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Design, Modelling and Assessment of Emission Scenarios Resulting from a Network of Wood Biomass Boilers

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Abstract The use of wood biomass as a fuel for domestic and industrial heating systems allows for a reduction of CO_2 emissions at a global scale, but it may also result in worse local air quality conditions, due to their emissions of particulate matter. The aim of this study is to assess the actual trend of atmospheric pollution in a study area, assuming that all heating systems are replaced by small size biomass boilers linked to the buildings through district heating network. Ground level concentrations of particulate matter, emitted by different heating systems, are therefore evaluated through numerical simulations performed by means of an atmospheric dispersion model (Sirane). As a first step, we have compared the environmental impact of a woodchip boilers network with that given by the use of traditional heating systems, i.e. wood stoves and natural gas boilers. As a second step, we have analysed the impact of such a network taking into account different emission scenarios, related to different boilers operating conditions. Results show that the environmental performances of a woodchip boilers network can be optimized by combining it with other renewable sources of energy devoted to the supply of hot water. The adopted analysis methodology can be applied to other real or hypothetic punctual sources on the territory.

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1 Introduction

The global consumption of energy produced from renewable sources is progressively increasing year after year [1]. Notably, a sharp increase of consumption concerns the wood biomass, since its costs are highly competitive compared to other sources of energy, especially for domestic heating [2, 3].

An environmentally sustainable use of this energy source depends mainly on a correct exploitation of the forest resources and on the control of atmospheric pollutant emissions. Assuming that the timber consumption is suitably regulated by the forest management policies [4], the environmental impact of these systems is almost fully related to pollutant emissions in the atmosphere. Replacing fossil fuels with wood biomass certainly reduce the total CO_2 emissions on a global scale [5], but may result in higher emissions of particulate matter (PM) [6], PAHs [7] and COVs [8], and therefore worse air quality conditions at the local scale.

There are two main pollutant emissions related to the use of wood biomass as a fuel. One is related to the release of combustion products from the heating systems, the other to the release of pollutant from vehicles transporting the wood. Therefore, large heating systems are clearly not sustainable in regions where the timber availability is limited [9], such as Alpine territories, since their adoption would require the transportation of huge amount of fuel, which would imply relevant vehicular pollutant emissions due to transport. In these conditions, smaller systems can be adopted instead, as far as their need can be supplied by the timber coming from the surrounding territory. Today, the use of reduced size

Table 1 Emission factors for wood and natural gas [23, 24]

Fuel	Traded forms	Aggregate emission factors (mg/kWh)									
		CO_2	N_2O	NO_X	CO	NMVOC	SO_2	PM_{10}	$PM_{2.5}$	PAH	PCB
Wood and similar	Average value	3.33E + 05	5.04E + 01	2.20E + 02	1.94E + 04	2.29E + 03	4.59E + 01	1.45E + 03	1.44E + 03	7.80E − 01	2.16E − 04
	Wood, chips, spruce			4.58E + 02	2.71E + 02			1.12E + 01			
	Pellet, spruce			2.92E + 02	6.14E + 01			3.97E + 01			
	Log wood, beech			5.23E + 02	6.68E + 03			3.34E + 02			
Natural gas		2.04E + 05	3.60E + 00	1.25E + 02	8.99E + 01	1.80E + 01		7.19E − 01	7.19E − 01		

systems is currently increasing in Alpine regions [10]. In a perspective of a subvention (and consequent spreading) of wood heating systems to replace traditional fuels, the environmental impact of these heating systems must be taken into account.

Theirs impacts, which are very different from case to case, can be very difficult to quantify a priori, so that their assessment requires specific procedures [11]. This largely depends on the technology adopted in the design of the system, as well as on the other factors characterising the whole supply chain on a given territory.

