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Methodology for Estimating Emissions from Small Domestic Fuelwood Appliances in Lombardy

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Estimates from many national emission inventories and air quality measurements (Gianelle et al., 2013) are showing the relevance of biomass burning in small domestic appliances as source of particulate matter and benzo(a)pyrene (BaP). For Lombardy region, the highest populated of Italy, domestic heating is determining 38% of the total particulate and among this fuelwood contributes for 99% of PM and is responsible of 66% of the total regional emission of BaP (INEMAR, 2018). In the framework of the emissions inventories, estimates are due to a combination of an average emission factor detailed for technology and pollutant and an activity indicator defined as the annual energy burned detailed for technology, reference year and geographic detail (e.g., region, district, sampling statistical cells, …).

This paper presents the methodologies and tools for monitoring combustion technologies evolution during the years, estimating annual energy amount burned and accounting the different profile of use. From CATI (Computer Aided Telephonic Interview) surveys it is possible by sampling statistics to obtain information on technologies diffusion and to estimate energy burned (Pastorello et al., 2011). Unfortunately, this data are quite discontinuous in the years. A methodology linking statistics and information arising from producers, chimneysweeper's associations and preliminary filling of biomass heater regional register has been developed to consider the evolution and substitution rate of burning technologies. A first picture of the numbers of biomass heaters for a reference year is evolved in the next years considering market information and technology share in new installations from installers and regional register. Obsolete and substituted appliances are calculated for each year considering a probability function due to appliance age. The probability of a technology to be substituted will increase with the age of the installation moving up to the appliances average lifetime and newly installed burners are not capable to a substitution in the next year.

With the developed procedure it is possible to obtain the evolution during the years of the number of different appliances and to project their evolution in the future. The introduction of coefficient for energy usage (overall annual energy burned from single user in a specific device) can allow the best evaluation of the positive effect of more efficient devices.

Information from regional energy balances can be used as propagating coefficients of the sampling statistics for calculating municipal information on total energy burned in domestic wood heaters, alternatively an algorithm for estimating the heating demand of dwellings can be implemented on the base of annual heating degree days (HDD), thermal dispersion coefficients, building age and heated total volume. The HHDs can be obtained from the diagnostic system of ARPA Lombardia for the time series between 2008 and 2016 and are commonly considered as a proxy of the thermal season allowing to calculate the biomass energy consumption for those years not covered by CATI surveys (GSE, 2017).

1. Air emissions from domestic wood burning

It is well known that biomass combustion produces different typologies of primary aerosol PM10: inorganic salts, soot and condensable organic compounds (COC). These aerosols are characterized by different chemical and physical properties, different toxicity, various behaviors in the application of primary and secondary abatement measures and can be connected to different combustion regimes. Wood burning is due to exothermic and endothermic steps: moisture evaporation, pyrolysis and volatilization, oxidation of volatiles and residues. The different interaction of these phases can strongly affect the emissions of atmospheric pollutants.

A complete combustion can lead to inorganic aerosols by optimal combustion condition: high temperature and correct oxygen ratio. Uncomplete combustion at high temperature but with zones with lower oxygen ratio can determine emissions of soot particle with high carbon content. The condensable organic compounds, can be also associated to tars, and are due to incomplete combustion. Biomass burning emissions form in the atmosphere also secondary organic aerosols (SOA) and secondary inorganic aerosols (SIA).

VOCs derive also from incomplete combustion, are potential precursors of SOA and are formed by similar mechanisms of COC. Sulphur and nitrogen content in fuel determines SOx and NOx emissions, precursors of nitrates and sulphates of the SIA. Combustion of lingo-cellulosic materials is also a pollution source of PAHs, in particular of benzo(a)pyrene.

2. Estimates air pollution emission from residential wood burning

In the residential heating, technology solutions for biomass burning are numerous. According to the international references of Task Force on Emission Inventories and Projections (TFEIP, 2014) wood burning in domestic appliances is a relevant source of PM emissions in many national emission inventories. The reference guidebook for emission inventories compilers (EMEP/EEA, 2016) estimates the emission of a pollutant as a product of an average emission factor, representative of a certain type of technology, and an indicator of activity defined as the total annual energy burned in the appliances of the same type.

