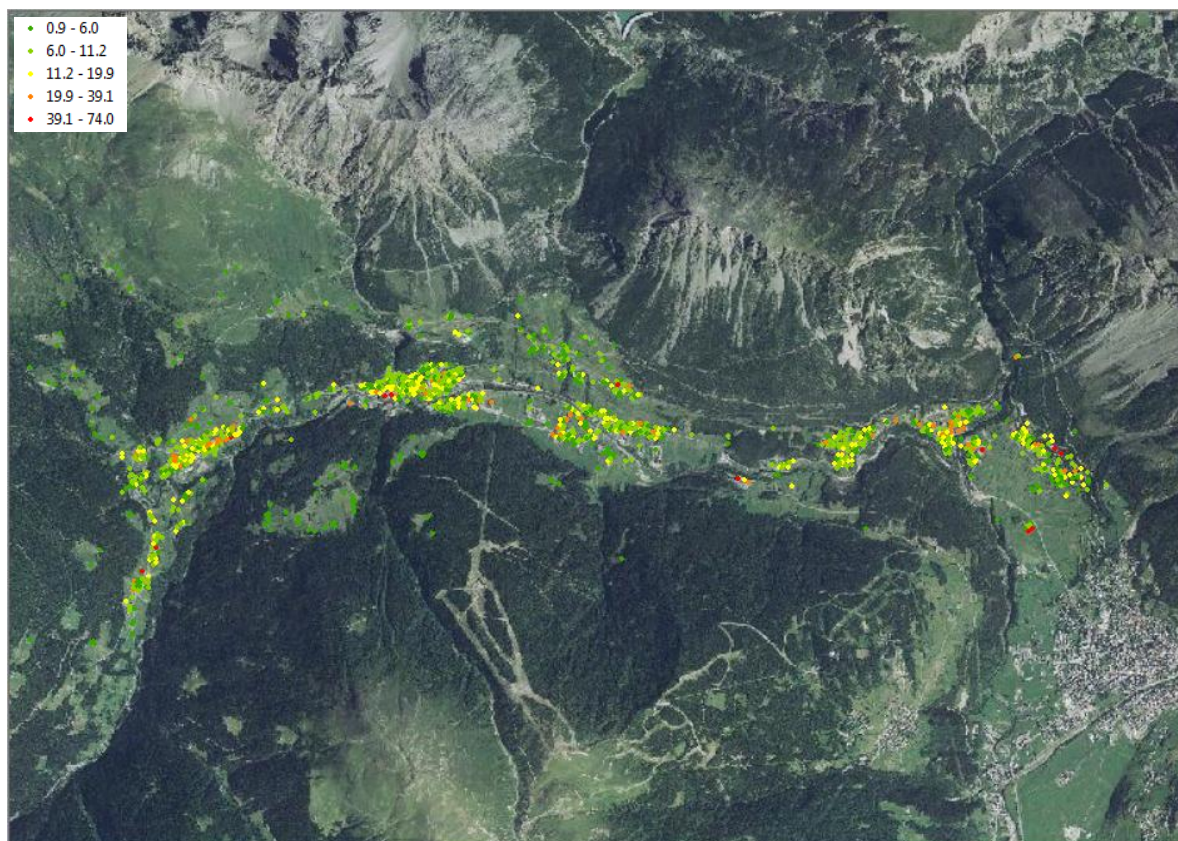


Figure S2.2: Valdidentro PM₁₀ emissions map (2010).

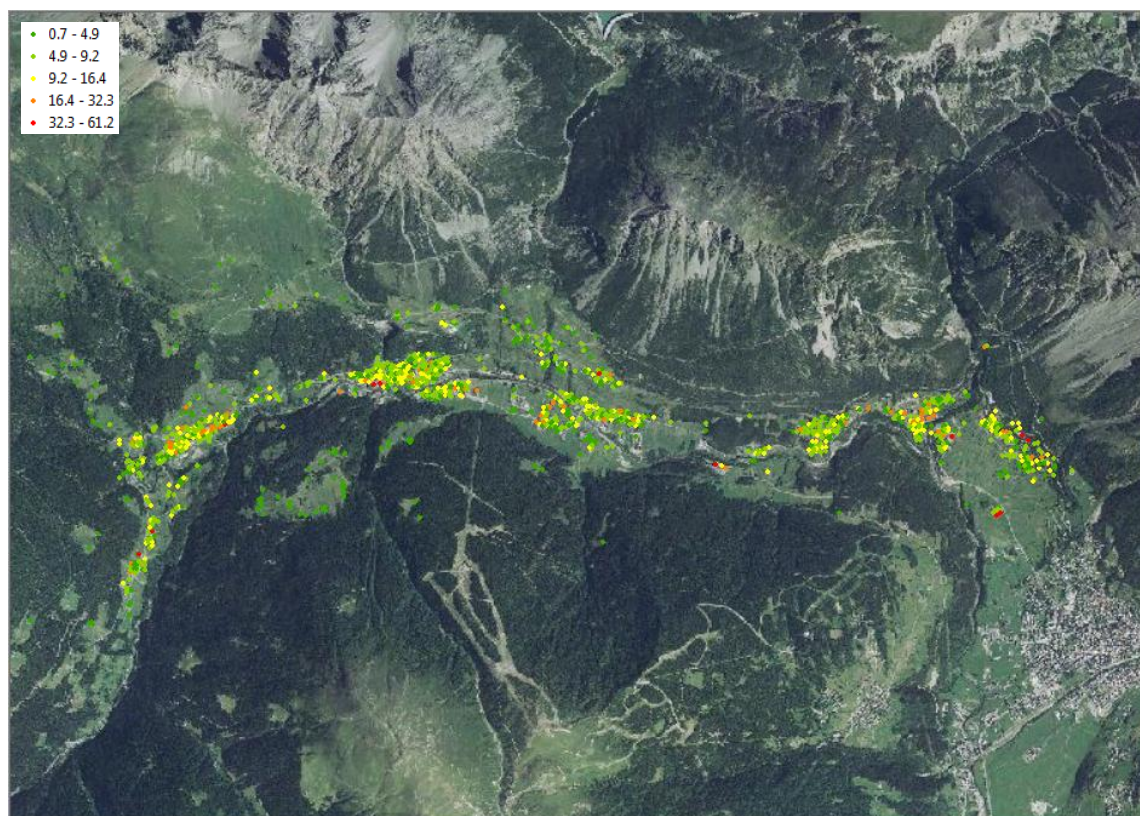


Figure S2.3: Valdidentro NO₂ emissions map (2010).

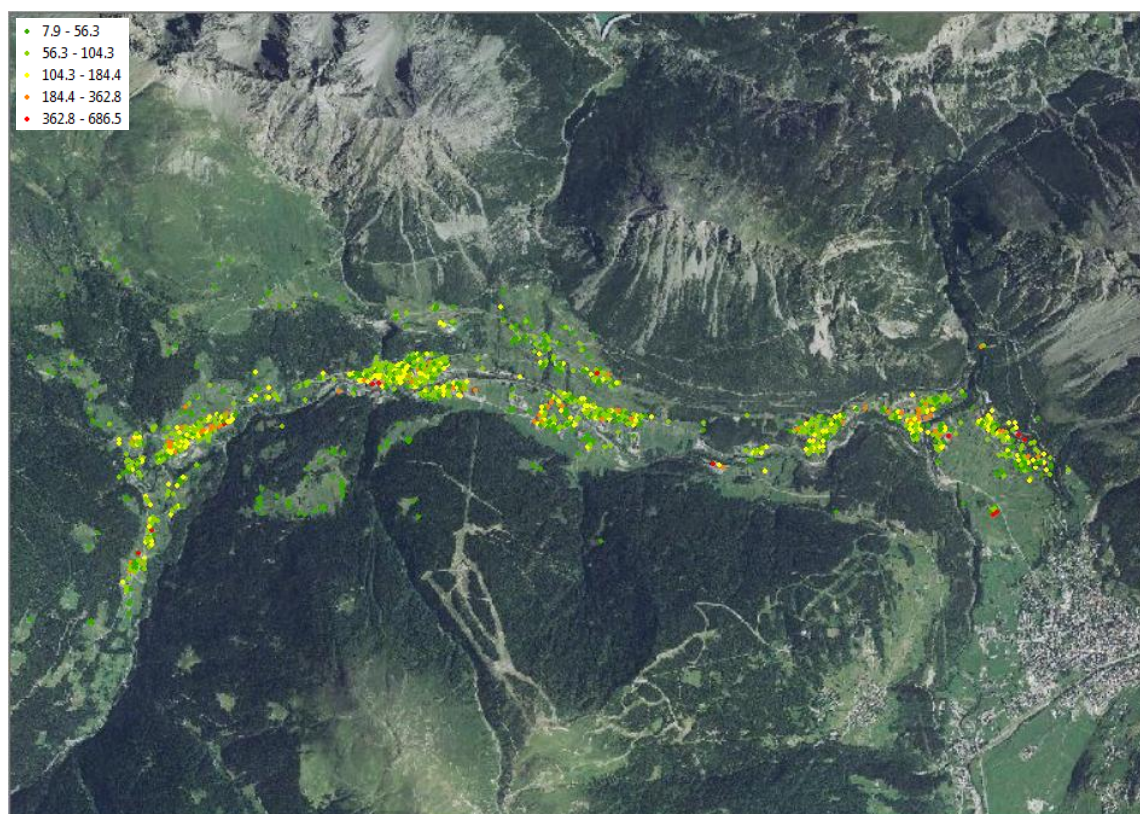


Figure S2.4: Valdidentro CO emissions map (2010).

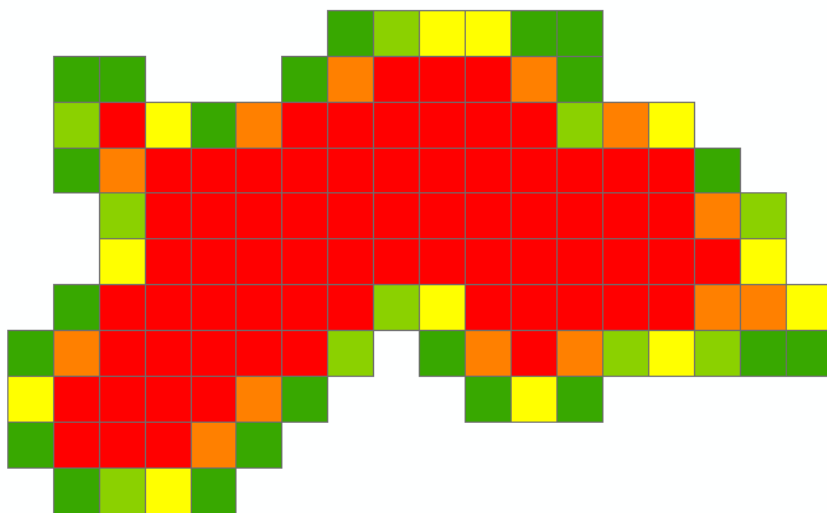


Figure S2.5: SO₂ yearly emissions map for Lunz am See (2010), tons/year.