The woody biomass is essentially made of cellulose (42–50%) and lignin (22–28%), with a varying percentage of mineral elements, depending on the substrate on which the tree grows. With ideal combustion conditions, i.e. the fuel is completely oxidised, combustion products are mainly CO_2, H_2O, with slight traces of NO_X, SO_2 and some other compounds, depending on the chemical composition of the wood and its eventual contamination (by ashes, sulphur, Cu, Pb, Zn and Cd [12]). Without a complete oxidation of the wood, its combustion can generate PM, CO, organic compounds, as well as high emissions of nitrogen oxides [13, 14]. This motivates the implementation of new technologies aiming in improving the combustion conditions.

The influence of the fuel characteristics on the quantity and composition of the emissions has been the subject of several studies [15, 16]. In general, the emissions depend on the type of timber, on the size of the wood pieces and on their moisture content. The solid nature of the fuel and its resulting lack of uniformity can result in local conditions of oxygen deficiency or low temperature in the combustion chamber. The ignition phase and the low-load functioning are particularly critical for the emission of unburned substances. Therefore, the biomass boiler is connected to an accumulation tank, in order to minimize fluctuations due to variations in user requests.

Several studies analysed the actual influence of these systems on air quality [17, 18], mainly focusing on the PM concentrations, given their well-known impact on human health [19, 20]. The suitability of the adoption of these systems has therefore to be carefully evaluated in regions where atmospheric PM concentrations are significant. This issue can be found in the Po Valley and all the neighbouring Alpine valleys [21]. These areas present critical air quality conditions which can be further worsened if other pollutants sources are added [22].

The objective of the present study is the assessment of the impacts of a network of wood biomass heating systems located within an Alpine valley in the north of Italy. We analyse the effects of emission scenarios due to a replacement of the entire traditional natural-gas heating system with small to medium size biomass boilers. The analysis focuses on PM and NO_X concentrations in air and aims in comparing the environmental impacts of woodchip boilers, traditional stoves and natural gas boilers.

2 Materials and Methods

2.1 Definition of the Emission Scenarios

The definition of a realistic emission scenario first requires the estimate of the emissions factors for wood and natural gas which are given in Table 1. PM emissions of natural gas systems are considered as negligible, as a first approximation [25, 26].

Values in Table 1 have to be considered as reference averaged values, taking account any kind of technological solution currently adopted in the conception of wood heating systems. These therefore include also traditional systems, such as woodstoves and fireplaces, whose emissions are known to be particularly high [27]. Nevertheless, modern wood chip plants are characterised by lower emission values [28], although not yet comparable with the emissions from natural gas boilers (see Table 1).

Note that, when considering the impact of wood heating systems, we also need to take into account emissions from the

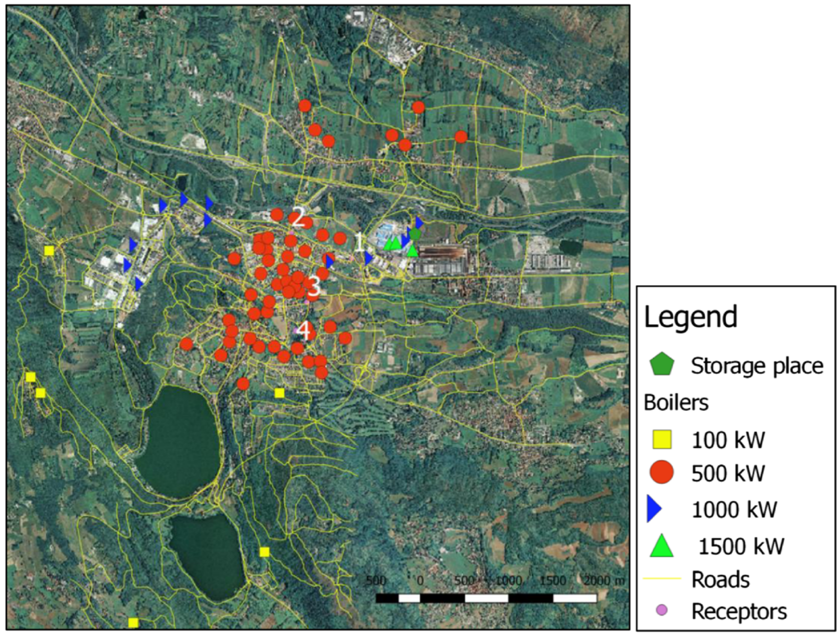

Fig. 1 Location and power of point and linear sources, i.e. the wood biomass boilers and road network considered for calculating the emissions of the transport means

transport phase, whose estimate require specific emission factors of heavy goods vehicles [29].

