

# Sustainable Heating Fuels and Technologies for Households not Connected to Natural Gas Grid in Po Valley, Italy

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Po Valley in Italy is characterized by severe air pollution problems in terms of particulate matter (PM) and nitrogen oxides (NO<sub>x</sub>). The study focuses on small mountain municipalities in this territory that are not connected to the natural gas grid and F-climate zones that are eligible for liquefied petroleum gas (LPG) subsidies. The sustainability of the main two residential heating fuel alternatives in the area (i.e., biomass and LPG) is investigated in terms of primary PM and NO<sub>x</sub> emissions by studying two emission reductions scenarios where the heating demand currently provided by solid biomass combustion is hypothesized to be covered with advanced wood pellet appliances or by LPG. The associated equivalent CO<sub>2</sub> emissions are also calculated. The study concluded that the turnover of biomass appliances reduces significantly the PM emissions but may not be an effective way to reduce NO<sub>x</sub> emissions in the area. Gaseous fuel (e.g., LPG) combustion may bring more benefits in this respect. Both wood pellets and LPG cause fossil CO<sub>2</sub> emissions to some extent.

## 1. Introduction

Over the past few years, the European Commission initiated infringement procedures against Italy due to its consistent and systematic violations of the particulate matter (PM) and nitrogen dioxide (NO<sub>x</sub>) limit values established by the Air Quality Directive. One of the areas where these breaches have been particularly problematic is the river Po basin. Especially regarding the particulate matter emissions, the non-industrial combustion of biomass in small domestic appliances is the main source of primary PM<sub>10</sub> in the Po-basin (ARPA Lombardia, 2022). Residential natural gas burning systems are highly prevalent in the Po basin, except for certain mountainous and hillside municipalities that are either not connected or only partially connected to the natural gas grid. These specific territories, with respect to the low land areas of Po basin, are not particularly interested by air quality problems in terms of average concentration values and exceedances. However, the particulate matter in the Po Valley is reported to be largely of secondary origin that is generated from the atmospheric reactions of precursors (e.g., NO<sub>x</sub>, SO<sub>2</sub>, non-methane hydrocarbons) all found in residential biomass combustion primary emissions (Thunis et al., 2021). Recent findings suggest that biomass combustion emissions in winter months may contribute to the formation of oxidized organic aerosol in the atmosphere without requiring any sunlight (Kodros et al., 2020). In this respect, the local reduction of primary PM and NO<sub>x</sub> emissions in mountainous areas could yield even beneficial regional effects, as it would contribute to the removal of precursors for secondary PM.

The present study determined the annual PM and NO<sub>x</sub> emissions associated with residential biomass combustion in the small mountain municipalities of Po Valley, northern Italy, where the households are not connected to natural gas grid. Since the reduction of primary emissions will potentially increase the environmental sustainability of residential heating, some emission reduction scenarios are studied for the identification of the potential benefits and drawbacks of selecting heating fuel and technology alternatives. In line with the main economic and fiscal incentive schemes regarding the heating fuel and technologies currently active in Italy, the present study examined a first emission reduction scenario encompassing the complete replacement of all biomass appliances in the study area with advanced biomass technologies. However, taking into account adverse effects of biomass combustion emissions on human health and heavy impact on air quality

(Naeher et al., 2007) an alternative scenario involving a fuel switch (i.e., from solid biomass to gaseous fuel) is also conceived. Given the inherent characteristics of the homogeneous combustion (i.e., gas phase) particulate emissions are expected to decrease with gaseous fuel combustion in heating appliances. In this direction, the second scenario involves the replacement of the existing biomass appliances with liquefied petroleum gas (LPG) appliances (i.e., fuel switch). LPG is chosen as an alternative because in the areas where natural gas connection is not available, a lower rate of excise duty applies to LPG to make it more affordable (Council Implementing Decision (EU) 2019/814). In addition, this fuel is also subject to reduced value-added tax (VAT). Nevertheless, the fossil origin of LPG contradicts with the ever-tightening policies aimed at reducing greenhouse gas emissions. For this reason equivalent CO<sub>2</sub> (CO<sub>2eq</sub>) emissions of the different scenarios are also reported.

