

Transition to an intelligent use of cleaner biomass stoves

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Abstract: *In Europe, inappropriate user behaviours in the operation of wood-burning stoves (WBSs) results in substantial energy losses where fireplaces and conventional stoves are major contributors to undue emissions of health damaging fine particulate matter (PM_{2.5}). The design and adoption of cleaner WBSs are relevant issues to save energy and avoid greenhouse gas (CO_{2e}) emissions. This work compares the operating performance of 3 types of biomass stoves used in Europe in their interaction with dwellings. Field studies were conducted in 24 houses in Portugal and Denmark to analyse wood-burning behaviours and their contribution to residential heating. Laboratory and energy simulations were performed to study their thermal efficiency, PM_{2.5} emissions and the influence of their usage on the indoor climate. This work shows that the operation of enclosed stoves in uninsulated Iberian homes emit more PM_{2.5} than the Ecodesign thresholds and cannot provide a stable comfort temperature. Despite reducing the CO_{2e} emissions by more than 3 times in relation to the use of open fireplaces, the operation of cast-iron stoves in insulated Nordic dwellings might cause overheating events. Independently of the European latitude, the adoption of more advanced stove retrofits and digital devices is a relevant measure to accomplish the Ecodesign goals through a better regulation of fuel loads and combustion air-inlets. Thus, the knowledge dissemination on cleaner wood-burning practices and the implementation of financial incentives towards a proper operation of biofuels in efficient installations according to each socio-economic context might support the transition to a carbon neutral use of WBSs.*

INTRODUCTION

As the most ancient energy behaviour, the inefficient use of wood for heating and cooking in fireplaces and conventional stoves remains a dominant practice worldwide. In Europe, the use

of wood-burning stoves (WBSs) persists as a main renewable heating source [1]. Here, firewood room heaters, tiled stoves and cookers dominate the European stock of residential wood combustion (RWC) appliances. According to a study conducted by Gram-Hansen in a suburb of Copenhagen [2], the energy use for space-heating varies from house to house. Other investigations suggest that the improper operation of wood fuels in traditional fireplaces and stoves is a common practice in European homes. As in developing countries, in Europe, RWC is a major contributor to the emission of climate forcing and health damaging inhalable particulate matter (PM_{2.5}) [3]. A study conducted in Southern-Europe by Vicente et al. [4] showed that lighting a wood stove from the bottom results in over 3 times more emissions of thoracic particulate matter (PM₁₀) than when doing it from the top. This work reported that these emissions are higher for a cold ignition than for a hot start condition. In this region, wood-burning occurs mostly in conventional systems [5]. Despite the environmental health risks caused by the inefficient use of WBSs, the adoption of cleaner wood-burning practices in efficient stoves and the reduction of the usage of fossil fuel based heating systems consists in strategic measures to reduce both greenhouse gas (CO_{2e}) emissions.

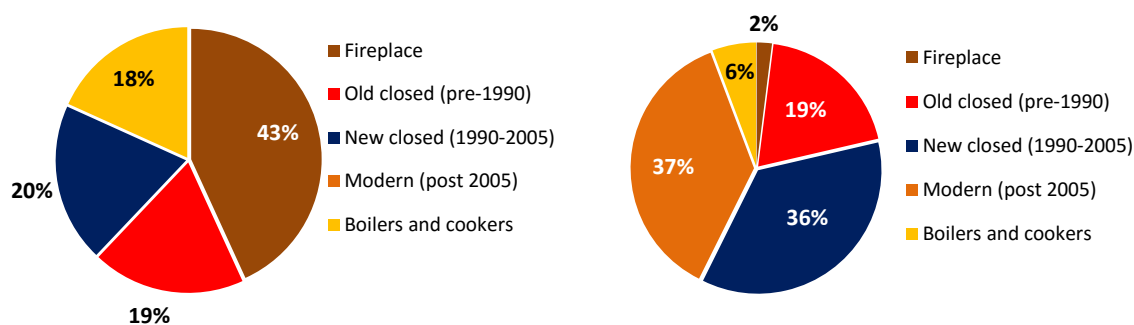


Figure 1-1. Stock of RWC appliances in Portugal (on the left) [5] and Denmark (on the right) [6].