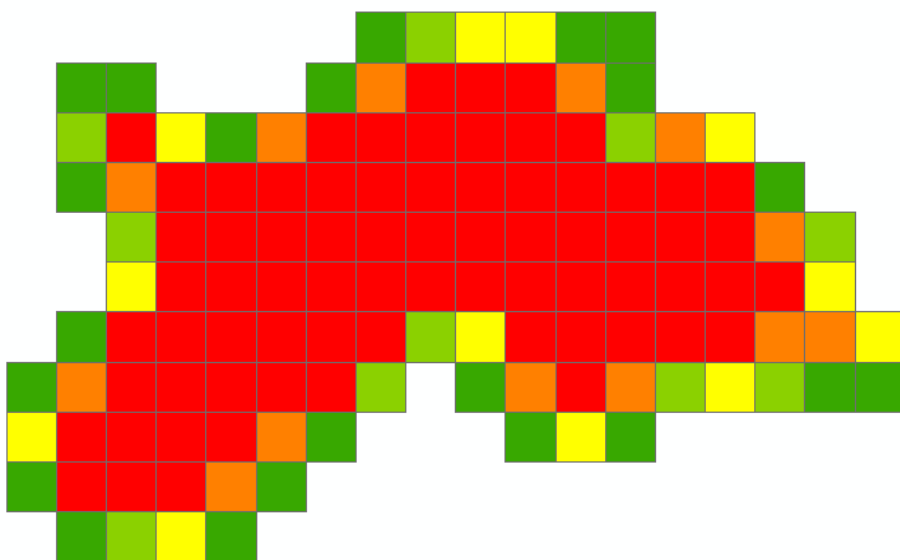


Figure S2.6: NO₂ yearly emissions map for Lunz am See (2010), tons/year.

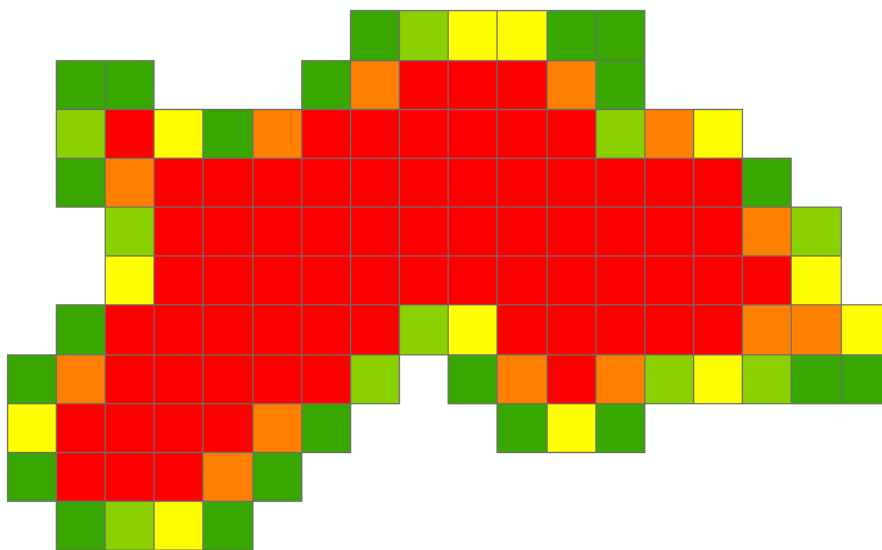


Figure S2.7: CO yearly emissions map for Lunz am See (2010), tons/year.

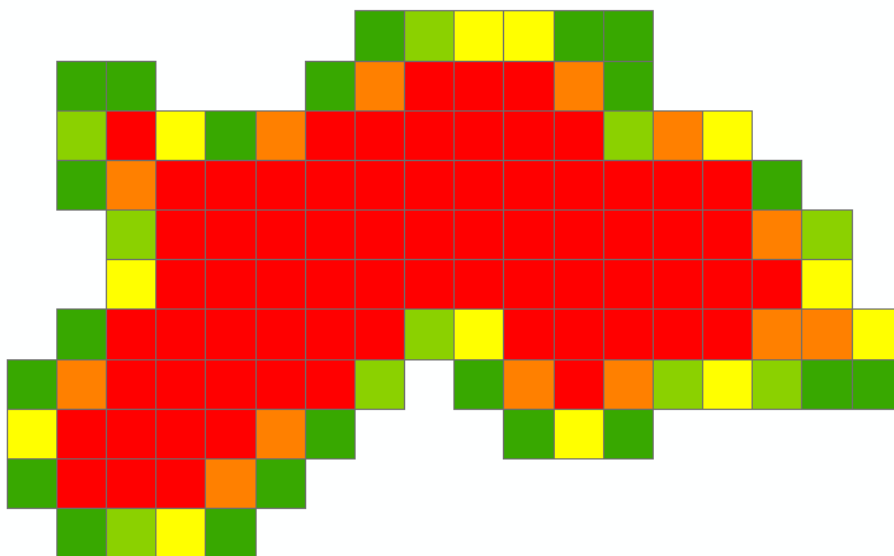
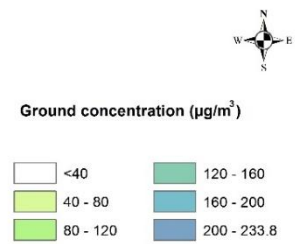
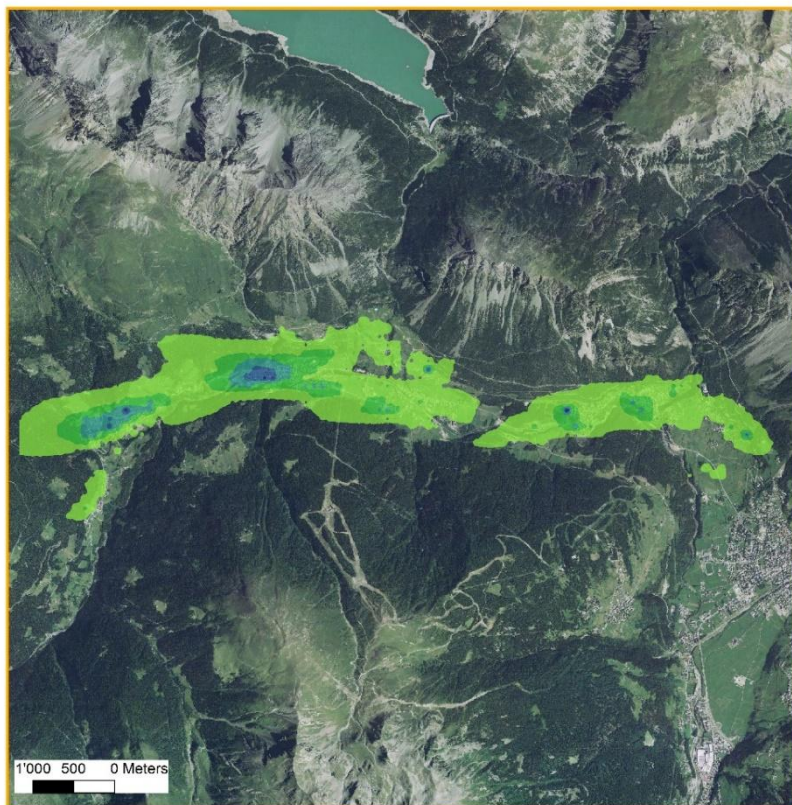
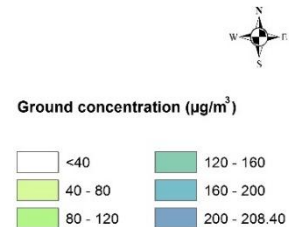
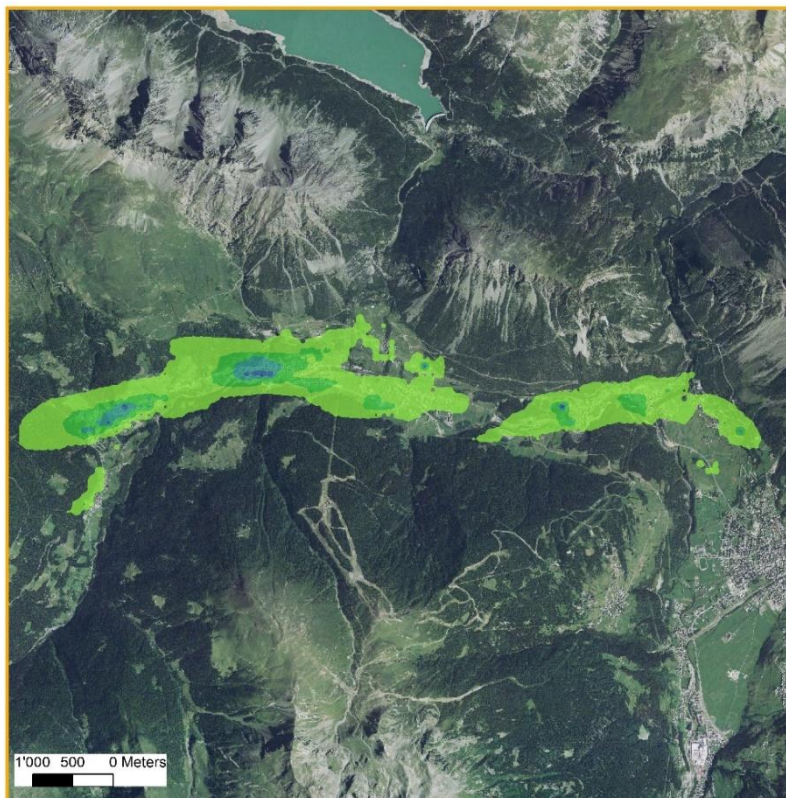


Figure S2.8: PM10 yearly emissions map for Lunz am See (2010), tons/year.



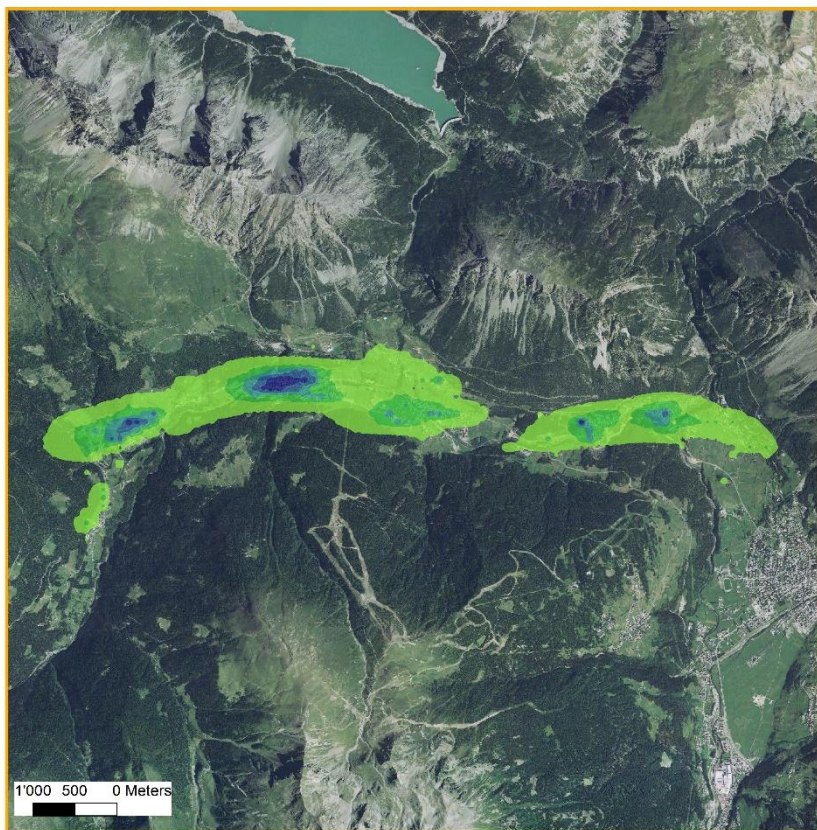
Case study Valldidentro	
Pollutant: CO	
Limit value: 10'000 $\mu\text{g}/\text{m}^3$	
Parameter: 8 Hours	
Scenario: Baseline	
October 2014	Table_08

Figure S2.9: Valldidentro: CO concentration map. Baseline scenario (2010). 8 hours basis.