## 2. Methodology

### 2.1 Study area description

The study focuses on a specific geographic area in the Po basin, which includes small mountain municipalities that are not connected to the natural gas grid and F-climate zones that are eligible for LPG subsidies.

The study area encompasses 929 mountain municipalities with a population of less than 10,000 inhabitants, representing about 5% of the total population of the Po Basin.

LPG consumption data for the study area is available only at a provincial level in the Po Valley but it can be said that the registered LPG consumption (Ministry for Business and Made in Italy 2021 data: 16.4 PJ) can be majorly attributed to use in the households not connected to natural gas grid, hence more or less representative of the study area.

Regarding the biomass fuel, there are about 392,000 biomass heating devices in the area, accounting for 13% of the total in the basin, and it is estimated that the biomass consumption is about 14.9 PJ (355.9 ktOE) or 1.1 million tons, about 17% of the total consumption in the Po Basin (data elaborated from PREPAIR Project results-LIFE 15 IPE IT013). The majority of the appliances considered in the study, for both wood log and pellet, are classified with less than 3 stars according to DM186/2017 categorizing the biomass appliances according to their environmental and energy performance. All the appliances result to be over 4 years old, indicating a need for appliance replacement.

### 2.2 Emission estimation

The assessment of emissions is performed following the Tier 2 technology-specific approach for small combustion provided in the EMEP/EEA air pollutant emission inventory guidebook (EEA, 2023) and the algorithm for the emission estimation is as follows:

$$E_{i,f} = \sum_{i,j,k} EF_{i,j,k,f} \cdot A_{j,k,f} \quad (1)$$

Where:

$E_{i,f}$ : annual emission of pollutant  $i$  (i.e., PM<sub>10</sub>, NO<sub>x</sub>, CO<sub>2eq</sub>) for fuel  $f$  (i.e., wood logs, pellets, LPG),

$EF_{i,j,k}$ : emission factor of pollutant  $i$  for appliance type  $j$  (i.e., closed and open fireplaces, stoves, boilers) and  $k$  performance category  $k$  (i.e., 1-3 and 5 star for biomass appliances, not pertinent for LPG appliances) (Table 1),

$A_{j,k,f}$ : annual consumption of fuel  $f$  in appliance type  $j$  and performance category  $k$  (Table 1).

### 2.3 Emission reduction scenarios

The reduction of emissions is a key factor in the investigation of the sustainability of heating fuel alternatives in the area. In light of the major appliance oriented economic incentive schemes (e.g., state incentive Conto Termico 2.0 for the substitution of existing residential heating appliance with highly efficient low-emission biomass heating appliances) and fiscal incentives (i.e., lower taxes on LPG), two emission reduction scenarios were conceived. Firstly, the focus was on enhancing biomass heating technologies (technological turnover), and subsequently, considering the well-documented impact of biomass combustion on air quality, particularly in terms of particulate emissions, consideration was given to transitioning to an alternative fuel, LPG with less expected impact on local air quality given lower emission factors for PM and NO<sub>x</sub>.

The “technological turnover” scenario entailed the replacement of all 392,000 biomass appliances in the study area with 5-star pellet appliances (i.e., room heaters and boilers). The “fuel-switch” scenario on the other hand involved replacing all biomass appliances in the study area with LPG appliances providing the same amount of domestic heat demand actually covered by biomass combustion. The results are then compared to assess the

potential benefits or drawbacks of both scenarios with respect to the “reference case” emissions calculated based on the current heating appliances in the area.