Indeed, in the Iberian countries, there has been a substantial increase in the usage of more efficient WBSs [7], being this already a common practice in Scandinavia. Although, in Portugal, more than 80% of the renewable energy delivered for space-heating is still a result from wood combustion in inefficient installations. Here, it is estimated that more than 50% of the residential building stock is dominated by non-certified dwellings (pre-1990) without any insulation. Thus, the annual wood consumption in this country is estimated to be around 35.3 TJ [8]. On the other hand, in Denmark, it is estimated that 30% of the energy end-use is associated with residential heating [9] where 60% of the delivered renewable energy is a result of the use of WBSs. Here, the annual wood consumption is estimated to be around 31.2 TJ [6]. Figure 1-1 illustrates the composition of the stock of RWC appliances in the two EU countries. The total number of units is estimated to be around 1.5 million in Portugal and 0.7 million in Denmark. According to Gonçalves et al. [5] and Plejdrup and Nielsen [6], the

annual PM_{2.5} emissions from this sector were estimated to account more than 30% of the primary emissions these countries. Despite these facts, the use of cleaner WBSs generates more renewable energy locally at low-cost, especially when harvested from people's backyards and near forests. During the past 10 years, in Mediterranean houses, the use of wood heating increased due to economic reasons. Here, WBSs have been being used as primary heating sources. On the other hand, in Nordic dwellings, efficient WBSs have been being very often used as recreational heat sources. By distinguishing these two dominant European wood heating practices, it is possible to overlook that the efficient use of biomass stoves might function as a sustainable and independent energy system. For these reasons, it is very important to rethink the development of WBSs as more efficient combustion technologies that can interact with users and dwellings through a proper operation of fuels and combustion air-intakes. On this background, the transition to cleaner wood-burning behaviours constitutes a promising energy efficiency measure to reduce particle emissions, reason why future local-space heaters should comply with the Ecodesign framework [10]. Several investigations were conducted to improve the performance of WBSs under controlled conditions. Few studies analysed their use in dwellings [11], [12]. This work focuses on the influence of the usage of more advanced stoves in the heating grid of European houses.

2. METHODS

This work combines experimental and energy modelling studies used to simulate two European residential wood-burning practices in the use of WBSs for: i) primary heating, and ii) recreational heating. This article presents an analysis on the influence of user behaviours on the thermal performance of 3 types of WBSs used in both uninsulated Iberian and insulated Nordic houses. First, interviews (2.1) were conducted to assess the use of WBSs in these regions. Second, laboratory experiments (2.2) were carried to determine the performance of traditional, improved and advanced stove installations. Third, energy simulations (2.3) were performed to study the stove operation in the heating grid of Portuguese and Danish dwellings by estimating the associated energy usage and CO_{2e} emissions. Fourth, indoor climate measurements (2.3) were conducted to analyse the performance of the integration of certified and advanced stoves in Danish dwellings.

2.1. Field interviews

Field interviews were carried out in the regions of Portugal and Denmark with the highest levels of PM_{2.5} emissions associated with RWC in order to collect data on user behaviours during the operation of fireplaces, wood stoves and automatic stoves. The selection of the locations was based on data provided by national inventories. The district of Aveiro in Portugal [5] and the metropolitan regions of Copenhagen and Aarhus in Denmark [6] were chosen for analysis. The work was conducted in 24 houses located in the peri-urban and rural areas around these cities. Information about the usage of biomass fuels, type of stoves, building envelopes and the annual heat consumption was collected.

2.3. Laboratory tests

The laboratory tests were conducted at the University of Aveiro to characterize the typical operating conditions of a fireplace (A), a wood stove (B) and a pellet stove (C). The thermal efficiency, heat output and PM_{2.5} emissions were determined for each installation. For the wood stove, two retrofits were tested, namely the use of a single-secondary combustion air inlet and a pre-heating system of the primary combustion air-inlet that recovered heat from an annular chimney. The use of 2 types of wood pellets (certified and non-certified) in the pellet stove was also tested. Based on the field work and guidelines established by the European testing standards (EN13229 and EN14785), a testing protocol was designed to simulate the systems' operation in daily life. The studied parameters were calculated for 3 combustion batches with the duration of 45-60 minutes by determining the heat losses by the dwelling. For the pellet stove, 3 replicates of 10 minutes were considered assuming that this system works under steady state conditions. A mean value and standard deviation (SD) was based in 3 replicates for each condition. Equations 1, 2 and 3 were used to determine the systems' thermal efficiency. Equation 4 was used to calculate the heat output:

$$\eta = \frac{\dot{Q}_{in} - \dot{Q}_{lost}}{\dot{Q}_{in}} \cdot 100 \quad (1)$$