Case study Valldidentro	
Pollutant: CO	
Limit value: 10'000 $\mu\text{g}/\text{m}^3$	
Parameter: 8 Hours	
Scenario: Replacement 2020	
October 2014	Table_16

Figure S2.10: Valldidentro: CO concentration map. Replacement scenario (2020). 8 hours basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.3	0.9 - 1.2
0.3 - 0.6	1.2 - 1.5
0.6 - 0.9	1.5 - 2.02

Case study Valdidentro

Pollutant: **NO₂**

Limit value: 40 $\mu\text{g}/\text{m}^3$

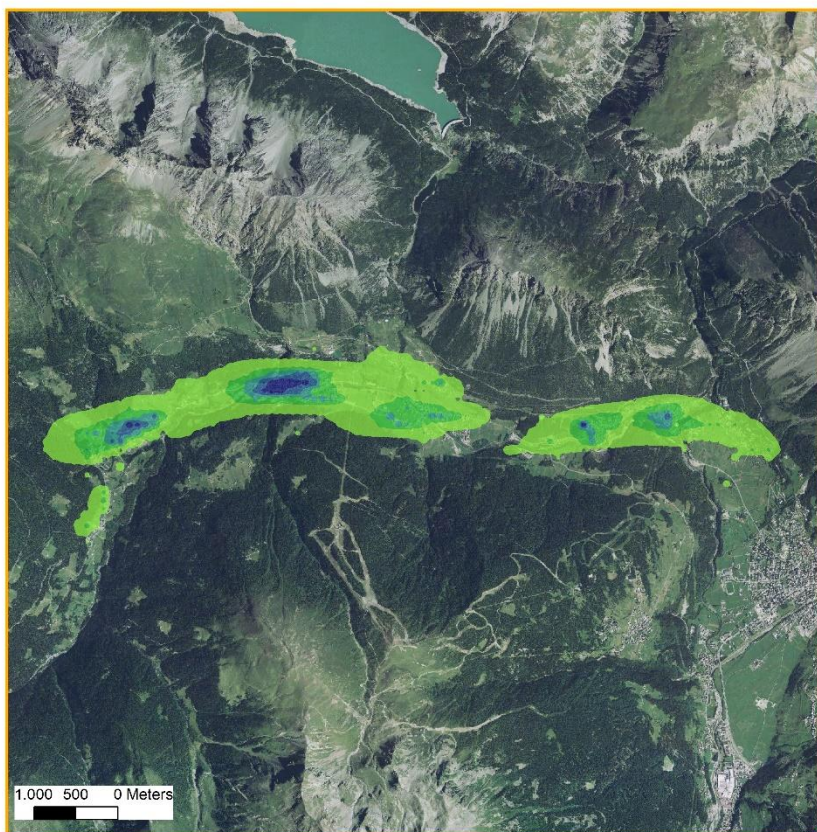
Parameter: **Year**

Scenario: **Baseline**

October 2014

Table_06

Figure S2.11: Valdidentro: NO₂ concentration map. Baseline scenario (2010). Yearly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.3	0.9 - 1.2
0.3 - 0.6	1.2 - 1.5
0.6 - 0.9	1.5 - 2.03

Case study Valdidentro

Pollutant: **NO₂**

Limit value: 40 $\mu\text{g}/\text{m}^3$

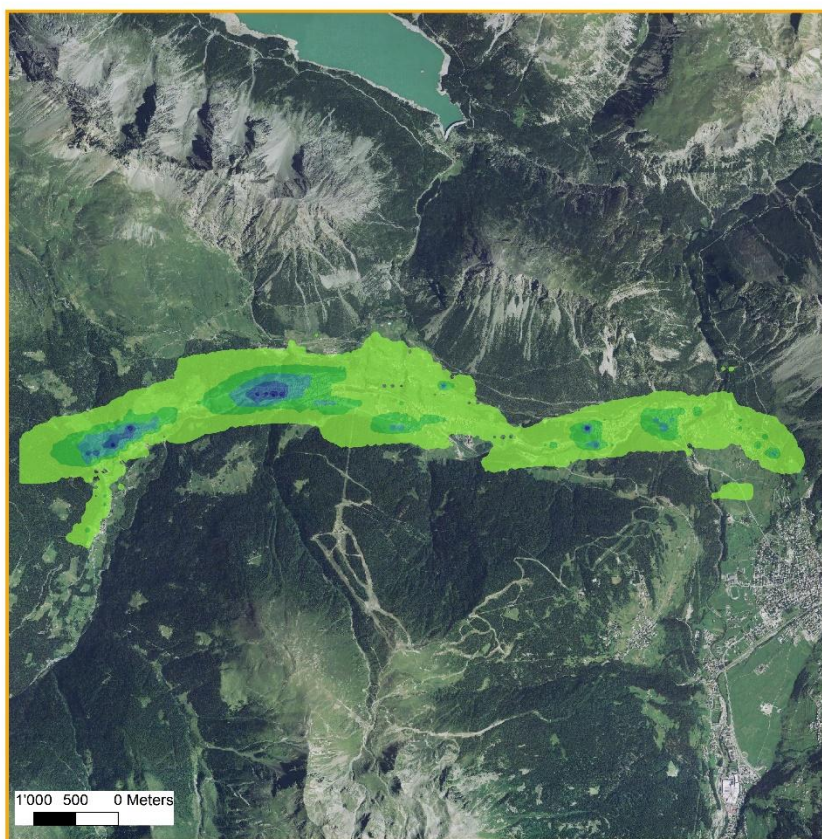
Parameter: **Year**

Scenario: **Replacement 2020**

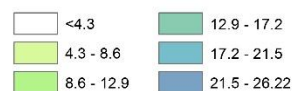
October 2014

Table_14

Figure S2.12: Valdidentro: NO₂ concentration map. Replacement scenario (2020). Yearly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: NO_2

Limit value: $200 \mu\text{g}/\text{m}^3$

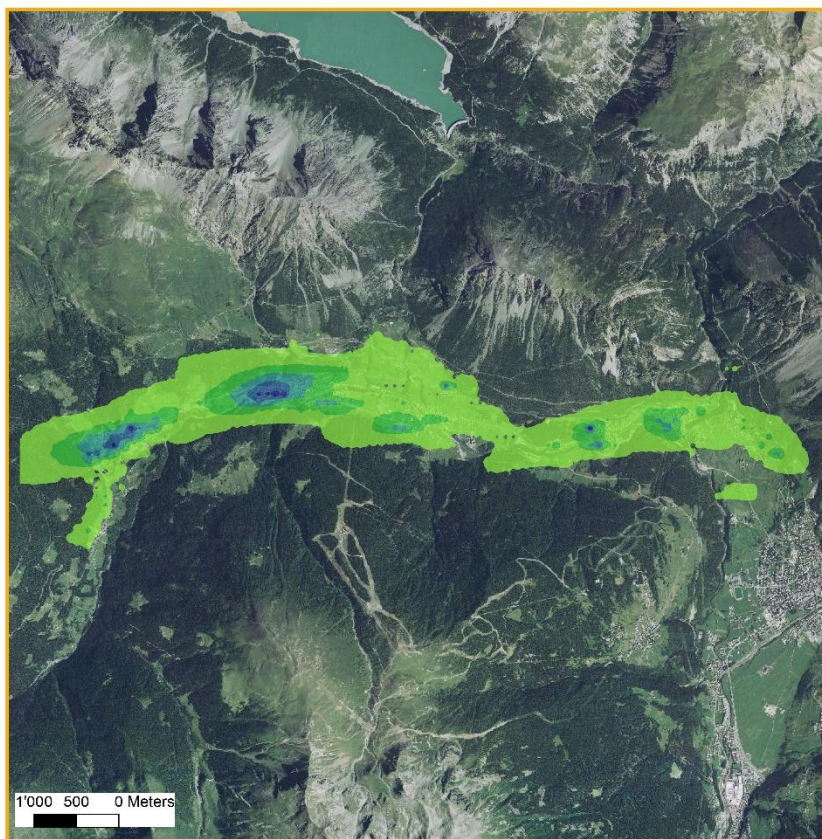
Parameter: Hour

Scenario: Baseline

October 2014

Table_07

Figure S2.13: Valdidentro: NO_2 concentration map. Baseline scenario (2010). Hourly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: NO_2

Limit value: $200 \mu\text{g}/\text{m}^3$

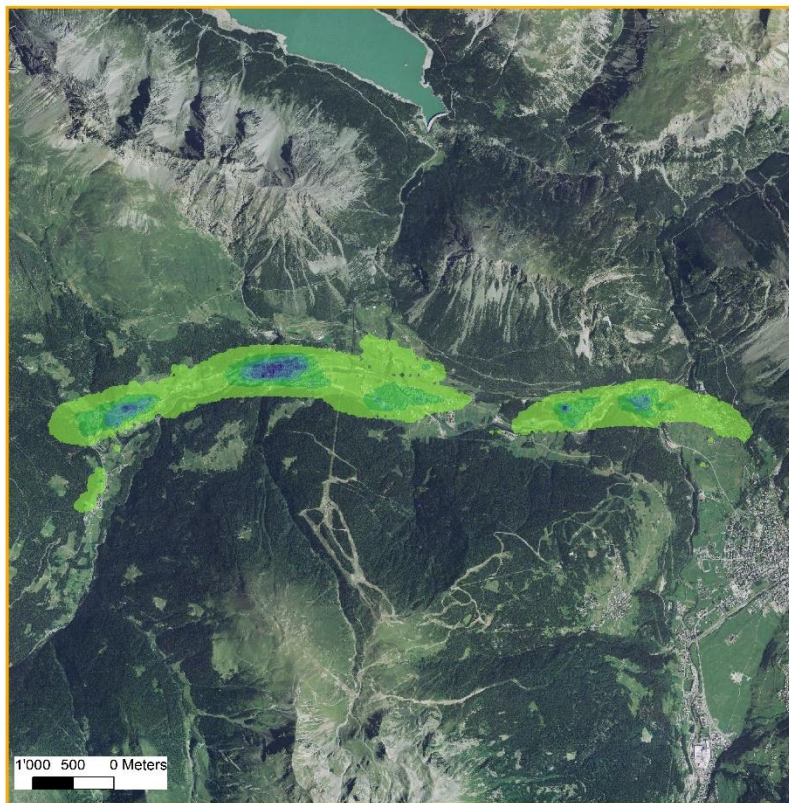
Parameter: Hour

Scenario: Replacement 2020

October 2014

Table_15

Figure S2.14: Valdidentro: NO_2 concentration map. Replacement scenario (2020). Hourly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: **PM₁₀**