Table 1: Fuel consumption data ( $GJ_{in}$ ) and emission factors used in the study ( $g/GJ_{in}$ )

Fuel	Technology	(ARPA Lombardia, 2022)							CO <sub>2eq</sub>	
		Fuel consumption			PM10		NOx	CO <sub>2eq</sub>		
		1-star	2-star	3-star	1-star	2-star	3-star	1-3 star		
Woodlog	OFP	1.9	0.4	0.2	847	463	284	50	9.7	(Pierobon et al., 2015)
	CFP	0.8	0.2	0.1	380	380	284	80		
	WS	4.4	1.4	1.3	760	463	284	50		
	WB	1.2	0.7	0.4	480	52	26	80		
Pellets	PS	0.4	0.5	0.6	60	60	60	80	56.8	(PoliMI AWARE, 2020)
	PB	0.1	0.1	0.2	60	34	19	80		
Pellet (5star)	PS		10.6			46.54		66.8		
	PB		2.3			8.594		80		
LPG	FP		10.2			0.2		39.9	94.83	(Martín-Gamboa et al., 2020)
	B		2.2			0.2		50		

### 3. Results and discussion

#### 3.1 Factors influencing the primary emissions from heating appliances

Primary emissions (e.g., PM, NOx) is a key factor in the investigation of the sustainability of heating fuel alternatives. There are several factors influencing the environmental and energy performance of the residential heating appliances such as fuel quality, appliance construction details (air and fuel control possibility), operating conditions (cold and hot start, nominal and partial load), user behavior (especially for manually fed appliances), as well as aging (appliance and stack maintenance conditions). Many of these factors have less to no effects on the environmental and energy performance of gaseous fuel (e.g., LPG) fed appliances due to negligible variations in fuel quality, premixed burners for low NOx and incomplete combustion product emissions, as well as less influence of transient operation by power modulation. The influence of these factors on biomass appliances are more significant and can be briefly described as follows.

**Fuel quality:** in biomass-fed appliances the environmental performance of the appliance are closely linked to fuel composition, particularly moisture, aerosol-forming species, and nitrogen content. Fuel quality depends on biomass type, densification treatment, and storage conditions. The impact of fuel quality has been shown both for pellet stoves, where emission factors double or triple with decreasing pellet quality (Venturini et al., 2018) and for firewood room heaters where increased emissions of particulate matter and carbon monoxide were observed as fuel ash content rises (Ozgen et al., 2017). Currently, only virgin biomass raw material is permitted, with A1 quality pellets (UNI EN ISO 17225-2) mandated for residential heating, however the quality control over firewood may be difficult. For instance, some users may burn household waste as well as waste wood in fireplaces and room heaters, which can negatively affect emissions.

**Appliance construction details (air and fuel control possibility):** The construction details of residential heating appliances, specifically in terms of air and fuel control possibilities, play a significant role in their performance. Pre-mixed burners are widely employed in LPG heating appliances. The precise ratio of LPG to air is carefully controlled to ensure complete combustion and maximize energy efficiency. By achieving a homogeneous mixture of fuel and air prior to combustion, pre-mixed burners can produce a stable flame with minimal incomplete combustion product emissions. The appliance construction gains more importance for biomass heating appliances, given the intrinsic difficulty of obtaining optimal operating conditions in heterogeneous combustion of solid fuels with respect the gaseous fuels. In this respect, appliances with automatic fuel and air feeding mechanisms (i.e., pellet stoves and boilers) exhibit superior combustion performance compared to manually fed appliances (e.g., firewood roomheaters), since these appliances achieve higher efficiencies, and reduce overall ignition and non-optimal operating periods, leading to lower emissions.

**Operating conditions (cold and hot start, nominal and partial load):** The operating conditions of residential heating appliances, including cold and hot start, as well as nominal and partial load conditions, play a significant role in their emission performance. This aspect is particularly crucial for conventional biomass heating appliances where the limited adjustment possibility for air-fuel ratio may cause non-optimal conditions and longer transitory periods characterized by higher incomplete combustion emissions.