Once identified these emission factors, the scenario was designed based on the following hypotheses:

- Substitution of the entire fossil fuel heating network with wood biomass boilers linked to the buildings through a district heating network.
- Heat demand determined by both residential and industrial buildings.
- Emissions due to biomass boilers and to the vehicles supplying wood, only.
- Unlimited availability of timber in the surrounding area.
- The entire building is characterized by a same average energy class.
- Typology of boilers are given by Best Available Technology (BAT) solutions.

This scenario is based on a simplifying assumption: decoupling the sizing of the boilers from the actual availability of wood in the surrounding areas. We stress that, in view its effective implementation, a sustainable design of the network requires it to be dimensioned avoiding a depletion of the local forest resources [30].

The main objective of the supply chain is to diversify the uses of timber to reduce as much as possible the waste production. The woodworking industry usually discards timber without optimal characteristics, such as treetops and branches. Therefore, the best quality timber is sent to the sawmill and used as a building material. The chipping process allows,

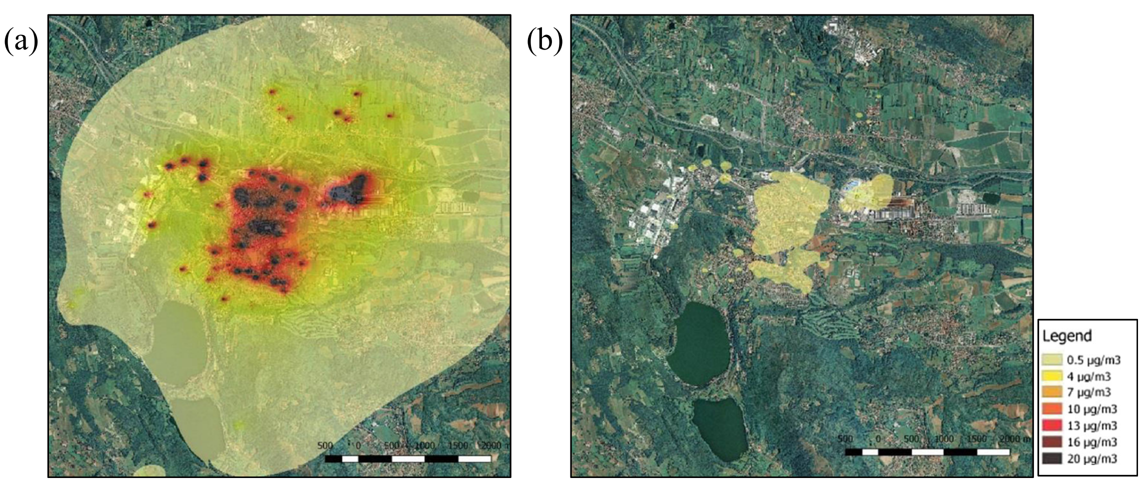

Fig. 2 Annual concentrations of PM due to the emissions of traditional wood stoves (**a**) and of biomass boilers and timber transport means (**b**)