As a matter of facts, the calculation is strongly affected by these variables: number of appliances and specific energy consumption for each typology, total annual energy demand, fuel types and characteristics and average emission factor.

Table 1: Appliances, substitution ratio, specific energy consumption and PM10 emission factors.

Appliance	x_t	C_t [t/y]	PM10 [g/GJ]	*PM10 total [g/GJ]*	*PM10 solid [g/GJ]*	*Solid/total*
				(EMEP/EEA, 2016)	(EMEP/EEA, 2016)	(EMEP/EEA, 2016)
Open fireplace	0 – 0.07	1.5	860	*840*	*260*	*0.3*
Traditional stove	0.08 – 0.115	2.6	480	*760*	*160*	*0.2*
Closed fireplace	0.15 – 0.22	2.6	380	*380*	*150*	*0.4*
Advanced stove	0.08 – 0.115	1.4	380	*380*	*150*	*0.4*
Pellet stove	0.55 – 0.62	1.4	76	*60*	*30*	*0.5*

2.1 Appliances definition and time evolution

Appliances must be carefully identified in relation with the available dataset of the emission factors and representative of the average distribution of wood burners. For Italy a set of appliances have been defined by experimental studies (Ozgen et al., 2014), compared with the EMEP/EEA guidelines and with previous and similar studies for the identification and quantification the type of fuel-wood appliances. The domestic wood burning technologies considered in the emission inventory of Lombardy are listed in table 1.

In the past several CATI (Computer Assisted Telephone Interviewing) investigations, consisting in making telephonic interviews, were used for the quantitative estimation of residential wood usage in Lombardy (Pastorello et al., 2010). In the years other relevant information arises from producers and chimneysweeper's association. During the last years new rules on heating plant registers has determined an increase of information for the new installations. It can be reasonable to consider this phase as a transition ending with the total fill of the register for residential biomass burners. The developed methodology for tracking the share of burning technology aims to consider the CATI information as a starting point to be harmonized according the partial filling of the registers. Starting from the year (y), considering a geographic dominion m (e.g., Province, Sampling Cells or Municipality) the number of appliances N of a certain appliance (t) and with an age from the installation i, can be represented by: $N_{y,i,m,t}$.

These variables will change during the years due to aging of the appliances, the change of older devices into newest one, in the extension or contraction of the users and by the aging of the appliances not substituted. For the aging of the appliances, it is assumed that the probability of replacement will be proportional to installation age i, determining the following, valid for i>1:

$$N_{y+1,i,m,t} = N_{y,i-1,m,t} - k \cdot (i-2) \cdot N_{y,i-1,m,t} \tag{1}$$

As stated by equation 1, the evolution of a certain technology will be determined from the aging of the previous year reduced by the fraction of substituted appliances. The parameter k represents the substitution rate of the appliances. From the previous equation the total number of appliances that can be substituted in the year y is due to equation 2:

$$R_{y,m,t} = \sum_{i}^{\infty} k \cdot (i-1) \cdot N_{y,i,m,t} \tag{2}$$

As a matter the new installation replacement in year y+1 of a certain technology t will be obtained by the equation valid for i=1:

$$N_{y+1,1,m,t} = x_{y+1,t} \cdot \sum_{t}^{\infty} R_{y,m,t} \tag{3}$$

Where $x_{y+1,t}$ is defined as the technology share among the newest installations as reported in table 1. These data have been obtained by the most recent installations, in the period between 2013 and 2016, recorded in the biomass appliances register in Lombardy (RL DG Ambiente ed ILSPA, 2016). For the previous period information were elaborated on the basis of producer reports in Italy.
The possible variation of technology number can be obtained by:

$$N_{y+1,1,m,t} = z_{y+1} \cdot x_{y+1,t} \cdot \sum_{i}^{\infty} \sum_{t}^{\infty} N_{y,m,t} \tag{4}$$

Where z_{y+1} represents the fluctuation in the years of the total number of appliances, it has been associated to small demographic fluctuation during the years in Lombardy.
Applying equation 2 to Lombardy with reference year 2008 it is possible to obtain a substitution rate of 8-9% of the total number of appliances. This value agrees with reference documentation (EC DG TREN, 2009) and with similar and previous studies (Galante, 2013) where the substitution rate was stated in 7-8%.
The above-mentioned methodology (Marongiu et al., 2016) has been implemented several times in the update of emission inventory estimates and considers as starting point the definition of sampling cells for CATI from 2008 obtaining the timeseries reconstruction of domestic biomass burners share in the period 2008-2016. In this paper the calculation is extended, by the same hypothesis on 2016, to longer period obtaining obtain technology share projection up to 2030.