Limit value: 40 $\mu\text{g}/\text{m}^3$

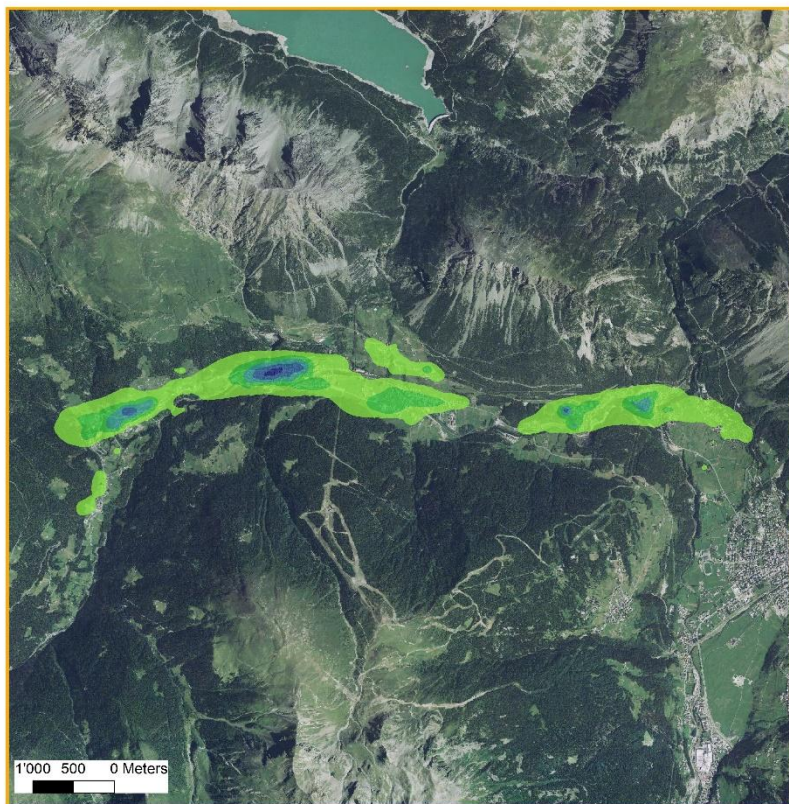
Parameter: **Year**

Scenario: **Baseline**

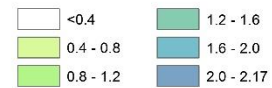
October 2014

Table_01

Figure S2.15: Valdidentro: PM10 concentration map. Baseline scenario (2010). Yearly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: **PM₁₀**

Limit value: 40 $\mu\text{g}/\text{m}^3$

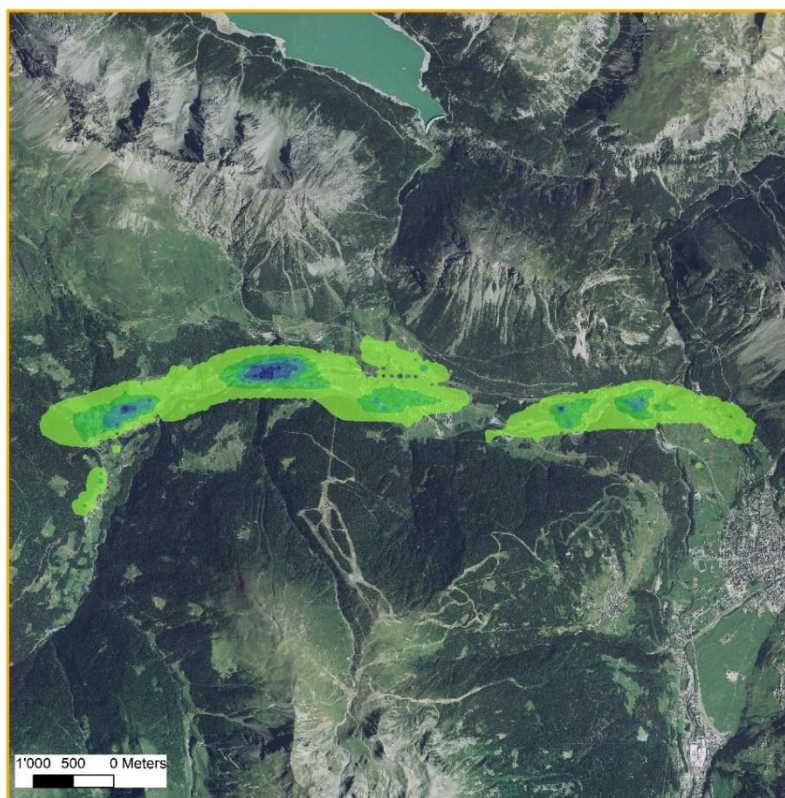
Parameter: **Year**

Scenario: **Replacement 2020**

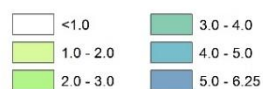
October 2014

Table_09

Figure S2.16: Valdidentro: PM10 concentration map. Replacement scenario (2020). Yearly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: **PM₁₀**

Limit value: 50 $\mu\text{g}/\text{m}^3$

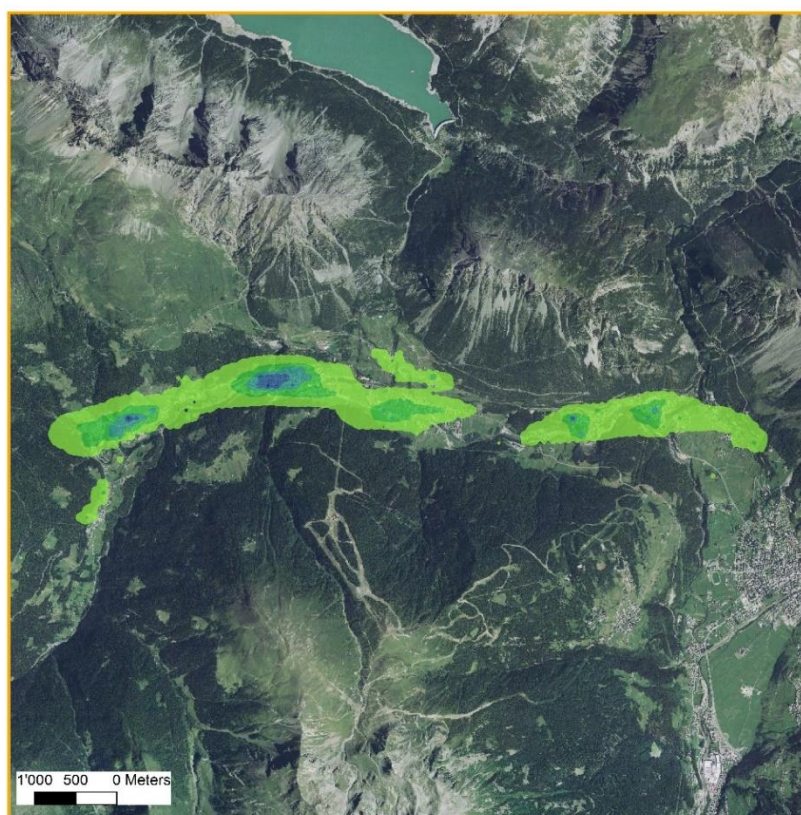
Parameter: **Day**

Scenario: **Baseline**

October 2014

Table_02

Figure S2.17: Valdidentro: PM10 concentration map. Baseline scenario (2010). Daily basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: **PM₁₀**

Limit value: 50 $\mu\text{g}/\text{m}^3$

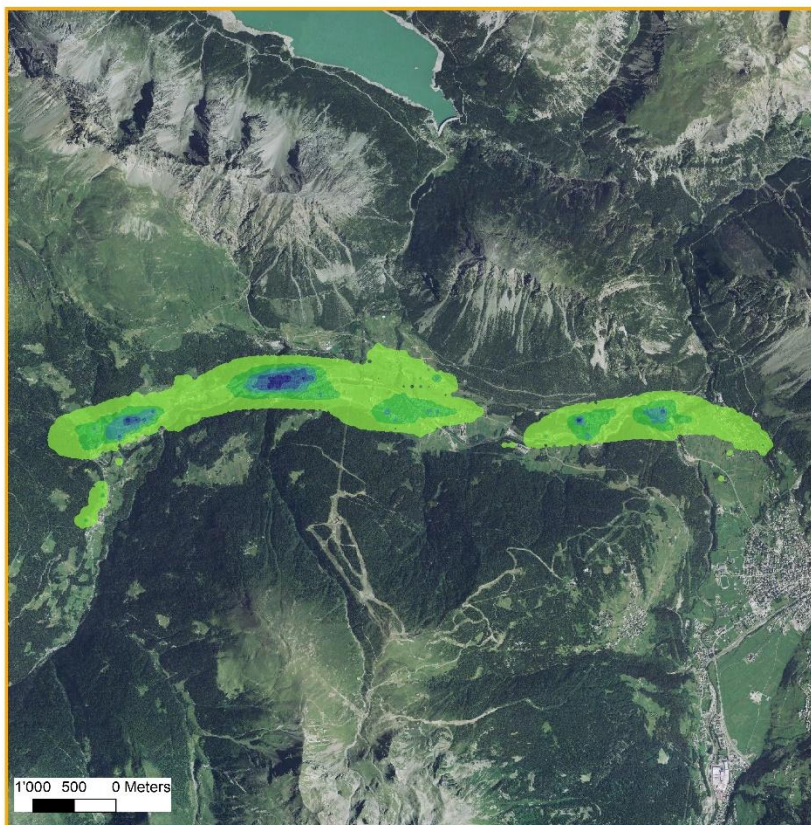
Parameter: **Day**

Scenario: **Replacement 2020**

October 2014

Table_10

Figure S2.18: Valdidentro: PM10 concentration map. Replacement scenario (2020). Daily basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: SO_2

Limit value: $20 \mu\text{g}/\text{m}^3$

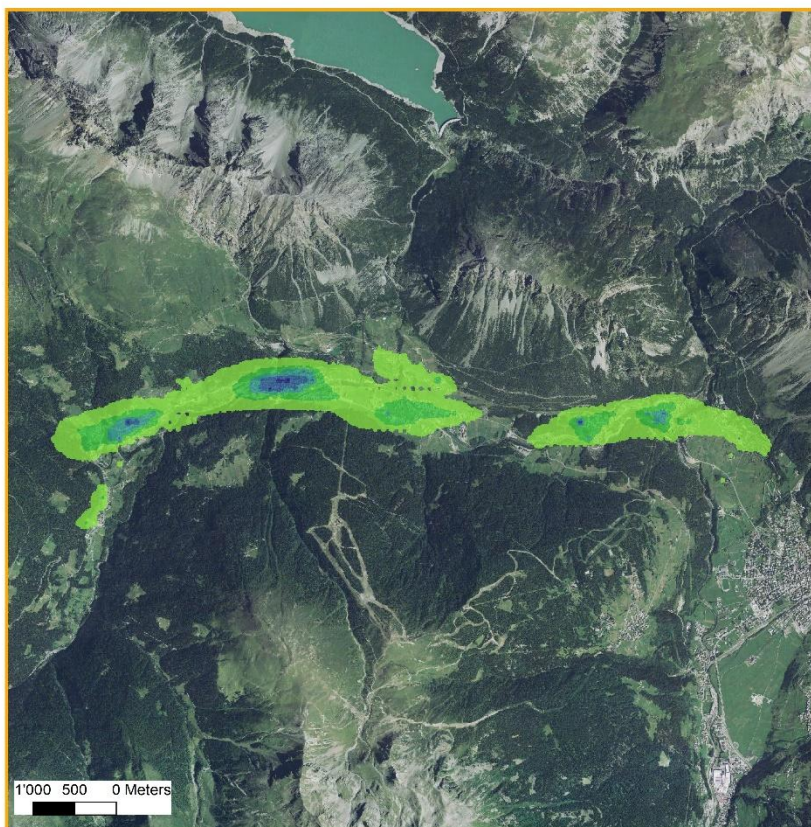
Parameter: Year

Scenario: Baseline

October 2014

Table_03

Figure S2.19: Valdidentro: SO_2 concentration map. Baseline scenario (2010) .Yearly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)