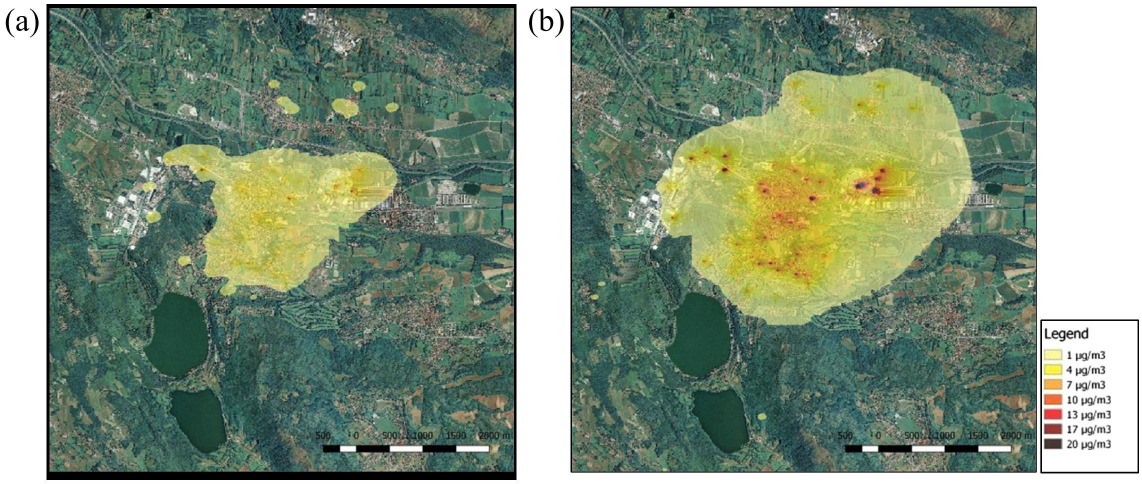

Fig. 3 Annual concentrations of NO_X from the emissions natural gas boilers (**a**) and wood biomass boilers (**b**)

however, the low-quality timber to be used for energetic purposes, namely in woodchips boilers.

The treetops and branches are chipped on site. The remaining part of the timber is transported to the storage yard where it is dried (naturally or artificially) before being in turn chipped and transported to the boilers. Note that the latter chips have better combustion features.

As a sample area, we have chosen a town located at the entrance of an alpine valley in the Northwest of Italy. This area covers about 25 km^2 and it is surrounded by woods that can potentially supply the heating network. The emissive scenario is designed evaluating separately the thermal needs of the residential, municipal and service buildings and of the buildings used for industrial activities.

To determine the heating requirements of residential buildings, needed to estimate the number of boilers and their power, we also took into account the consumption of domestic hot water. A proper evaluation of the distribution of boilers over the territory should take into account the size, the architectural characteristics and the thermal properties of the building [31, 32]. Since we do not dispose here of all this information, their spatial distribution is assumed to depend on the density of the resident population, only.

The heating requirement for the industrial buildings is based on the cubic footage. Considering the thermal needs in the industrial areas, we assume to install there higher power boilers compared to those in residential areas. One of these higher power boilers will be the one devoted to the drying of the wood for the whole area. We will also consider that the wood will be stored and chipped close to this boiler, i.e. that all trucks transporting the wood will be directed there (Fig. 1).

Overall, we have assumed that the heating requirement is guaranteed by 76 boilers with powers ranging from 100 to 1500 kW (Fig. 1). This correspond to a global power of 44.6 MW, which is consistent with a high-efficiency thermal network, therefore including all technical upgrading to minimize thermal losses [33].