$$\dot{Q}_{in} = \dot{m}_b \cdot LHV_b + \dot{m}_{ca} \cdot h_{ca} \quad (2)$$

$$\dot{Q}_{lost} = \sum_{i=1}^{i=n} \dot{n}_i \cdot \bar{c}_{p_i} \cdot (T_{FG} - T^0) + \dot{m}_b \cdot w_{wF} \cdot h_{fg} \quad (3)$$

$$\dot{Q}_{room} = \dot{Q}_{in} - \dot{Q}_{lost} \quad (4)$$

Where $\eta(\%)$ is the thermal efficiency of the combustion system, \dot{Q}_{in} (kW) is the heat generated from wood-burning, \dot{Q}_{lost} (kW) is the heat loss by the dwelling, LHV_b (kJ/kg_F) is the low heating value of the biomass, \dot{m}_b (kg_F/s) is biomass burning rate, \dot{m}_{ca} (kg_F/s) is the mass flow rate of the combustion air, h_{ca} (kJ/kg_F) is the specific enthalpy of the ambient air, \dot{n}_i (mol/s) is the molar flow rate of the gaseous compound i , \bar{c}_{p_i} (kJ mol⁻¹K⁻¹) is the mean heat capacity of the flue gas, T_{FG} (K) is the mean temperature of the flue gas, T^0 (K) is the reference temperature considered to be 273K, w_{wF} (%) is the moisture content in the fuel, h_{fg} (kJ/kg_F) is the latent heat of vaporization of water and \dot{Q}_{room} (kW) is the heat transferred to the house, being n the number of combustion products. The heat loss with the combustion flue gas from the dwelling was determined by measuring the gas flow rate, its temperature and composition at 3.5 meters (top of the chimney), considered to be the typical internal height of the chimney inside a single-family house in Europe. The gas flow rate at the exit was determined by measuring the velocity inside the chimney at each 10 minutes using a pitot tube connected to a differential pressure sensor Testo 512, except for the measurements conducted for the fireplace where a differential pressure transmitter Jumo 404304 with a lower detection limit was used to determine the velocity of the flue gas in a duct with a larger section. The temperature in inside the chimney exhaust was measured using a K-type thermocouple. The flue gas composition in terms of CO₂, CO, TOCs and H₂O was measured at 180°C in a Fourier Transform Infrared

Spectroscopy (FTIR) analyser (Gasmeter, CX4000). The O₂ concentration was measured in a gas analyser ADC Model O2-700 with a Servomex Module. For both the wood stove and the pellet stove, the combustion air flow rate was determined using an air flow meter KURZ Model 500-2.0-P40 installed at the primary combustion air inlet. In the fireplace, it was not possible to measure the combustion air-flow rate due to the open configuration of the installation. Here, this parameter was estimated by applying a mass balance model based on both the wood-burning and flue gas flow rates and both the composition of the biomass fuel and the flue gas, considering the measured composition of the flue gas. The real-time wood-burning rate was monitored by a weight sensor DS-Europe Model 535QD-A5. Except for the measurements conducted in the FTIR analyser and differential pressure meters, all the collected data was saved in a computer based data control and acquisition system. The emission factors for PM_{2.5} were determined by collecting a partial flue gas sample from a diluted flue gas in a dilution tunnel under isokinetic conditions and at the ambient temperature. The samples were collected (in 47 mm quartz) for gravimetric analysis using a TCR TECORA (model 2.004.01) instrument operated at a flow rate of 2.3 Nm³h⁻¹. The PM_{2.5} emission factor for the fireplace was obtained from a previous study conducted at the same laboratory facilities by Gonçalves et al. [5].

2.3. Building simulations and measurements

The building simulations were conducted using the software BSim to evaluate the thermal performance of a fireplace and two types of stoves (manually and automatically operated) in two residential building models with the same dimensions, but with different external walls (with and without insulation). In both cases, a floor heated area of 114.3 m² and a net volume of 322.4 m³ were considered. The climate data used in these models was downloaded from the BSim website, corresponding to the meteorological information for a Typical Reference Year (TRY) in the cities of Coimbra (Portuguese model) and Copenhagen (Danish model), assuming that the climate in these two cities is representative of the typical conditions found in these two countries. Table 2-1 describes the information used to perform the building simulations of the heat flows in the two different types of buildings, taking into account the characteristics of their building elements and energy systems (e.g. materials, thickness of the walls, windows, insulation). In the model of the typical uninsulated Portuguese dwelling, it was considered that wood-burning was the only heating system in the house. The Danish building model had a central heating system operating in function of a set point temperature of 19°C. In this work, six simulations were conducted in order to collect data on the energy usage and greenhouse gas (GHG) emissions (in CO_{2e}) from heating installations and their influence on the heating grid and indoor climate. The CO_{2e} emissions associated with the usage of gas boilers in the Danish installations were determined by multiplying the energy consumption by the associated CO_{2e} emission factor for natural gas. The heat output for the 6 installations was obtained from the laboratory tests and references [13], [14].

