ENVIRONMENTAL IMPACT OF DOMESTIC AND CENTRAL NATURAL GAS HEATING BOILERS - A RESIDENTIAL BUILDING CASE STUDY

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SUMMARY

In the present paper comparison between emissions from natural gas heating systems applied to a residential building and its apartments located in Florence (Italy, EU) is shown. Two building designs were considered: the reference residential building proposed as a standard model by the Italian Association of Air Conditioning, Heating, Refrigeration (AICARR) and its single flats. Both these two cases were studied with higher insulation. The operating response of different boilers due to the hourly heating power demand of the building was studied. CO and NO_X emissions were evaluated during the heating season and during each month. Results show that the centralized boiler is more suitable for building heating demand and has a lower emissions impact.

INTRODUCTION

High ozone levels, summer smog in cities, forest depletion and the threat of irreversible changes in climate require drastic reduction of air pollution as the only solution. The White Paper [25] introduced emissions standards in the European Communities Countries focusing on the fact that a third of our energy consumption and the resulting emissions can be ascribed to domestic heating and hot water production. The Kyoto Protocol for greenhouse gases and the introduction of emission standards rouse several studies and technologies for low NO_X emission of small-scale combustion equipment [8,17,18].

There are many measures adopted in building design as well as many laws in Europe on energy saving and integrated energy use with particular attention to sustainable development and environmental pollution [24,25].

There are many certification schemes to identify products with different degrees of energy efficiency. Some are specifically oriented to environmental effects, taking into account emissions from the use of appliances along with the life-cycle sustainability of the product. There is abundant literature [5,10,12] concerning greenhouse gas emissions reduction. Nonetheless literature on the emissions from domestic heating systems for different buildings is not widespread yet [3,14,18].

Boilers for residential purposes, space and domestic hot water heating, are usually characterized by the type of fuel utilization [6,7]. The most common are either gas-or-oil fired. Occasionally electric resistance boilers are installed. In the case of oil fired boilers the most efficient improvement used is to replace the existing burner with a new one and thereafter to control mix of fuel and air blown into the boiler.

This control is typically a regular maintenance measure. Residential heating systems' efficiency is strictly connected to building heating demand, depending on its envelope and specific thermal capacity, and to environmental impact due to pollutant emissions of different types of burners and boiler's regulation system.

The utilization of condensing boiler for gas-fired boilers can increase boiler efficiency and reduce emissions. This solution maximizes heat recovery from the exhaust gases by including the latent heat released during condensation of the flue gas water vapour, but it must be verified comparing hourly heating demand of building to its operating conditions.

The introduction of a new gas burner technology using the V-shaped flame stabilized at the centre of the burner blade [8,12,13,14,16], the modulating fan powered premixed low NO_X burners [16], and the new catalytic combustion technology for different applications for condensing boilers and water heaters [23], should permit high combustion efficiency and low pollutant emissions. The V-shaped flame technique bases on an extended bladed combustion front with low mean temperatures and low NO_X, CO_X, HC emissions [14,17]; fully aerated premixed burner technology provides the lowest NO_X emission values and low CO_X and other air borne pollutants [3,8]. Likewise flameless catalytic combustion applied to domestic heating systems, then catalytically stabilized and completely catalytic radiation boiler permit low environmental emissions.

These recent studies are not applied in the real plant systems [12,13]. Obviously looking at the existing heating old systems in buildings, not all of them are able to meet these new combustion techniques.

In particular there are no studies of domestic and centralized natural gas boiler applications in transient conditions.

The aim of this work is to analyze the incidence of energy saving and fuel consumption reduction on pollutant emissions, due to different heating energy need of building provided by different boilers and burners combinations.

Environmental impact of the whole building provided by a central gas heating system for space and hot water heating, was compared to that one due to each flats provided by single domestic facilities. Transient condition emissions experimental data for different types of burners have been used [4].Hourly space heating load and hourly hot water load of the studied building were computed for the heating season. Climatic data of the standard year of Florence (Italy, EU) were used [2]. CO_X and NO_X emissions due to heating systems working hours at different load were analyzed.