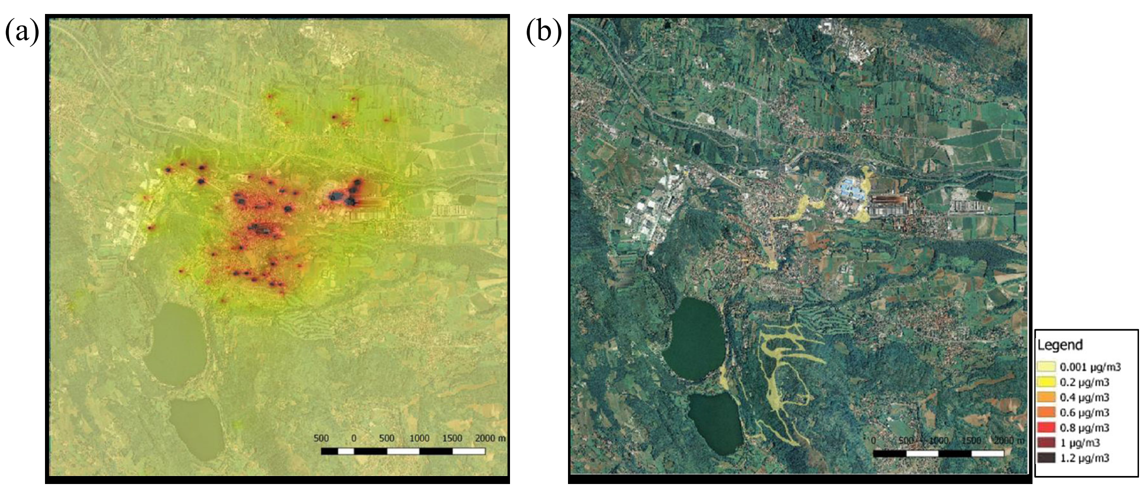

Fig. 4 Annual concentrations of PM from the emissions of biomass boilers (**a**) and timber transport means with reduced concentration scale (**b**)