Case study Valdidentro

Pollutant: SO_2

Limit value: $20 \mu\text{g}/\text{m}^3$

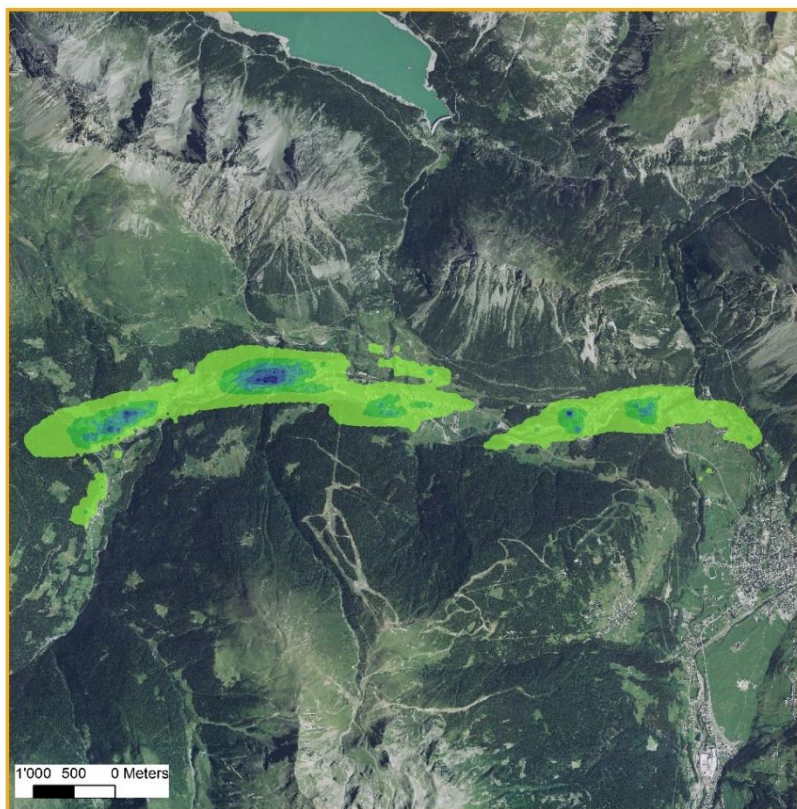
Parameter: Year

Scenario: Replacement 2020

October 2014

Table_11

Figure S2.20: Valdidentro: SO_2 concentration map. Replacement scenario (2020). Yearly basis.

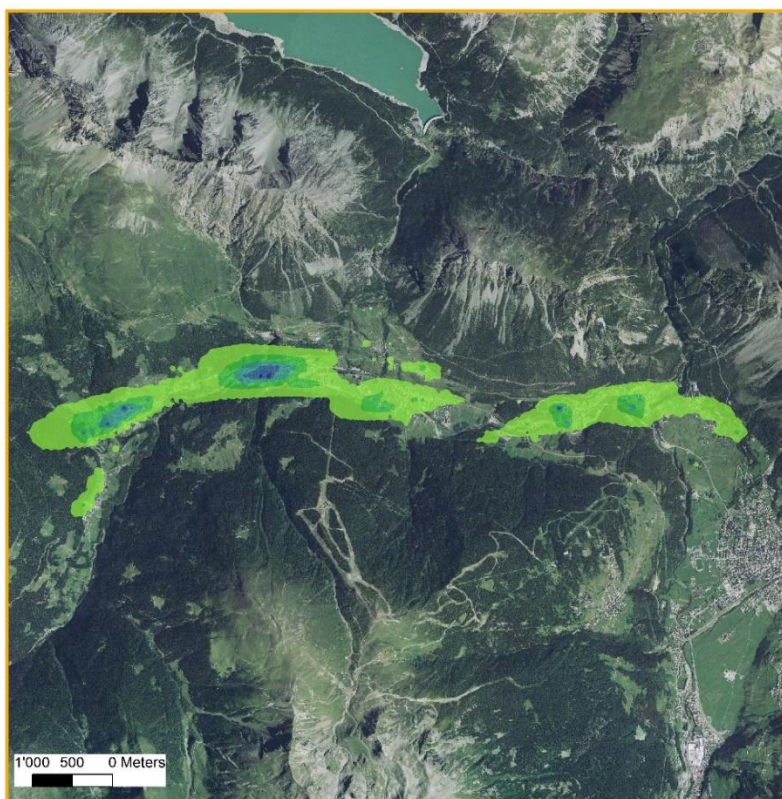


Ground concentration ($\mu\text{g}/\text{m}^3$)

<1.1	3.3 - 4.4
1.1 - 2.2	4.4 - 5.5
2.2 - 3.3	5.5 - 6.96

Case study Valdidentro	
Pollutant: SO_2	
Limit value: $125 \mu\text{g}/\text{m}^3$	
Parameter: Day	
Scenario: Baseline	
October 2014	Table_04

Figure S2.21: Valdidentro: SO_2 concentration map. Baseline scenario (2010). Daily basis.

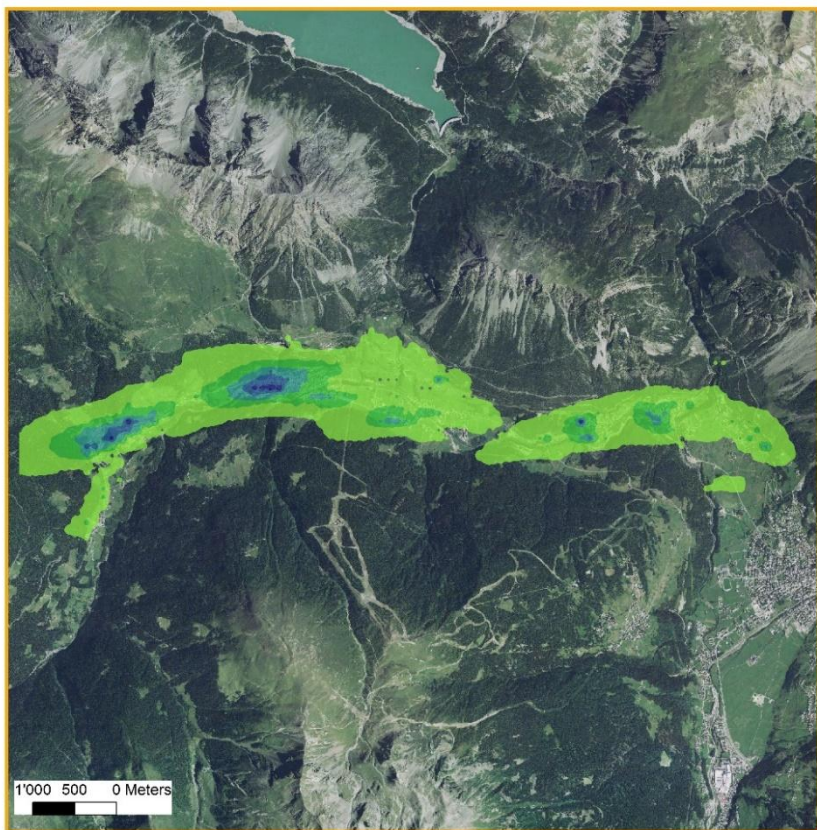


Ground concentration ($\mu\text{g}/\text{m}^3$)

<1.1	3.3 - 4.4
1.1 - 2.2	4.4 - 5.5
2.2 - 3.3	5.5 - 6.4

Case study Valdidentro	
Pollutant: SO_2	
Limit value: $125 \mu\text{g}/\text{m}^3$	
Parameter: Day	
Scenario: Replacement 2020	
October 2014	Table_12

Figure S2.22: Valdidentro: SO_2 concentration map. Replacement scenario (2020). Daily basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)

<2.5	7.5 - 10.0
2.5 - 5.0	10.0 - 12.5
5.0 - 7.5	12.5 - 15.74

Case study Valldidentro

Pollutant: SO_2

Limit value: $350 \mu\text{g}/\text{m}^3$

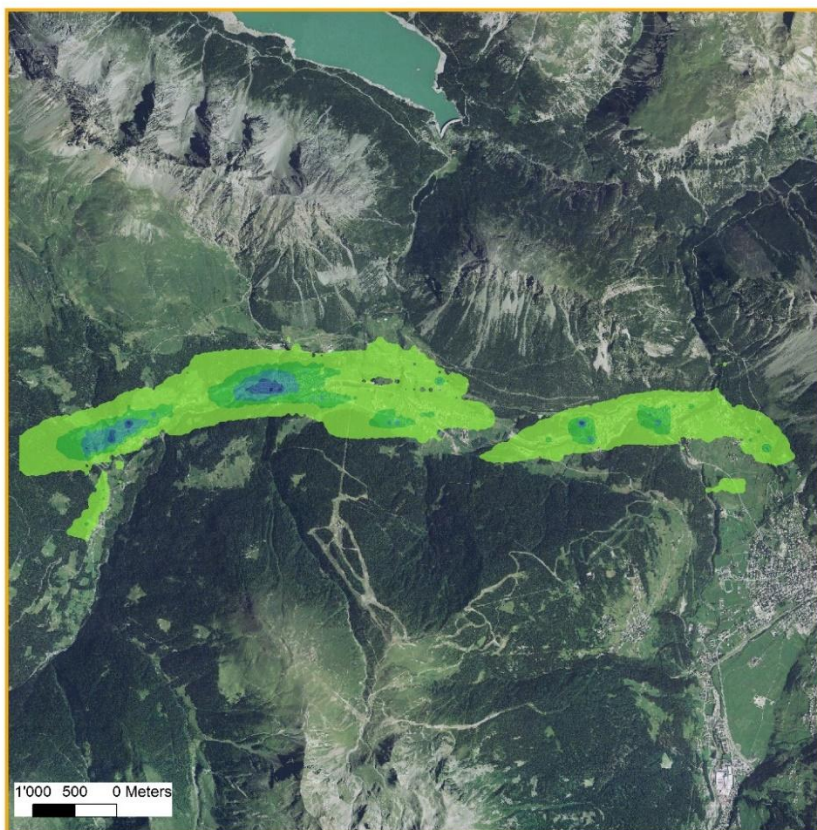
Parameter: Hour

Scenario: Baseline

October 2014

Table_05

Figure S2.23: Valldidentro: SO_2 concentration map. Baseline scenario (2010). Hourly basis.



Ground concentration ($\mu\text{g}/\text{m}^3$)

<2.5	7.5 - 10.0
2.5 - 5.0	10.0 - 12.5
5.0 - 7.5	12.5 - 14.42

Case study Valldidentro

Pollutant: SO_2

Limit value: $350 \mu\text{g}/\text{m}^3$

Parameter: Hour

Scenario: Replacement 2020

October 2014

Table_13

Figure S2.24: Valldidentro: SO_2 concentration map. Replacement scenario (2020). Hourly basis.

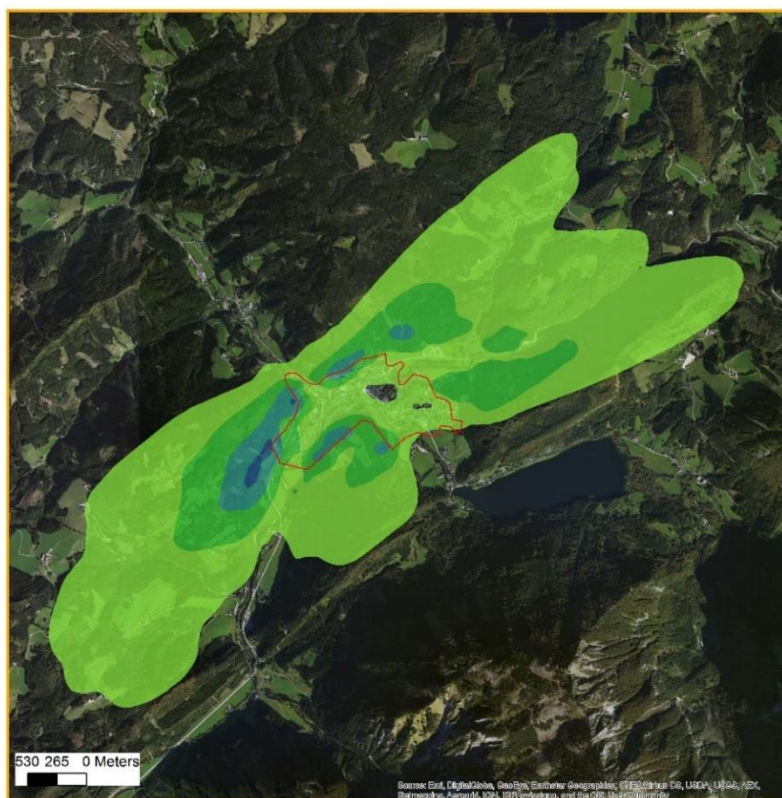


Figure S2.25:Lunz Am See: CO concentration map. Baseline scenario (2010). 8 hours basis.