METHODOLOGY

Building design (structure, envelope and connected heat losses) and heating plant were considered as an integrated system. Different space heating and domestic hot water heating facilities were taken into account. Three types of heating boilers and gas burners regulations were studied:

- a wall mounted boiler with room sealed, 25 kW nominal power and modulating low NO_X burner with drawing up fan;
- a base boiler with open chamber, low NO_X burner with on-off regulation and 35 kW nominal power;
- a wall mounted boiler with conventional burner (Bunsen flame), on-off regulation and 25 kW nominal power.

Experimental results from direct measurements of CO, CO_2 and NO_X emissions for the considered boilers, published by the authors in a recent paper [4], were used. Data refer to cycles of tests with alternative on-off phases were conducted and breaks of 5, 10, 30, 120 minutes starting from different combustion chamber temperatures and test cycle at nominal load was composed by a set of 30 minutes tests, followed by increasing time breaks when the boiler is switched off. Breaks of 5, 10, 30, 120 minutes were chosen to study transient working conditions of boilers, starting from different combustion chamber temperatures.

Experimental results [4] used in the present paper for three different boiler and burner combinations are shown in figures 1,2. Emissions impact, when the whole studied building or each single flat of it are provided by these boiler types, were compared. The residential building proposed as a standard model by the AICARR in the '60's [20] was considered. Four similar flats located on two floors compose the building. The total building volume is 865 m^3. The mean volume of a single flat, with a mean height of 2.7 m is 216 m^3. Heat losses trough the envelope of the building and of the single flat were computed before and after some retrofitting measures. Table 1 shows thermal parameters of the envelope for these two conditions. In tables 2-3 peak load for the building and a single flat are reported.

Italian Standard procedures [21,22] were used to evaluate heating energy needs and peak loads, for the whole building and for each flat, before and after retrofitting measures. Local climatic conditions, solar thermal gains for opaque and transparent surfaces and internal thermal gains were taken into account for the steady state energy balance of each zone of building and flat. An appropriate computational tool was built by using interactive spreadsheets. Hourly climatic data of the standard year were used [2] to evaluate temperature differences between inside and outside ambient.

The utilisation factor shows the part of energy gains (solar irradiation and internal energy gains such as heat from electrical appliances and people), when available, can be stored in building constructions to be transmitted into the zone. The utilization factor of free solar and thermal gains of building was evaluated as a function of all thermal gains to load ratio and of building thermal inertia. This last parameter was expressed by the time constant of all the zones for each flat and for the whole building. Each flat and building were evaluated separately, because of different heating systems with different types of burners. Taking into account some retrofitting measures the heating energy need for building agrees with the imposed value due to Italian Standard [19], considering a fixed internal temperature value of 20 °C with a tolerance of ± 2 °C. Whole building and one flat, before and after retrofitting (table 1, 2, 3), were considered provided with the different studied boilers. Duration of boiler's working and turning off, that are function of temperature difference, of building heat capacity and of the boiler typology, was evaluated for the on-off regulation system. Emissions impact of boilers were compared. The nominal power of the studied boilers is higher than the maximum thermal load calculated for building and flats. Hot water demand was calculated separately from heating demand (table 4).

Table 1 Building envelope thermal characteristics for a single flat and for the building.

Before retrofitting measures	Thermal transmittance [W/m^2 K]	After retrofitting measures	Thermal transmittance [W/m^2 K]
Windows single glazed in steel frames	5	Double glazing for all the windows not buffered by conservatory or balcony enclosure	2.3
External walls: concrete, brickwork 27 cm	1.22	Additional insulation with external sandwich elements of 5 cm width for all the external walls	0.5
Roof structure: concrete poor insulation	1.52	Roof with added insulation of 12 cm mineral wool	0.51
Ground Floor with poor insulation	1.4	Ground floor with added insulation 5 cm polyurethane	0.34

Table 2 Total thermal loss coefficient and nominal peak load for building

Building	Thermal loss coefficient U [kW/K]	Nominal peak load [kW]
Before retrofitting measures	1.09	30.49
After retrofitting measures	0.53	19.85

Table 3 Total thermal loss coefficient and nominal peak load for a single flat

Flat	Thermal loss coefficient U [kW/K]	Nominal peak load [kW]
Before retrofitting measures	0.28	7.94
After retrofitting measures	0.13	4.78

Table 4 Sanitary equipments flow rate for a flat.