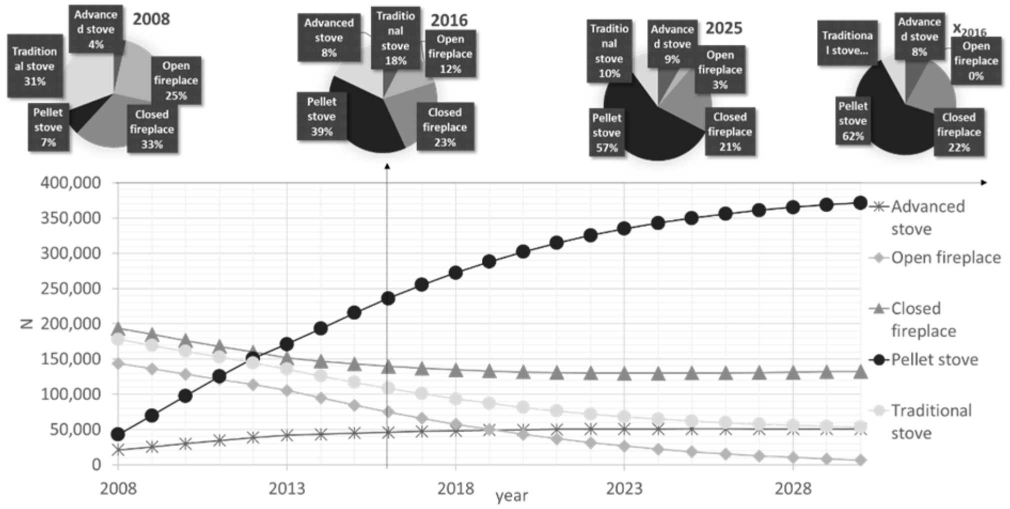

Figure 1: Timeseries 2008-2016 and projection to 2030 of appliances number in Lombardy.

Figure 1 shows the number of different burning technologies estimated for Lombardy between 2008-2016 and their projection to 2030. Starting from CATI information's, calculations are performed applying equations from 1 to 4, substitution rate as reported above and share of new appliances obtained from producers and the compilation of the domestic heating appliances register. The comparisons of pie-charts and projections clearly shows that, with the information available now, the distribution of appliances will tend to the new installation distribution x_{2016}, which depicts the partial filling of the heating register.

2.2 Specific energy consumption of appliances

As stated by the investigation on energy consumption by Italian families (ISTAT, 2014), the annual average specific consumption of for a pellet device clearly differs from a wood-log burner increasing from 1.4 t/y to 3.2 t/y. This difference can be explained by technical characteristics (e.g., automatic instead manual, average differences in thermal yield, different users profile, …). The modality of use of burners can affect emissions levels of the appliances and real-world burning cycles have been tested reaching higher emissions instead certification cycles (Ozgen et al., 2014).

The previous paragraph reports how the parameters $N_{y,i,m,t}$ can be estimated. For the emission calculations indicators on energy burned are necessary. The annual potential energy share for the devices can be obtained by:

$$CF_{y,m,t} = \frac{C_t \cdot \sum_i^{\infty} N_{y,i,m,t}}{\sum_t C_t \cdot \sum_i^{\infty} N_{y,i,m,t}} \tag{5}$$

Where C_t is the annual average specific consumption for each technology, defined in table 1 and the parameter $CF_{y,m,t}$ represents the energy burned share for each technology at a fixed year and for a specific geographic dominion. Note that these variables are normalized for each geographic dominion m, they represent the potential usage of energy determined by burners characteristics.

2.3 Annual energy demand and time evolution

The calculation of total energy burned for each burner type at municipal level requires information on energy balance, $E_{y,m}$. For Lombardy these indicators are available from the regional energy balance referred on 2014. For the reconstruction of time-series it is possible to implement an approach (GSE, 2017) based on trend of the heating degree days, $HDD_{y,m}$. The HHDs are calculated as the sum, for all the days of an annual heating seasons, of the positive differences between room temperature, conventional 20°C, and the daily average temperature out of the buildings. The annual value of HHD for a locality increases as the external registered temperature are lower. The time-series of $HDD_{y,m}$ is available from ARPA Lombardia according to the calculation daily performed by the air quality modelling suite.