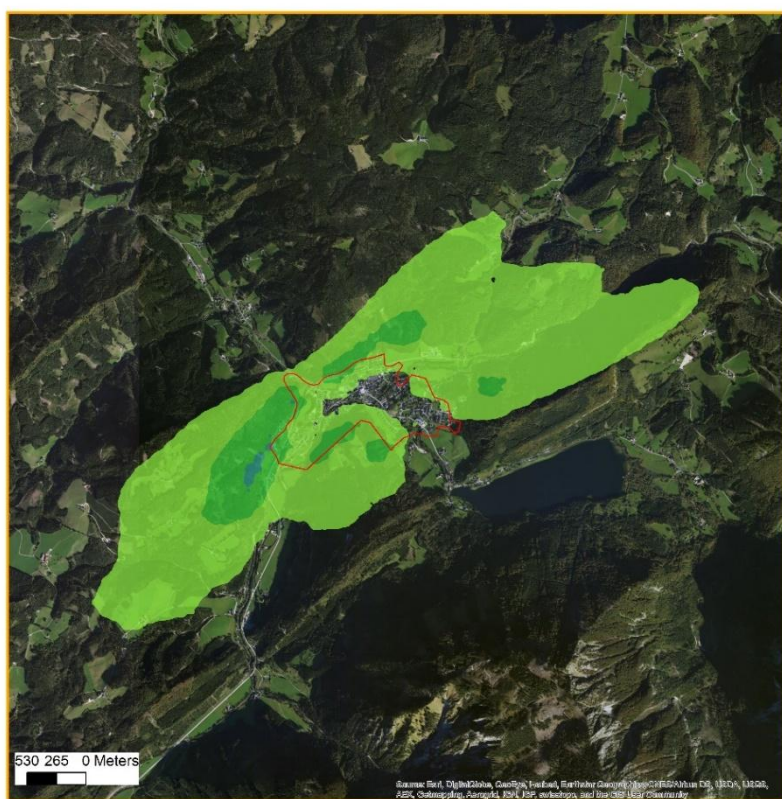


Figure S2.26: Lunz Am See: CO concentration map. Replacement scenario (2020). 8 hours basis.

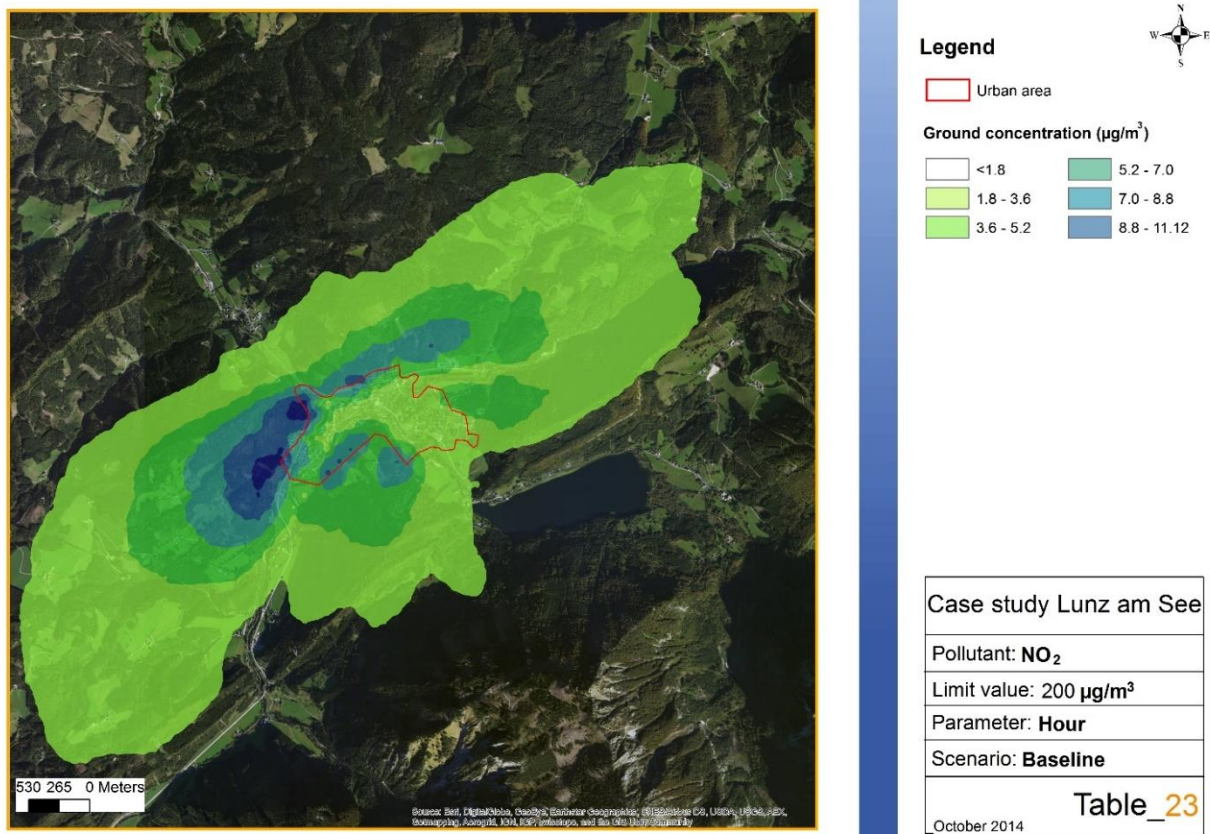


Figure S2.29: Lunz Am See: NO₂ concentration map. Baseline scenario (2010). Hourly basis.

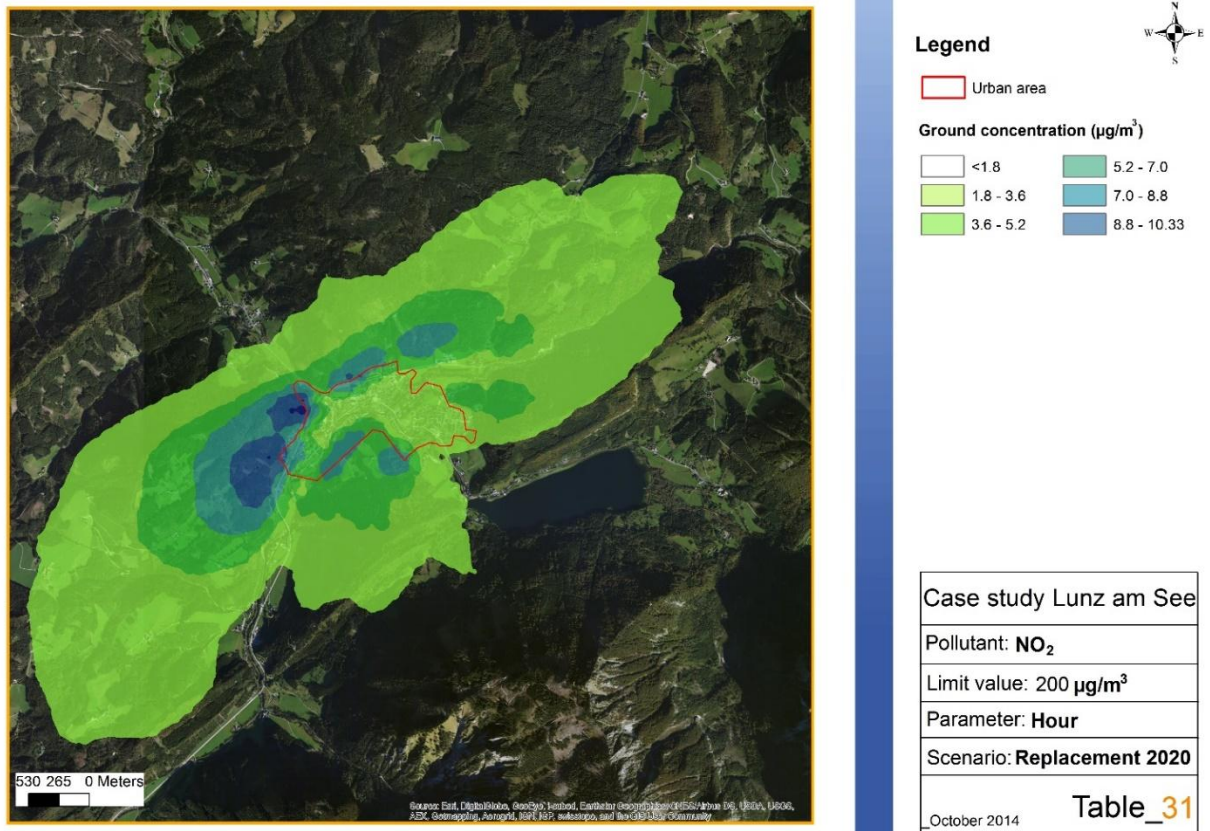
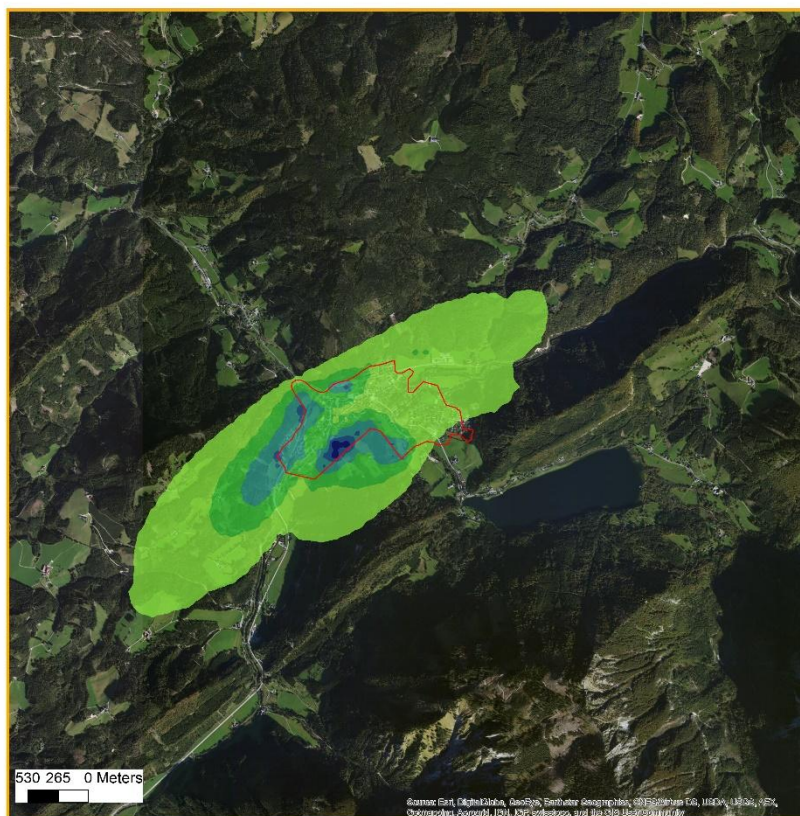