Sanitary equipments	Water flow rate [l/s]
1 bath sink	0.10
1 bidet	0.10
1 kitchen sink	0.20
1 shower	0.15

A correlation equation that relates the water needs per hour, W, was built with reference data [1,11] as a function of the mean number of users for flats, N:

$$W = 27.702\ N + 28.884\ ;\quad R^2 = 0.93 \qquad (1)$$

where R is the R-squared value used to evaluate the reliability of the regression line. Regression equations reported in some reference models [9] are comparable to the above calculated. Hourly typical domestic hot water load, for an average family composed by 3 persons, has been obtained from experimental data [1,9] as it is shown in figure 3.

Considering for each flat that a tap opening duration of about six minutes, hot water demand controls the power supply. Hot water demand for each hour is calculated taking into account the supply water temperature at 50°C for a temperature difference of 30°C. Then for a water mass flow of 0.2 kg/s with a rise temperature of 30 °C, the requested power is 25 kW, which meets the boiler's one. Total hot water consumption evaluated considering same taps opening, is greater than that shown in figure 3. The 35 kW boiler can not satisfy hot water power demand for the whole building. So that a water storage tank was considered. By taking four delivering taps for each flat, results a contemporary factor of 30% [15]. Table 4 provides the considered water flow rates for different sanitary equipments. Under these conditions a 300 litres hot water storage tank is enough for the whole building. The 35 kW boiler can easily provide the needed water also with a 50°C rise temperature. For an on-off burner regulation, the building heat capacity C was calculated for a temperature variation of 4 K, to estimate the working and turning off period of the boiler as function of temperature difference. The value of thermal capacity of building considered is 144 MJ/K. The working and turning off periods are calculated by:

$$\tau_{on} = (C\ \Delta T) / (P - H_{tot}) \qquad (2)$$

$$\tau_{off} = (C\ \Delta T) / H_{tot} \qquad (3)$$

With t_i=20°C and: $H_{tot} = U\ (t_i - t_e)$ (4)

Daily CO and CO_X emissions due to heating and to hot water demand were evaluated:

$$E_{tot_{CO}} = \sum E_{CO}\ \varepsilon\ P\ \tau_{on} + \sum E_{CO}\ P\ \tau_{H_2O} \qquad (5)$$

$$E_{tot_{NO_X}} = \sum E_{NO_X}\ \varepsilon\ P\ \tau_{on} + \sum E_{NO_X}\ P\ \tau_{H_2O} \qquad (6)$$

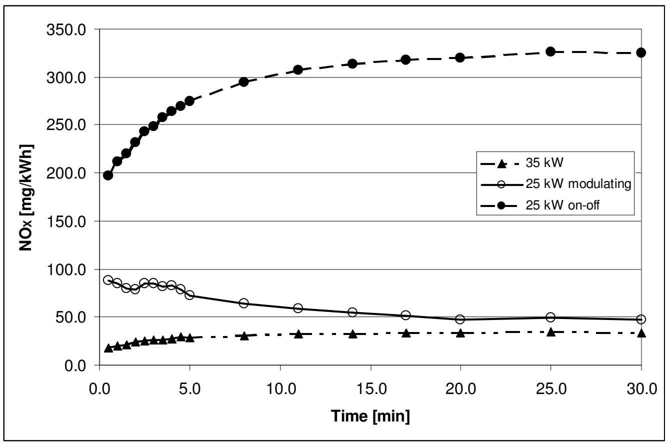

Figure. 1 NO_X emissions of the studied boilers for test cycle at nominal load composed by a set of 30 minutes tests.

where E concerns the (total) daily CO and NO_X emissions due to heating and hot water demand; P is the boiler's power; ε is the percentage of the (peak) nominal power, assumed always 1 for the on-off boiler. This computation was extended to the legal heating season for Florence (Italy, EU) and from 6 a.m. to 10 p.m. of each day.