Table 2-1. Building models, space-heating systems, stove heat output and its patterns of usage.

Model	Climate data	U-value (W/m ²)	Combustion system	Heat output (kW _{th})	Space-heating systems	Season	Day time
Portugal	Coimbra	0.7	None	0.0	None	Nov-Mar.	18-23
			Fireplace	2.0			
			Enclosed	4.8			
			Digital	3.0			
Denmark	Copenhagen	0.2	None	0.0	District heating	Oct-Apr.	6-8 & 18-22
			Fireplace	2.0	Natural gas		
			Enclosed	6.5	Heat pump		
			Digital	6.0			

Some of the tested stoves were using digital control devices (HWAM auto-pilot and Aduro smart) that guided users in the operation of fuel loads and combustion air-inlets. The indoor and outdoor temperatures were recorded in Tiny Tags for each 5 minutes in a winter month.

3. RESULTS

The field study conducted in Southern Europe suggests that the Iberian stoves are usually operated without secondary combustion air-inlets. In addition, the laboratory tests revealed that the manual operation of wood heating systems did not achieve thermal efficiencies higher than 70% and did not comply with the Ecodesign requirements for the emission of PM_{2.5} [10]. The building simulations estimated that in Portuguese dwellings the operation of cast-iron stoves did not provide stable indoor temperatures in the different compartments of the uninsulated house. In Nordic countries, the experimental and modelling studies showed that, in some circumstances, the manual operation of the cast-iron stove caused indoor overheating in some of the new Danish houses. On the other hand, the installation of secondary air-inlets and heat exchangers in the wood stove increased its performance to similar levels of those achieved by gas boilers. The automatic stoves provided a better regulation of the heat output in both types of dwellings.

3.1. Energy behaviours

According to the interviews, all the studied biomass local-space heaters were used in a daily basis. Table 3-1 describes the characteristics of the studied installations in terms of age, other heating sources, ventilation, biomass fuels and energy conversion technology as well as the associated types of use (e.g. space-heating, domestic hot water production). Table

3-1 describes that natural gas (NG) and oil (FO) boilers as well as heat pumps (HP), district heating systems (DH), solar energy systems (SE) and electric heaters (EH) were found in the houses. The building age was categorized in 3 types, namely old (prior 2000), old new (2000-2008), new (2008-2010) and brand new (after 2010). Table 3-1 shows information on the types of stoves used, showing that the fraction of house owners using wood stoves (WS) was higher than the amount of people using fireplaces (FP), masonry stoves (MS) and automatic stoves (AS). The interviews also revealed that all the homes in the Aveiro region had natural ventilation systems while in Denmark few houses had mechanical systems. Most of the interviewees in Portugal revealed to operate their wood stoves at higher wood-burning rates ($2-4\text{kg}_{\text{Fuel}}/\text{h}$ in wet basis) than the Danish interviewees ($1-3\text{kg}_{\text{Fuel}}/\text{h}$ in wet basis). Most of the Portuguese stoves were old systems with larger combustion chambers than the Danish ones. Typically, the Portuguese dwellings had no insulation and were equipped with stoves used for primary heating. Here, in some occasions, these appliances were also used as cookstoves.

Table 3-1. Information collected in the field interviews on energy use behaviours in Portugal and Denmark.

Installation by region	Building age	Ventilation	Energy systems	Fuel use ($\text{kg}_{\text{F}}/\text{h}$)	Stoves	Operation mode	Application practice
Aveiro	92% old; 8% brand new	Natural	HP;SE;NG;FO;EH	2-4 wood 0.8-1.3 pellets	25%FP; 58%WS 17%AS	67%M; 17%H; 17%D	Space-heat., cooking & domestic hot water
Copenhagen & Aarhus	42% old; 33% old new; 25% brand new	Natural Mechanic.	HP;NG; DH	1-3 kg /h Wood	17%MS; 50%WS 33%AS	58%M; 42%D	Space-heating

The interviews also revealed that more than half of the interviewees in Portugal operated their stoves manually (M), and the rest used more advanced applications such as hydronic (H) heaters or digital (D) devices. In both cases, it was possible to verify that the adoption of certified wood stoves and advanced applications increased the wood fuel savings in the range of 40-76% in relation to the use of fireplaces, being the minimum value associated with the manual operation of the appliances and the maximum one related to the adoption of automatic applications. A considerable reduction in the fuel consumption obtained by the adoption of certified wood stoves instead of fireplaces was reported.