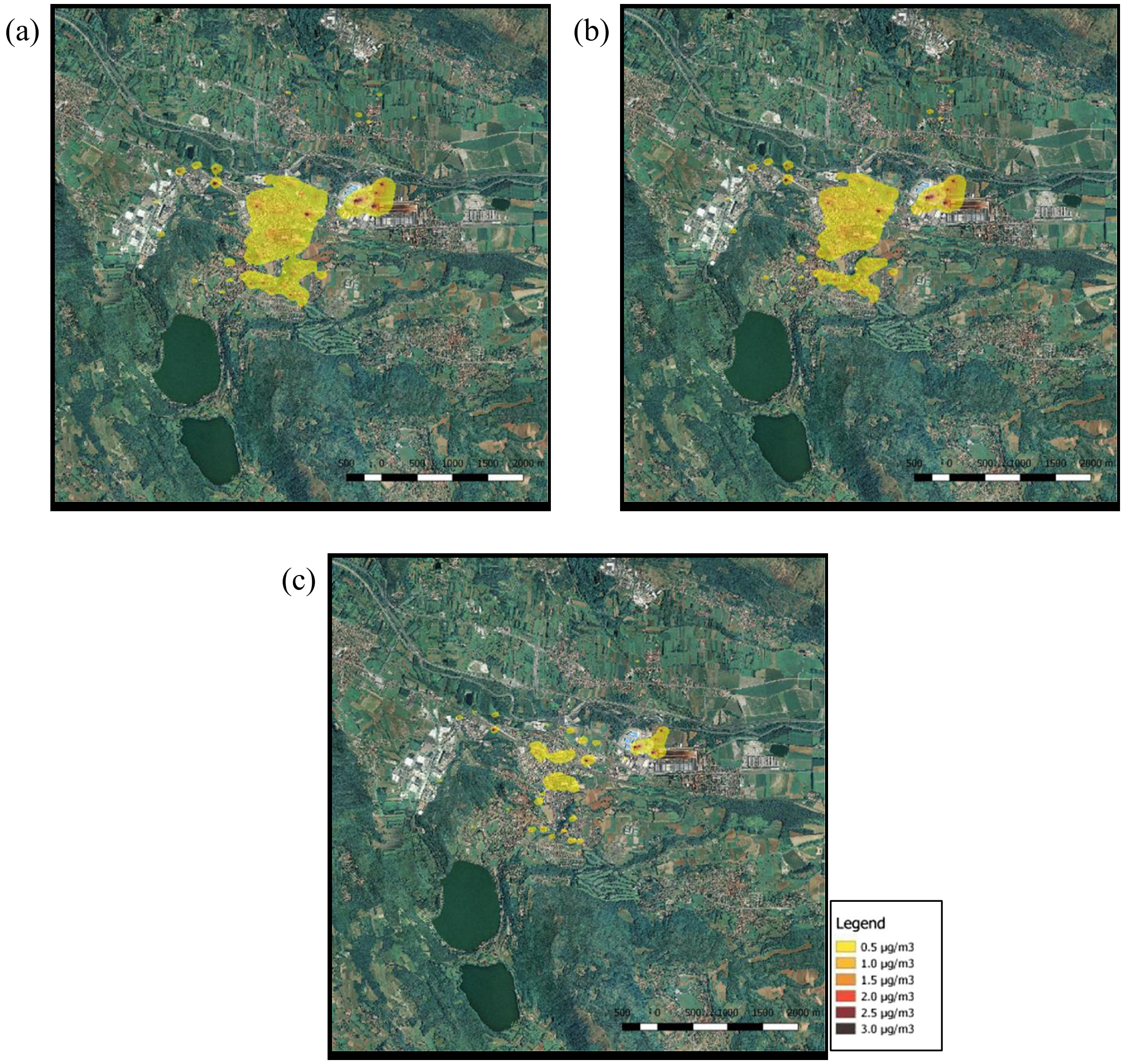

Fig. 5 Annual concentrations of PM from the emissions of biomass boilers in the three scenarios considered: with scheduled working conditions for the whole year (**a**) with modulated, according to the external temperature; working conditions for the whole year (**b**); and switching off in the summer months (c)

Concerning the modulation of the emissions, we have assumed full or part load-operating boilers, according to the season and the hour of the day. We have determined the whole required quantity of wood chips according to the number, the power and the operating boilers. The traffic flows (vehicle per hour) for the wood transport and their hourly modulation over the whole year were determined by imposing the typologies of trucks and identifying preferential hours for the chips' delivery. The domain was divided in areas with a known number of boilers to determine the traffic flow for each section of the road network. Pollutant emissions were subsequently computed based on vehicle typology and flow.

The analysis is performed using the meteorological data for the year 2015. Temperature values during 2015 are rather high compared to long-term temperature statistics. These can be, however, considered as representative of climatic conditions in the next future, as induced by the trends observed in the last decades due to the global warming.

In order to observe how the influence of varying operating conditions can affect air pollutant concentrations, we have analysed three different scenarios:

1. Scenario 1. Scheduled operating conditions for the whole year (with reduced power in summer to supply the hot water);
2. Scenario 2. Modulated operating conditions, based on the external temperature, over the whole year (with reduced power in summer to supply the hot water);
3. Scenario 3. Modulated operating conditions, based on the external temperature, and compete switch off in the summer, i.e. excluding their use for the supply of hot water.