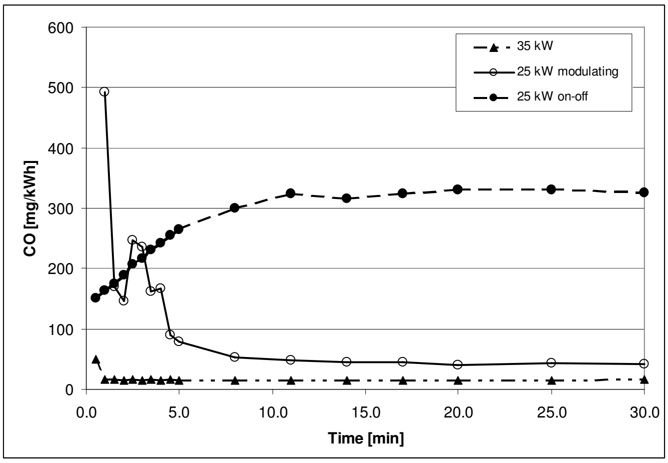

Figure. 2 CO emissions of the studied boilers for test cycle at nominal load composed by a set of 30 minutes tests.

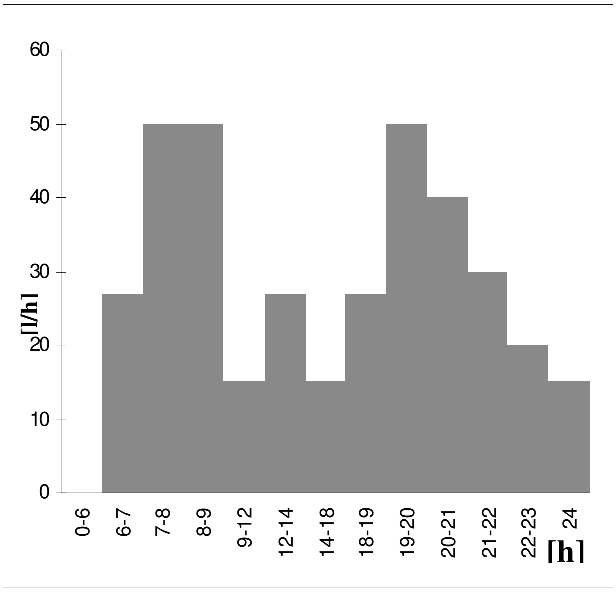

Figure 3 Typical domestic hot water load - 3 persons, average family

RESULTS

Hourly heating load and hourly hot water demand were calculated for flats and building. Results were obtained for each month of the heating season. Florence heating season is 151 days per year (starting from 15 November). Heating and hot water CO and NO_X emissions for the six months were calculated for the low NO_X burner with on-off regulation on 35 kW nominal power boiler, for the 25 kW boiler with modulating low NO_X burner, and for the 25 kW boiler with on-off regulation conventional burner (Bunsen flame). The 35 kW nominal power boiler was used for the building; the last two boiler typologies were used for each flat.

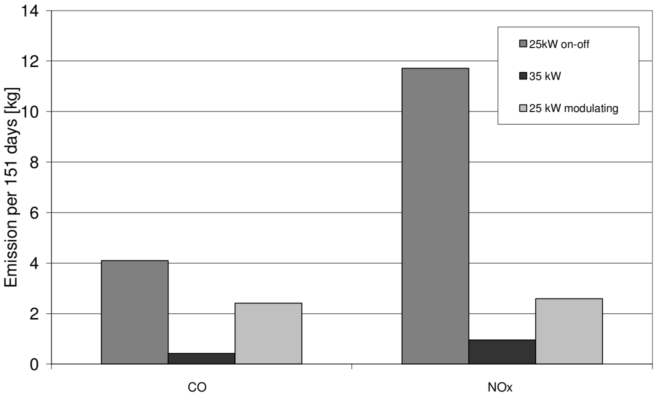

Figure 4 CO and NO_X emissions for the heating season (151 days per year)– Building and four flats after retrofitting measures.

The emissions results, obtained for building and flats with high-insulated envelope (tab. 1) were compared.

The 35 kW boiler considered for the higher insulated building, produces lower CO and NO_X emissions, during heating season and each month, than the corresponding values calculated for the other two boilers considered for all the four insulated flats (figures.4,5). Comparing monthly and seasonal CO and NO_X emissions, obtained for the reference building and four flats, with the corresponding values obtained for the higher insulated building and flats (figures.6,7), the 35 kW boiler always provides lower values than the 25 kW on-off and modulating boilers.