Figure 3-1 shows the results concerning the heat supply in Portuguese and Danish houses. In Portugal, WBSs mostly worked as primary heating sources while in Denmark they operated as secondary systems. According to the presented results, the annual heat supply from wood-burning in the Aveiro region ranged between 0.8 MWh for the “New house J” and 10.1 MWh for the “Old house D”. In the Copenhagen region, these values ranged between 1.0 MWh for the “Old new house F” and 8.1 MWh for the “Old house A”. The annual heat supply from all heating sources in the Aveiro region ranged between 1.1-10.4 MWh for the same houses. In the Copenhagen region, these values varied between 7.3 MWh for the “New house L” and

39.7 MWh for the “Old house A”. In Portugal, the use of the WBSs was secondary for the “Old new house E” and “New house L” both using solar panels. In Denmark, the 2 advanced applications were used as primary sources in the “New house H” and “New house L”.

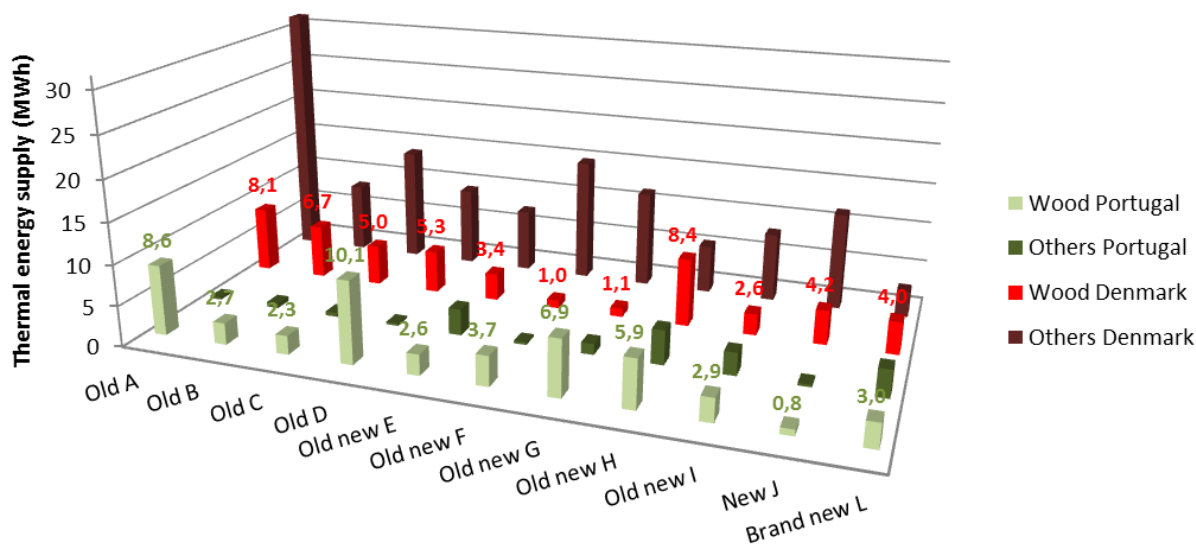


Figure 3-1. Heat supply from wood-burning and other systems in Portuguese (PT) and Danish (DK) houses.

For both cases, this field study suggests that the adoption of digital applications reduced the fire tending frequency during the operation of certified stoves.