Figure S2.30: Lunz Am See: NO₂ concentration map. Replacement scenario (2020). Hourly basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.12	0.36 - 0.48
0.12 - 0.24	0.48 - 0.60
0.24 - 0.36	0.60 - 0.76



Case study Lunz am See

Pollutant: PM_{10}

Limit value: $40 \mu\text{g}/\text{m}^3$

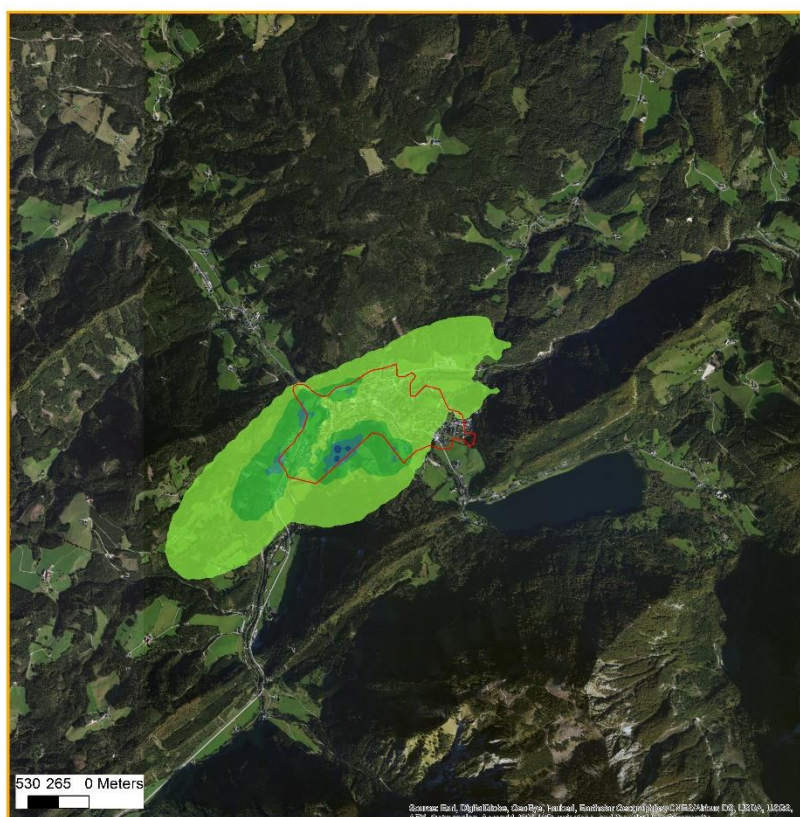
Parameter: Year

Scenario: Baseline

Table_17

_October 2014

Figure S2.31: Lunz Am See: PM10 concentration map. Baseline scenario (2010). Yearly basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.12	0.36 - 0.48
0.12 - 0.24	0.48 - 0.59
0.24 - 0.36	



Case study Lunz am See

Pollutant: PM_{10}

Limit value: $40 \mu\text{g}/\text{m}^3$

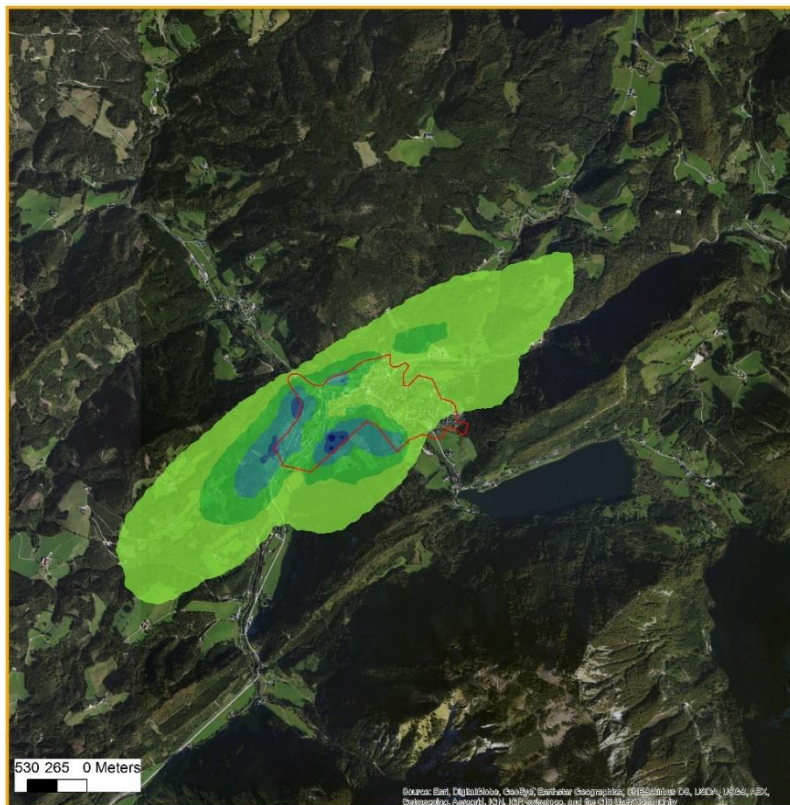
Parameter: Year

Scenario: Replacement 2020

Table_25

_October 2014

Figure S2.32: Lunz Am See: PM10 concentration map. Replacement scenario (2020). Yearly basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

 <0.3	 0.9 - 1.2
 0.3 - 0.6	 1.2 - 1.5
 0.6 - 0.9	 1.5 - 1.8



Case study Lunz am See

Pollutant: **PM₁₀**

Limit value: **50 $\mu\text{g}/\text{m}^3$**

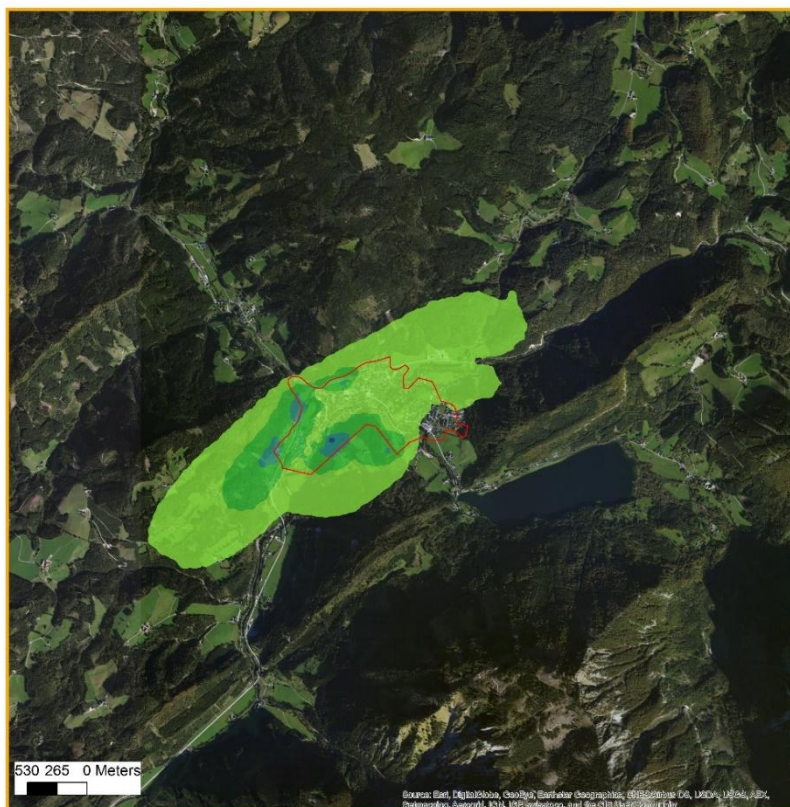
Parameter: **Day**

Scenario: **Baseline**

October 2014

Table_18

Figure S2.33: Lunz Am See: PM10 concentration map. Baseline scenario (2010). Daily basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

 <0.3	 0.9 - 1.2
 0.3 - 0.6	 1.2 - 1.39
 0.6 - 0.9	



Case study Lunz am See

Pollutant: **PM₁₀**

Limit value: **50 $\mu\text{g}/\text{m}^3$**

Parameter: **Day**

Scenario: **Replacement 2020**

October 2014

Table_26

Figure S2.34: Lunz Am See: PM10 concentration map. Replacement scenario (2020). Daily basis.

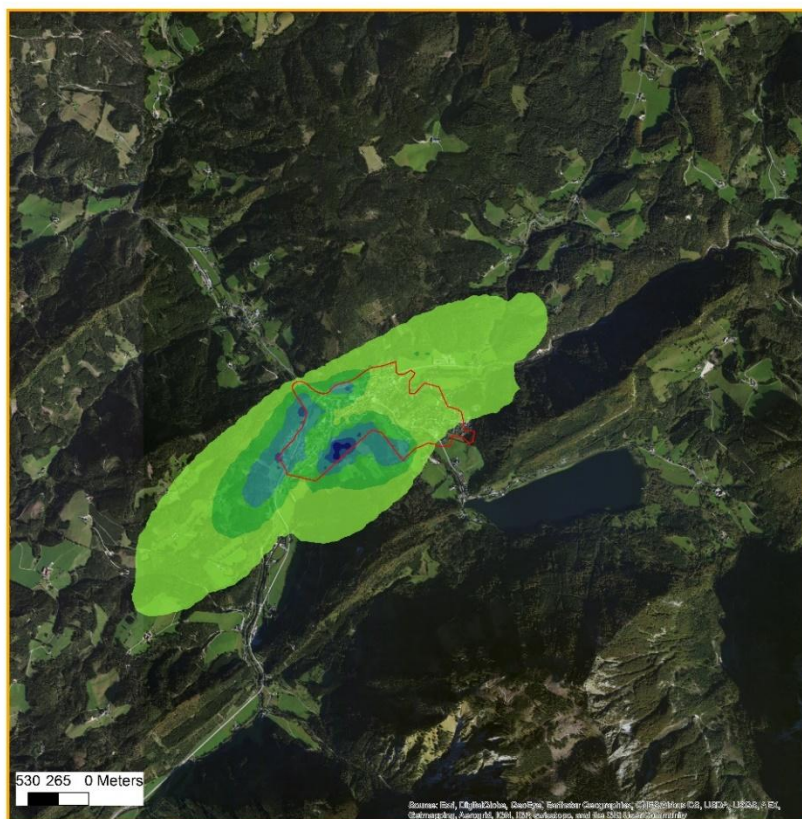


Figure S2.35: Lunz Am See: SO₂ concentration map. Baseline scenario (2010) .Yearly basis.