Moreover, the same comparison between 25 kW on-off boiler with the modulating one, shows that the CO and NO_X monthly and seasonal emissions for this last kind of boiler are lower than the first one.

Boiler with a modulating burner, works continually and it stops only when the power demand is lower than 20% of nominal power.

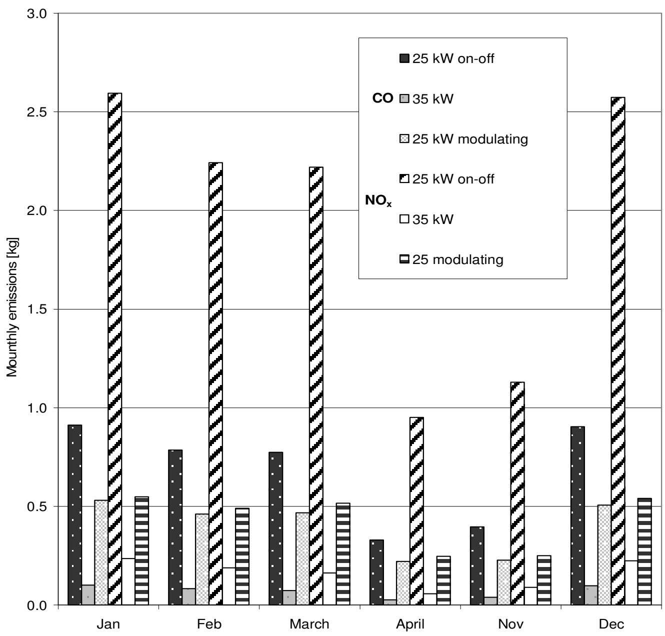

Figure 5 Monthly CO and NO_X emissions – Building and four flats after retrofitting measures.

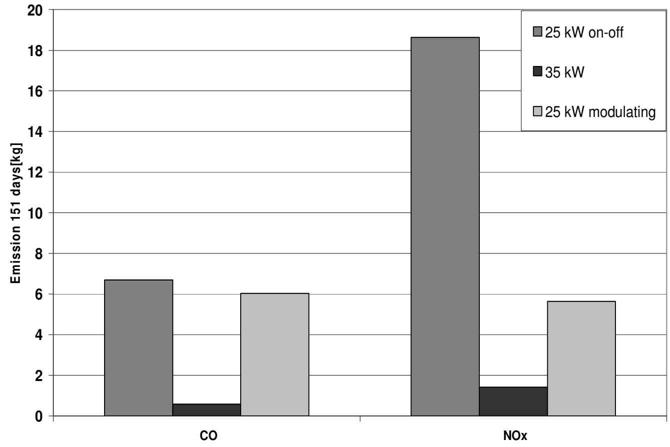

Figure 6 CO and NO_X emissions for the heating season – Building and four flats before retrofitting measures.

A day of the heating season, when the outside air temperature value is 0°C, that corresponds to the 13th January, was considered because hourly thermal load of this day for building, corresponds to design building peak load due to the 20°C temperature difference between inside and outside ambient air.

Figure 8 shows that modulating boiler for a single flat, without retrofitting measures, works at about 30% nominal load from 6 a.m. to 22 p.m. If the retrofitting of flat is considered, it modulates on 20% nominal load only from 6 a.m. to 12 a.m.. Load peaks on the graph are due to hot water demand.

As it can be seen by comparisons, at specific climatic conditions and considering building retrofitting measures, it is more convenient by energy, economic and environmental impact point of view, to use the centralized base boilers with low NO_X burner, because of the lower number of starts. Comparison shows that our 35 kW nominal power base boiler provides lower emissions for all the heating season and for each month.