**User behavior:** One of the most important factor hindering the environmental sustainability of conventional batchwise biomass heating appliances (i.e., firewood roomheaters) is the strict dependence of the appliance

emissions on the user actions such as the ignition method (i.e., bottom-up or top-down), fuel amount per batch, draught conditions, and adjustment of air valve settings for combustion air supply. The use of automatic appliances would result more environmentally sustainable than the firewood room heaters. (Reichart et al., 2016)

Aging (appliance and stack maintenance conditions): Aging of biomass appliances and the associated maintenance conditions have been shown to have a significant impact on their efficiency and environmental performance. Over time, fouling occurs in both the appliance and the flue gas stack, which adversely affects the draft and combustion conditions, leading to increased instability and unpredictability in combustion. This manifests as periods of poor combustion, characterized by excessive incomplete combustion products (such as PM, OGC, and CO), followed by regular combustion phases (Innovhub, 2017).

### 3.2 Primary emissions and reduction alternatives

The annual emission levels associated with the residential biomass combustion were calculated for the existing biomass heating appliances in the study area ("reference case"). The particulate matter emissions amount to approximately 7,400 t/y, while those of NO<sub>x</sub> are approximately 900 t/y, representing each 17% of the respective emissions generated from biomass heating in the Po Valley. The information provided in section 3.1 is confirmed since the study revealed that the majority of PM<sub>10</sub>, accounting for 99% of the total, are attributed to firewood room heaters and despite representing 14% of the total number of appliances, pellet appliances contribute only 1% to the total PM<sub>10</sub> emissions, indicating higher environmental sustainability given the relatively low impact compared to firewood room heaters. In this respect, the emission reduction scenario, known as the "technological turnover" demonstrates substantial reductions of 93% in PM<sub>10</sub> emissions. However, this strategy of transitioning to advanced biomass heating technologies fails to obtain any benefit in terms of NO<sub>x</sub> emission reduction. This is due to the fact that NO<sub>x</sub> emissions in biomass combustion primarily originate from the fuel nitrogen content without a notable effect of appliance type and operation (Ozgen et al., 2021). The "fuel-switch" scenario on the other hand, which involved the transition to LPG fuel for residential heating instead of biomass, exhibited a remarkable potential nearly zeroing PM emissions and, diversely from "technological turnover", achieving also a 43% reduction in NO<sub>x</sub> emissions as well.

Regarding the greenhouse gas (GHG) emissions, one thing should be specified before reporting the assessed equivalent CO<sub>2</sub> (CO<sub>2eq</sub>) emissions. The debate on the carbon neutrality of forest biomass is still ongoing and there is not a consensus among scientists on this issue (Berndes et al., 2016). A significant portion of the CO<sub>2</sub> emissions released firewood room heaters is attributed to biogenic carbon dioxide (Pierobon et al., 2015) but the inclusion of biogenic emissions and removals remains a topic of discussion internationally, as they are often assumed to be equivalent to the carbon absorbed by forests and therefore neglected. International standards and guidelines typically do not account for biogenic carbon dioxide in life cycle assessment (LCA) studies, assuming carbon neutrality for biomass combustion. However, other co-emitted pollutants for example such as methane, cannot be offset by the activity of absorption of trees and must be included in the accounting and reported as CO<sub>2eq</sub>. The production and supply chain can also influence the overall GHG emissions of biomass fuels. This is specifically the case of pellets especially due to generally longer distance travelled for supply and fossil fuel utilization in the pelletization process (Martin-Gamboa et al., 2020). The present study has chosen to assume carbon neutrality (i.e., biogenic CO<sub>2</sub> excluded) and has taken as reference the emission factors for the long supply chain. With these assumptions the CO<sub>2eq</sub> emissions associated with existing biomass heating appliances are 189 kt/y. When all biomass appliances are replaced, the transition to LPG fuel results in a six-fold increase in CO<sub>2eq</sub> emissions (1088 kt/y), while the technological turnover scenario leads to about a three-fold increase in emissions (647 kt/y). In any case, CO<sub>2eq</sub> emissions calculated for the two scenarios in the present study result to be limited compared to those generated by non-industrial combustion (i.e., household heating with natural gas and other fossil fuels), as reported by various regional emission inventories in the Po basin (e.g., Lombardia (2019): 13885 kt/y; Emilia Romagna (2020): 6140 kt/y; Veneto (2019): 6675 kt/y; Piemonte (2010): 7064 kt/y).