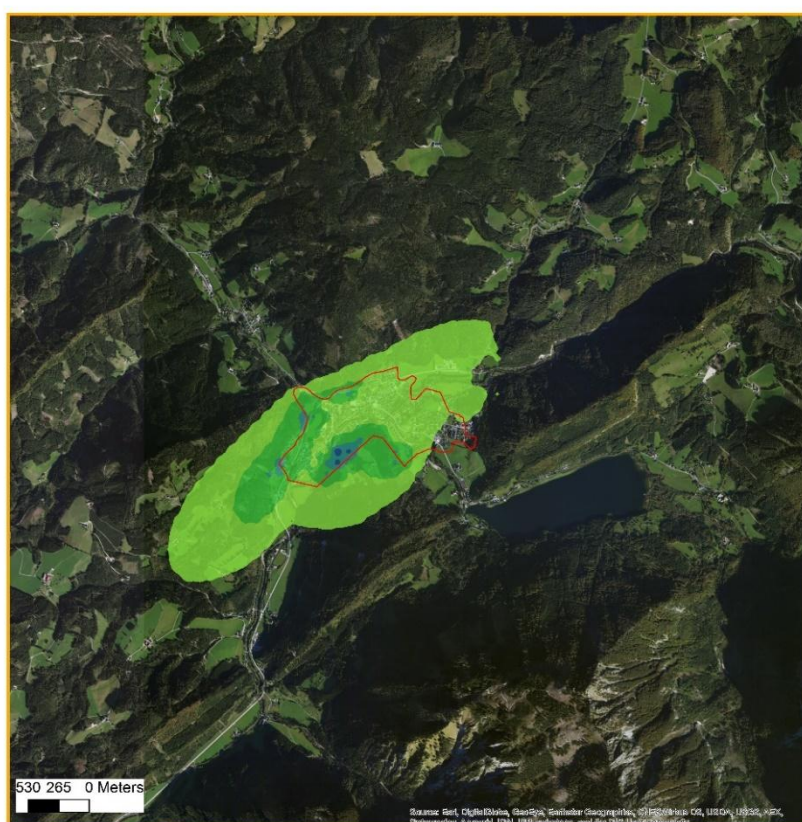
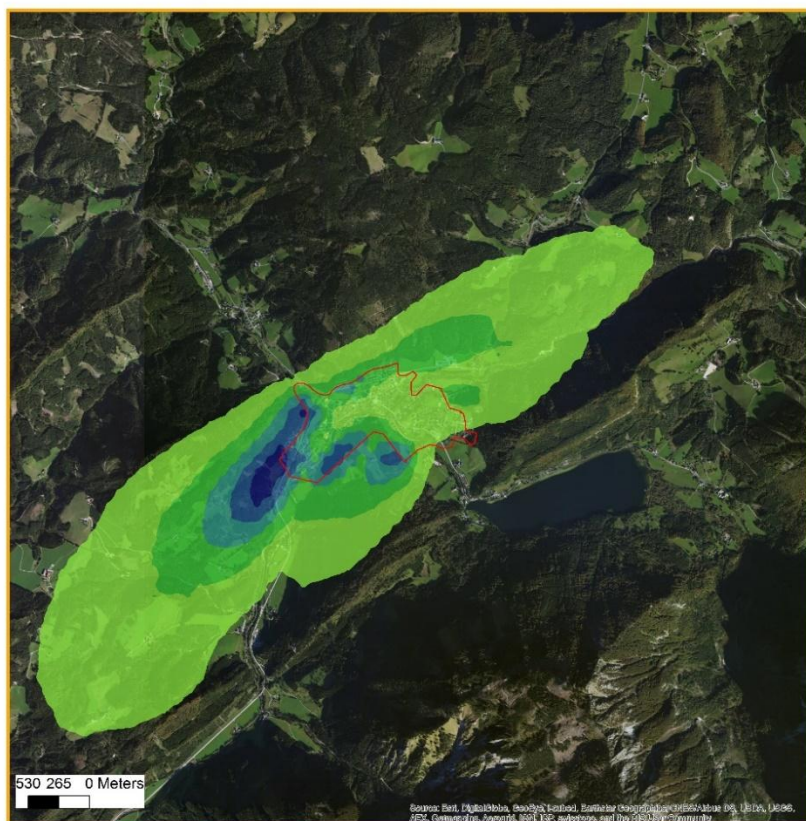


Figure S2.36: Lunz Am See: SO₂ concentration map. Replacement scenario (2020). Yearly basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.4	1.2 - 1.6
0.4 - 0.8	1.6 - 2.0
0.8 - 1.2	2.0 - 2.52



Case study Lunz am See

Pollutant: SO_2

Limit value: $125 \mu\text{g}/\text{m}^3$

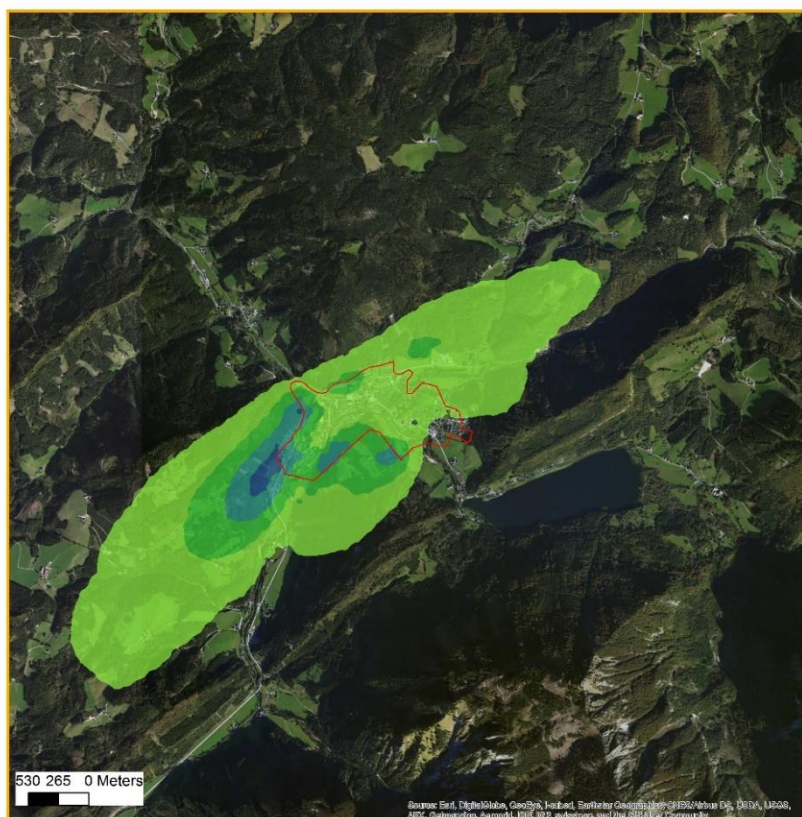
Parameter: Day

Scenario: Baseline

October 2014

Table_20

Figure S2.37: Lunz Am See: SO_2 concentration map. Baseline scenario (2010). Daily basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<0.4	1.2 - 1.6
0.4 - 0.8	1.6 - 1.93
0.8 - 1.2	



Case study Lunz am See

Pollutant: SO_2

Limit value: $125 \mu\text{g}/\text{m}^3$

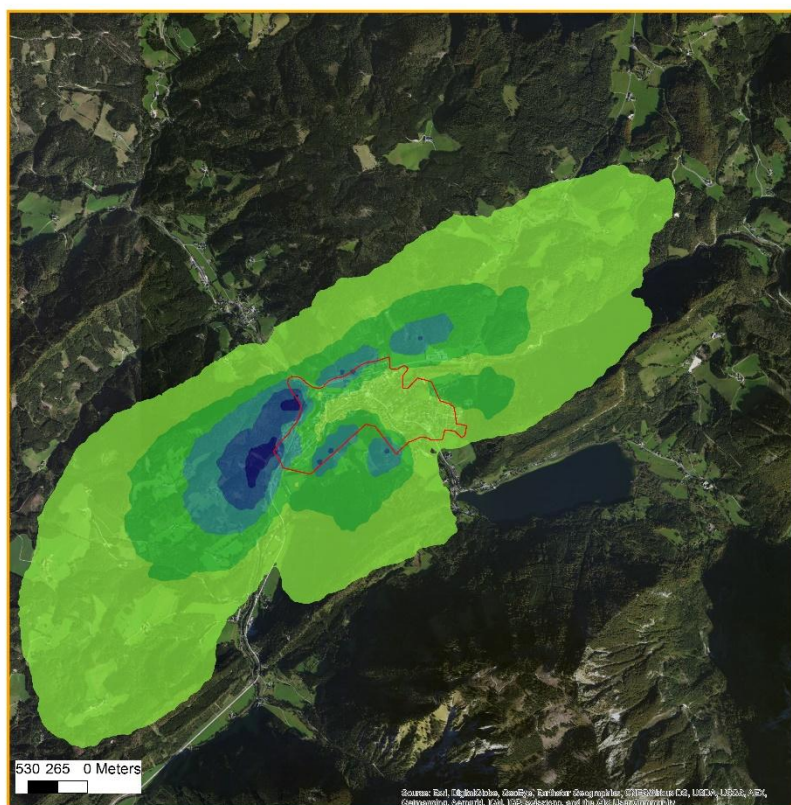
Parameter: Day

Scenario: Replacement 2020

October 2014

Table_28

Figure S2.38: Lunz Am See: SO_2 concentration map. Replacement scenario (2020). Daily basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<1.0	3.0 - 4.0
1.0 - 2.0	4.0 - 5.0
2.0 - 3.0	5.0 - 6.28



Case study Lunz am See

Pollutant: SO_2

Limit value: $350 \mu\text{g}/\text{m}^3$

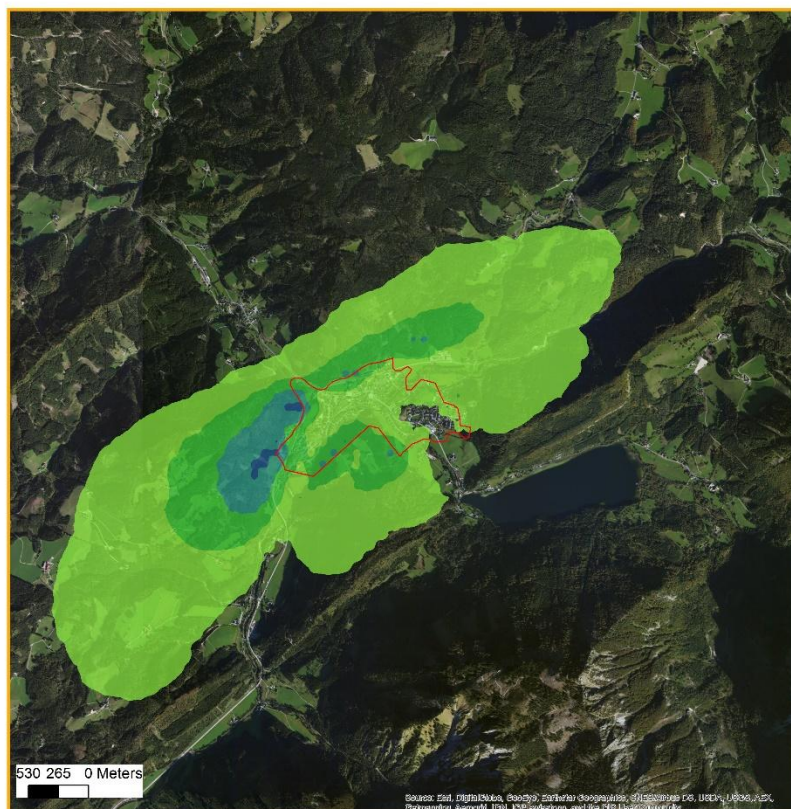
Parameter: Hour

Scenario: Baseline

October 2014

Table_21

Figure S2.39: Lunz Am See: SO_2 concentration map. Baseline scenario (2010). Hourly basis.



Legend

Urban area

Ground concentration ($\mu\text{g}/\text{m}^3$)

<1.0	3.0 - 4.0
1.0 - 2.0	4.0 - 4.83
2.0 - 3.0	



Case study Lunz am See

Pollutant: SO_2

Limit value: $350 \mu\text{g}/\text{m}^3$

Parameter: Hour

Scenario: Replacement 2020

October 2014

Table_29

Figure S2.40: Lunz Am See: SO_2 concentration map. Replacement scenario (2020). Hourly basis.