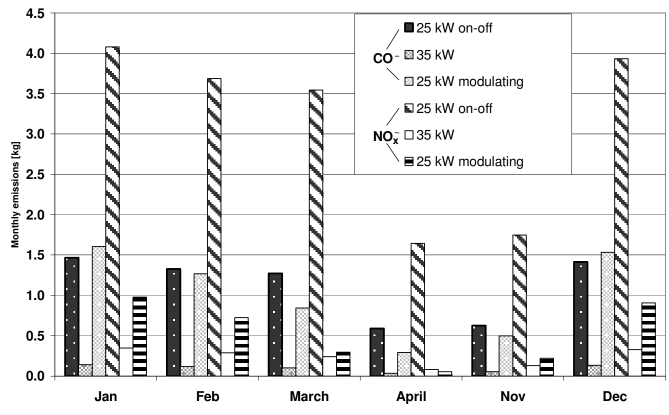

Figure 7 Monthly CO and NO_X emissions –Building and four flats before retrofitting measures.

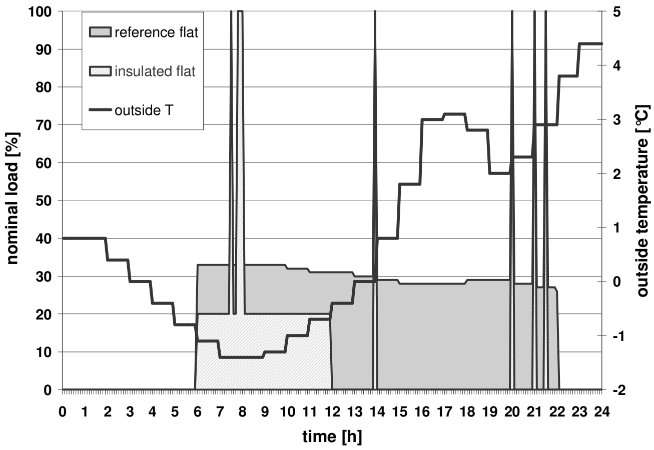

Figure 8 Rate of nominal load for the modulating boiler Flat with and without retrofitting measures 13th January

CONCLUSIONS

The more reliable domestic boiler application depends on local climatic conditions and connected building heating energy demand, but also on its operating conditions during defined daily heating time. Existing and new centralized base boilers are more suitable for buildings energy retrofitting especially if they are connected to the actual gas and temperature sensors [9]. The present study was limited to the available data; this is the reason because a centralized modulating boiler was not taken into account. At present transient condition emissions data, for a condensing boiler of the same power and with modulating gas burner, are not available, but Authors believe they will be lower.

Results show the importance of transient conditions for the environmental impact due to CO and NO_X emissions. This effect is not only due to the lower energy consumption but to the start characteristics of boilers. Consequently, both from the energy point of view and pollutant emission, in order to have a boiler continuous working it is better to use small size boilers with heat storage.

NOMENCLATURE

C	heat capacity [MJ/K]
E	daily emission [mg/day]
H	heat losses [W]
N	users number eq.(1)
P	boiler's power [W]
R^2	regression coefficient
t	temperature [°C]
ΔT	temperature difference [°C]
U	total thermal loss coefficient [W/K]
W	water demand [kg/d]
Greek symbol	
ε	percentage
τ	time [s]
Subscripts	
CO	carbon monoxides emission
e	outside
H_2O	water
i	inside
NO	nitrogen oxides emission
off	not working boiler
on	working boiler
tot	total

REFERENCES

[1] Furbo S., Jørgen R.,Vejen NK. Retrofitting of heating system for space and domestic hot water heating. (Vandbesparende foranstaltninger. Miljøudvalget) Report Building and Energy Institute IBE, Technical University of Denmark, DTU DK, February 1993 (in Danish).

[2] Alabisio M., Sidri R. Gestione archivio anno tipo, Ente Nazionale Energia Elettrica Centro Ricerche ENEL CRTN, Milano, 1995.

[3] Foster T., Dupont V., Pourkashanian M., Williams A. Low-NOx Domestic Water Heating Appliances. The Journal of Institute of Energy, 1994, 472, pp.101-108.

[4] Grazzini G., Balocco C., Sarti M. Transient conditions emissions from low-power gas heating systems. XXIII Nat. Conf. on Heat and Mass Transfer – Italian Union of Thermal-Fluid Dynamics, Parma (Italy, EU) 20 th - 22th June 2005.