The implementation of time proxy by HDD annual variation implies the hypothesis that the dwelling and heating system characteristics will not highly change from one year to another, assuming that the heating demand and the connected energy consumption will be more due to seasonal effects. Considering equation 6, $E_{y,m}$ variation on the years will be controlled by $HDD_{y,m}$:

$$E_{y,m} = HDD_{y,m} \cdot \sum_j \left(S_{m,j} - \sum_{not\ biomass} S_{m,j,f,y}\right) \cdot \left(A_{g,j} \cdot \mathrm{SV}_m + B_{g,j} + C_P \cdot \alpha_j \cdot n_j\right) \cdot \frac{\lambda_g}{\eta_j} \cdot \frac{86.4 \cdot 10^{-6}}{LHV} \cdot H_j \tag{6}$$

Where j indicate the age of the residential building, f the heating fuel type if different from biomass, k the typology of heating plant if autonomous or centralized and g the climatic class in Italy. Equation 6 shows that annual consumption of biomass for each municipality is proportional to HDD and to the effective heated dwelling surface S expressed in m2. The correction term on surface data must be considered for a determined year the surfaces resulting heated by other fuels (eg: combining updated information on natural gas distribution, substracting dwellings linked to district heating network, …). The parameters A and B, are coefficient modelling the thermal dispersion of the shell, calculated by technical and normative evolution. SV is the shape factor of buildings, calculated as an average for each municipality on the base of ISTAT dwelling census. The energy dispersion by ventilation is modelled by n, number of air changes, Cp specific heat of air and α correction factor for building age. Parameter H describes the average floor height (m) and λ the daily duration of heating system (for 24h set to 1). η is the annual average global thermal yield of the heating plan, estimated by the elaboration on available data on build energy demand classification CENED in Lombardy. LHV is the lower heating value of wood set to 12,5 GJ/t corresponding to first class wood-logs with moisture content less than 20% w according UNI EN-14961-5.

Equation 6 can be written in the form:

$$E_{y,m} = HDD_{y,m} \cdot \sum_j \left(S_{m,j} - \sum_{not\ biomass} S_{m,j,f,y}\right) \cdot \mathrm{P}_{m,g,j} \tag{7}$$

This relation put in evidence how is possible to estimate municipal biomass consumption by two types of variables: the effective surfaces heated by wood and municipal HHDs. Coefficients $P_{m,g,j}$ are defined by more technical parameters regarding buildings and heating systems, are defined as annual consumption of tons of biomass specific for floor unit and degree days. Combining all the available information, these parameters are shown in figure 2 for all the Italian municipality. Note that climatic classification of municipality is defined from the HDDs registered for a reference year. Equation 7 can be also adapted to estimate energy consumption and relative emissions of residential biomass heating day by day, introducing the daily contribution of municipal HDDs, both in diagnostic and forecasting estimates.

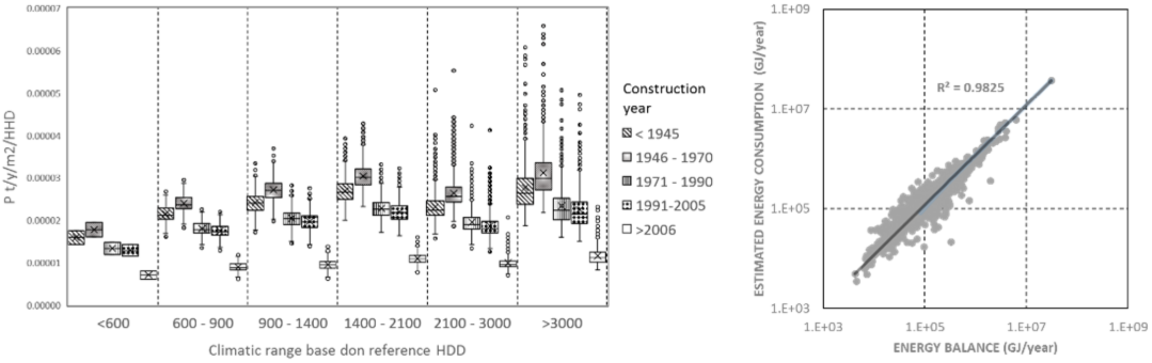

Figure 2: Biomass usage average coefficients for the entire municipalities of Italy (right panel), comparison between municipal energy balance in the residential sector in Lombardy and calculations.