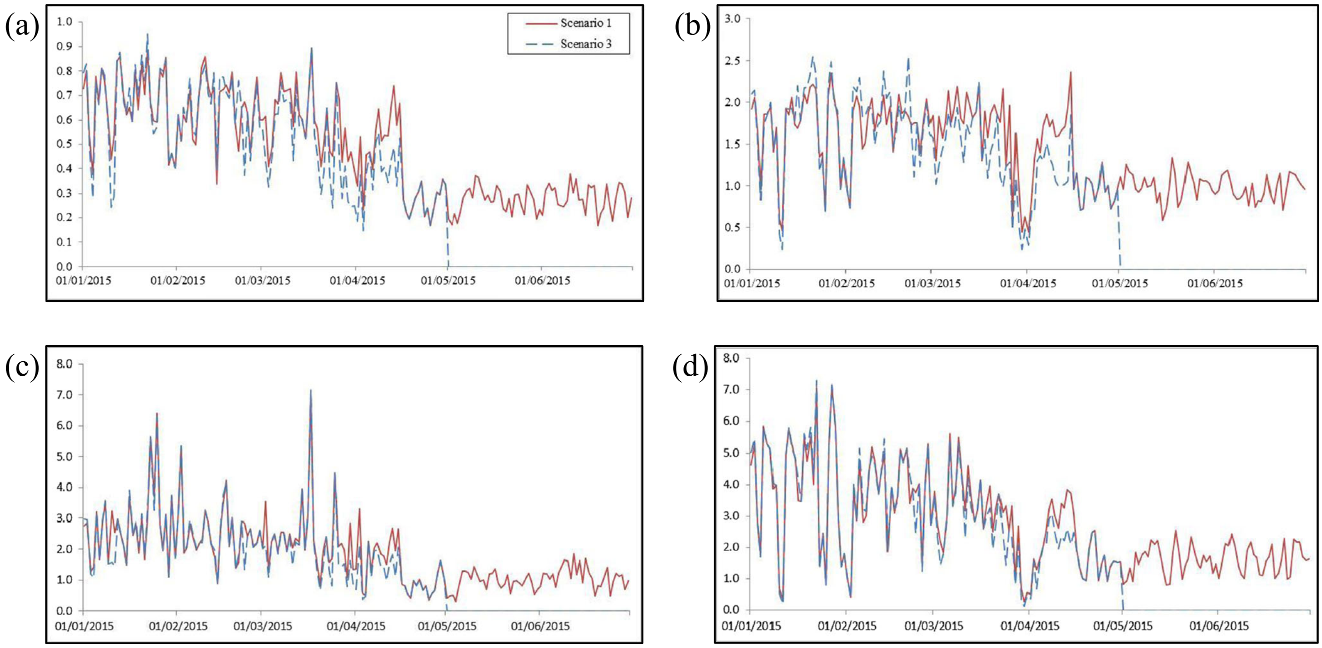

Fig. 6 Average daily concentrations trend for the Scenario 1 and 3 in receptors R1 (**a**), R2 (**b**), R3 (**c**) and R4 (**d**)

In all cases, we assume a modulation at lower loads in the middle of the day and at night. The height of the emission stack varies from one source to the other and depends on the height of each single building in the domain. As a general rule, we have estimated the stack height by adding 3 m to the height of each single building within the domain.

2.2 Atmospheric Dispersion Modelling

To estimate the air concentration of PM at ground level, we performed simulations of atmospheric dispersion with the model SIRANE [34, 35]. SIRANE is a model conceived to simulate pollutant dispersion emitted from line sources (e.g. traffic emissions) and punctual sources (e.g. chimneys) at a local scale. The model calculates the concentration of pollutants with an hourly time-step over domain whose dimensions can reach 30 km × 30 km. The SIRANE model requires input of the meteorological data, the emissions of pollutants (from punctual, linear and area sources) and the pollutants background concentration (measured outside the analysed domain). SIRANE is a second generation Gaussian model, i.e. it models the air flow in the lower atmosphere as a boundary layer, according to the Monin-Obukov similarity theory. Pollutant dispersion is modelled by a Gaussian plume, with transversal and vertical spread parameterised according to local velocity statistics [33]. In the modelling of particulate matter emissions, we have assumed the particles characteristics comparable to those of PM_{10}.

3 Results

The first feature we aim to enlighten is the different impacts of woodchip boilers compared to traditional heating systems, i.e. wood stoves and natural gas boilers. To that purpose we compare the concentration field at ground level obtained with these different heating systems and consider the first of the three emission scenarios presented in Sect. 2.1.

The comparison with wood stoves is presented in Fig. 2a, where we plot the annual average concentration of PM. The differences between the two fields are striking. In case of traditional stoves, PM concentrations exhibit significantly larger with peaks exceeding 20 μg/m^3 in several parts of the domain, and locally reaching 40 μg/m^3. Therefore, the sole contribution of emission related to traditional stoves (and without taking into account the role of background pollution) would imply exceeding the limiting value (40 μg/m^3) indicated by the European legislation for PM10. Conversely, in case of woodchip boilers, concentration values are significantly reduced. These are generally in the range 0–0.5 μg/m^3 (Fig. 2b) and hardly exceed 1 μg/m^3.