[5] Hamelinck CN. Potential for CO_2 sequestration and enhanced coal-bed methane production in the Netherlands. NOVEM, Utrecht, the Netherlands. NWS-E-2001- 07.

[6] Hoefer U., Frank J., Fleischer M. High temperature Ga_2O_3-gas sensors and SnO_2-gas sensors: a comparison. Sensors and Actuators B Chemical, 2001, (78), pp. 6-11.

[7] Jacob L., Norris J. Domestic water heating in UK. European Renewable Energy Magazine, Sun at work in Europe, June 1996,11, (2).

[8] Joynt B., Wu S. Nitrogen Oxides Emissions Standards for Domestic Gas Appliances - Background Study. Environment Australia Report, February 2000.

[9] Lawaetz H., Bøhm B. Systems for heat supply - Mathematical model for heat production, distribution and heat demand. (Varmeforsyningsalæg-Matematiske modeller for produktionion distribution og varmebehov) Technological Institute of Copenhagen, October 1984 (in Danish).

[10] Marion J., Nsakala YaN., Griffin T., Bill A. Controlling power plant CO_2 emissions: a long-range view. DOE Publication, 2001.

[11] Mazin M., Maleki M. Optimization of the hot water supply system - Project Report (Optimering af varmt brugsvandssystem-Ekasamensprojekt Hovedrapport), Thermal Insulation Research Laboratory, Laboratoriet for Varmeisolering, Technical University of Denmark, DTU DK, July 1995 (in Danish).

[12] Miller F. Heating without polluting: the flameless burner. Fraunhofer Inst. for Solar Energy Systems, Friburg 5 February 1997.

[13] Moallemi F., Batley GA., Dupont V., Williams A. Experimental and Modelling Studies of Catalytic Burners. Eurotherm Sem. N. 54, Compact Fired Heating Units, 11-12 Dec. 1997, Leuven, Belgium.

[14] Ritter H., Benke G. Natural gas for domestic appliances in Austria. SAVE-Conference: Energy Efficiency in Household Appliances and Lighting, Naples, Italy, 27-29 Sept. 2000.

[15] Riva F. Guida agli impianti tecnici-Impianti idrosanitari: criteri di dimensionamento ed installazione, PEG, Milano, 1985.

[16] Solero G., Beghi M. Experimental fluid dynamic characterization of a premixed natural gas burner for domestic and semi-industrial applications. The Inst. of Energy's II Intern. Conf. on Combustion and Emissions Control, 4-5 Dec. 1995, London, UK; pp. 39-48.

[17] Toqan M., Nicholson J., Briggs O., Borio R., Beér J. Low NO_X Burners for Boilers and Furnaces: Design and Application. Power-Gen. Europe 97 Conf., Madrid, Spain, June 17-19, 1997.

[18] Twist TH., Hargreaves KJA. Emissions control and its implications on the domestic gas burner manufacturer. The Inst. of Energy's II Intern. Conf. on Combustion and Emissions Control, 4-5 Dec. 1995, London, UK; pp. 29-38.

[19] UNI 10344 Riscaldamento degli edifici. Calcolo del fabbisogno di energia. Comitato Termotecnico Italiano CTI, November, 1993

[20] UNI CTI Esempio di calcolo dell'isolamento termico di un edificio residenziale di nuova costruzione. L'Installatore Italiano, anno 32, n.1 January 1981, pp.11-50.

[21] UNI EN ISO 13789 Prestazione termica degli edifici - Coefficiente di perdita di calore per trasmissione. Metodo di calcolo, March 2001.

[22] UNI EN832 Prestazione termica dell'edificio. Calcolo del fabbisogno energetico per il riscaldamento degli edifici residenziali, June 2001.

[23] Vaillant SRo, Gastec AS. Catalytic combustion in a domestic natural gas burner. Catalysis Today, 1999, (47), pp.415-420.

[24] Vekemans G. Boiler inspection in the EU: achievements and challenges for the future. SAVE Conference, 8-10 Nov.1999, Graz, Austria, Vol. I-I-10.

[25] White Paper - An Energy Policy for the European Union, EU, (Una politica energetica per l'Unione Europea) COM (95) 682, December 1995 (in Italian).