The estimates of annual energy consumption, not only of biomass, from the residential sector can also obtained adapting equations 6. Figure 2, on the left panel, reports a comparison between model predictions and municipal energy balance for Lombardy in the residential sector. The scatter plot confirms the good agreement of the proposed approach with existing estimates on residential energy consumption.

2.4 Average emission factors

Fuel typology and quality, presence of contaminants, burning technology, real cycle of combustion and maintenance level can affect pollutant emissions. According the experience from emission inventory compilers (TFEIP, 2014) average emission factors can show higher variability also on the same type of appliance, suggesting the selection of emission factors based on large bibliography analysis. In the recent edition of the EMEP/EEA guidebook it is taken into evidence how the sampling method of PM emissions can determine very different range of emission factors. Two different approaches can be defined: one considers the collection of emissions in hot-flue gas and the other in diluted or cooled gases (Denier van der Gon et al., 2015). In the second approach fraction of gases can condense increasing the sampled PM mass. In the emission inventory of Lombardy this approach has been considered as more conservative. Table 1 reports the emission factors EF_t used in this study, they can be compared with the reference data of EMEP/EEA defined as total PM10, different from the value of PM10 solid, not considering the condensable. The ratio between solid and total mass can vary from 20% to 50%, decreasing for the lowest emissive appliances.

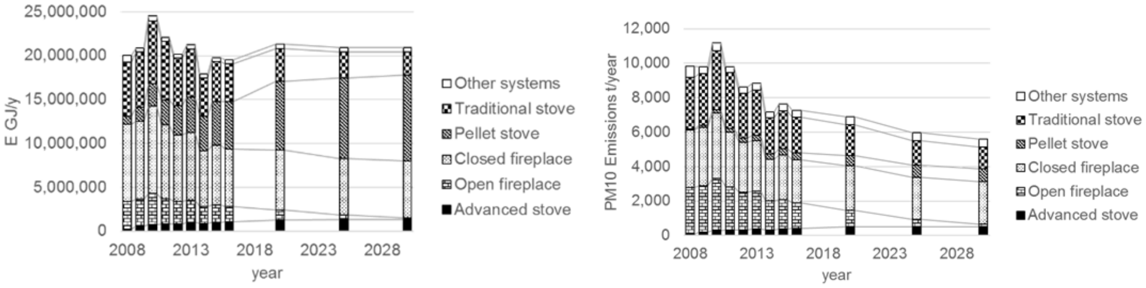

Figure 3: Time-series and projection of energy consumption and PM10 emissions in Lombardy for different typologies of wood domestic heaters.

3. Results and emission projections

By the combination of equations 5 and 6 is possible to obtain the indicator of energy burned in different appliances at the municipal level. Figure 3 reports the energy consumption for Lombardy for the period considered. Projection of total energy consumption from wood assumes a limited increase on the calculate value for 2016. As a matter, emissions are due by the combination energy consumption and the emission factors of table 1, as in the following equation:

$$Emissions_{y,m,t} = E_{y,m} \cdot CF_{y,m,t} \cdot EF_t \quad (8)$$

4. Conclusions

The entire methodology for reconstruction time-series for emissions from residential wood heaters has been presented and detailed. This approach has been extended for the development of emission projection with the effective case of Lombardy up to 2030 and results as an effective solution for similar estimates in the years where no data on CATI or other sources are available or scheduled. The harmonisation with domestic heater registers will allow to track the transitory compilation phase in combination with other data sources with less frequency of updating. In this paper the striking relationship is also presented between domestic biomass pollutant release estimates and the coherence with local energy balances, analysing the existing approaches of time-series reconstruction by HDDs variation and proposing, on the base of a huge number of variables, shortcuts technical variables for the calculation of local domestic biomass consumption. This methodology will be helpful in reconstructing older time-series or completing data, in propagating disaggregation of inventories or sampling statistics as CATI and in near real-time estimates of emissions from biomass in residential sector.

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