### 3.3 Sustainability of fuel and technology alternatives in the area

Regarding the pellets, as a densified fuel it presents standardised properties, low moisture and high-energy content, high density (i.e., ease of transport, storage and handling) which combined with the capability of keeping optimal air/fuel ratios thanks to automatic feeding in room heaters and boilers under variable heating loads, results to be more sustainable compared to unprocessed biomass (i.e., firewood) use in conventional heating appliances (Ozgen, 2022). A further positive sustainable factor is the relatively lower health impact of PM from pellet heating appliances in terms of toxicity (Corsini et al., 2017; Jalava et al., 2012) and genotoxic potential (Marabini et al., 2017). However, for pellets appliance use as a sustainable alternative it can be said that there is room for improvement.

When considering the utilization of LPG as a replacement for biomass in traditional residential heating appliances like boilers and stoves, with the aim of improving air quality, it is important to recognize that LPG should be viewed only as a temporary solution due to its fossil CO<sub>2</sub> emissions. The use of bioLPG - the renewable form of LPG produced from renewable feedstocks such as plant and vegetable waste material may ensure that this solution is in line with decarbonization efforts. BioLPG offers the advantage of being a drop-in fuel that can be used in existing boilers, but further research and development (R&D) may be necessary to optimize its production. Especially, the carbon footprint should be analyzed using a life cycle assessment approach, which considers all emissions and energy consumption associated with its production, transportation, and use. With the perspective of using bioLPG, other incentivized renewable energy technologies such as gas driven heat pumps (gas engine heat pumps, gas absorption heat pumps) (Pawela and Jaszczur, 2022) can also constitute a sustainable alternative solution. It is shown that gas engine heat pumps can have better environmental performance compared to electric heat pumps both in heating and cooling operations (Rosselli et al., 2021). Gas absorption heat pumps in particulate enable fuel saving and the exploitation of renewable energy even in heating systems based on radiators, which require high supply temperature (Famiglietti et al., 2021; Brenn et al., 2010). Even though residential heating examples exist (Rosselli et al., 2021; Scoccia et al., 2018), there is still R&D need on appropriately sized products for small heating applications.

#### 4. Conclusions

The study investigated the sustainability of the main residential heating fuel and technology options in terms of primary PM<sub>10</sub> and NO<sub>x</sub> emissions in small mountain municipalities in the Po Valley where households are not connected to the natural gas grid. For this purpose the current emissions from residential biomass combustion are calculated and emission reduction scenarios inherent with the technology and fuel oriented economic and fiscal incentive schemes active in the area were assessed.

It is seen that in line with the main factors influencing the environmental and energy performance of the residential heating appliances (i.e., fuel quality, appliance technology, operating conditions, user behavior, appliance and stack maintenance conditions) technology oriented strategies such as “technological turnover” of biomass appliances (i.e., replacement of existing biomass heating appliances with 5-star pellet appliances) would bring an important reduction in PM emissions (93%) but would not be completely effective since no significant benefit is seen for NO<sub>x</sub> emission when transitioning to advanced biomass appliances. On the other hand if the same amount of heat demand in the area were provided with gaseous fuel fed appliances, other than almost zero PM emissions, a net reduction in NO<sub>x</sub> emissions (43%) could also be obtained. LPG use may bring benefits only if, in line with decarbonization efforts, the fossil CO<sub>2</sub> emissions are compensated in the short to medium term, before a gradual transition to bioLPG takes place.

#### Nomenclature

B: boiler	WB: wood boiler
CFP: closed fireplace	WS: wood stove
FP: fireplace	PB: pellet boiler
OFP: open fireplace	PS: pellet stove

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