The comparison with natural gas boilers is instead based on annual averaged concentrations of NOx, since their PM emissions can be considered as negligible. Results are presented in Fig. 3 and show that the use of woodchip boilers, compared to natural gas ones, induces a relevant increase of ground level concentration with local peaks that exceed 20 μg/m^3 (Fig. 3b).

To further characterize the woodchip boilers emission scenario, we evaluate separately the emissions from punctual sources, due to boilers missions, and linear sources, due to traffic related emissions (Fig. 4a). This shows that the contribution of boiler emissions to ground level concentration largely exceed those from traffic (Fig. 4b). In this latter case concentration values are in the range $5.9 \times 10^{-6} \div 0.026$ μg/m^3, several order of magnitude smaller than those observed considering boilers emissions. The only relevant contribution on local concentration can be detected south of the city centre, around the location where we have assumed that the timber was harvested (at which therefore all heavy goods vehicle trajectories had to converge).

Note that, all results presented so far refer to the Scenario 1, in which emissions are assumed to be constant over the whole year. For a more comprehensive evaluation of the impact assessment of these heating systems, we therefore turn to the results referring to the other scenarios, in which the emissions data have been modulated according to the measured external temperature and to the hot water supply.

Results show that a modulation of the emissions based on the ambient temperature induces a slight reduction of yearly averaged ground level concentration (see Fig. 5a and b). Conversely, a significant improvement of air quality can be obtained by completely switching off of the boilers during the ‘hot’ months, i.e. from beginning of May to the beginning of October (see Fig. 5c). This implies that these heating systems have to be coupled with some other renewable energy sources in order to heat water for domestic and industrial uses.

The reduction of concentrations in Scenario 3, compared to Scenario 1, is also depicted in Fig. 6, where we show time evolution of PM concentrations at four different receptors within the domain.

As it is shown, a relevant contribution in the ground level concentration is due to the switching off in summer, which implies null emissions and therefore null ground level concentrations. We observe a more significant difference in the day with higher temperatures where a correct modulation of the boiler can significantly influence the concentration trend.

4 Conclusions

Woodchip boilers are emerging heating system which are attractive for their reduction of CO_2 emissions, but whose use may worsen local air quality conditions compared to traditional heating systems. The aim of this paper is to assess the environmental impact of a network of small wood biomass boilers, by comparing it to that of other traditional heating systems, such as traditional wood stoves and natural gas boilers. To that purpose we have simulated the dispersion of pollutants at the local scale in different emissions scenarios, taking into account both the pollutant directly emitted by the boilers and those emitted by the vehicles transporting the woods needed to feed them. Simulations of pollutant dispersion were performed with SIRANE, a second generation Gaussian model.

Results show that the environmental performances of woodchip boilers, at the local scale, are not as good as those of natural gas boilers. However, the effect on local air quality of woodchip boilers is significantly lower than those of traditional stoves, since they induce ground level PM concentrations which are almost reduced by an order of magnitude.

The analysis of the dispersion model results take into account three different emission scenarios based on different hypothesis on the operating conditions of the boilers. Namely the results show that an adequate modulation of boilers emission, based on ambient air temperature, can reduce ground level concentrations of PM. However, the most relevant reduction can be attained by switching off these systems during the whole summer. We therefore have to conclude that the best environmental performance of these systems can be achieved by combining their use with other renewable energy sources for the heating of water. Note that this solution would also reduce the needs in wood and would, therefore, be more sustainable since it would avoid the risk of depleting the forest resources of a given territory.

It is worth noting that, even in this latter case, this kind of network could not be used as a general solution in Alpine regions, due to the limited availability of timber. We may, however, expect a spreading of these networks as far as the energetic performances of buildings will generally improve, which will significantly reduce their energy demand.

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