3.2. Stove performance

The laboratory tests showed that the typical use of the automatic stove (C) using 2 different biofuels (EN-plus and locally produced pellets) achieved a thermal efficiency 4 times higher (up to 90%) than that obtained for the fireplace (A). The operation of the pellet stove (C) emitted around 4 times less PM_{2.5} than that observed for the use of the fireplace (A). The PM_{2.5} emission factor for the fireplace was 30% higher than for the wood stove (B), operating both in the same range of heat output in the order of 4-8 kW. Figure 3-2 shows the results on the energy and environmental performance of the fireplace A, of the wood stove and 2 retrofits as well as of the pellet stove. Here, it is possible to observe that the adoption of the advanced stove (C) contributed to reduce the emission of PM_{2.5} by more than 20% in relation to the use of the stove B, achieving values lower than 2.4 g/kg_{Fuel} (more than 40% below the Ecodesign targets) [10]. Here, the operation of the certified biofuels in the pellet stove caused 2 times less PM_{2.5} emissions than the use of locally produced (non-certified) pellets. The experiments on the design of the low-cost retrofits showed that the thermal efficiency of the wood stove can be increased by more than 10% by

the adoption of the annular chimney as a heat exchanger to pre-heat the combustion air, achieving values of thermal efficiency more than 3 times higher than those reached for the fireplace. However, except for the condition for use of the pellet stove and the usage of the retrofitted version of the wood stove B with a secondary air-inlet, the PM_{2.5} emission factors obtained for all the other systems did not comply with the Ecodesign framework (Fig. 3-2).

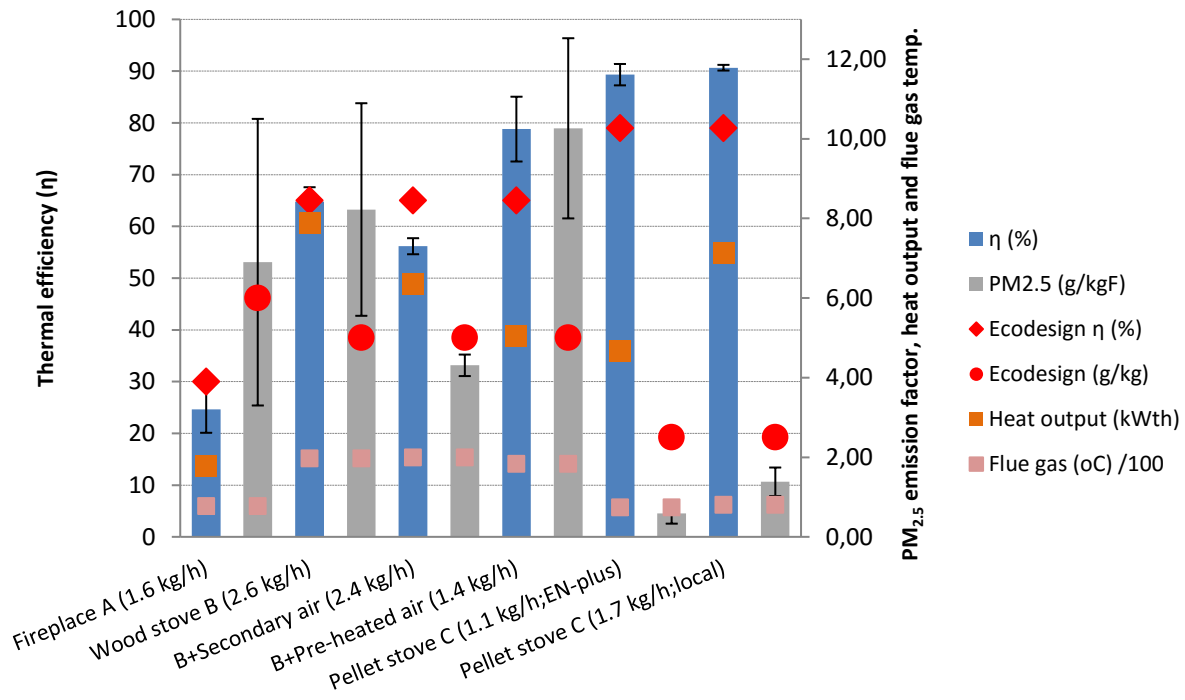


Figure 3-2 Thermal efficiency and PM_{2.5} emission factors of fireplace A, wood stove B and pellet stove C.

At the same time, the use of a single secondary air in-let in the wood stove B provided a reduction in the heat output from 7.8 kW (without any retrofit) to 6.2 kW. In this study, it was possible to confirm that the operating performance determined for the systems A and B was more influenced by behavioural aspects than that obtained for the installation C.

3.3. Heating performance

The total heating supply estimated in the energy simulations ranged between 3.3-8.9 MWh for the Danish building model and 0.0-5.9 MWh for the Portuguese one where the minimum values correspond to the situation where no stove was considered to be used and the maximum ones to the condition where the operation of a wood stove was taken into account. The contribution of the wood-burning systems to the heating grid ranged between 3.4-8.1 MWh and 1.8-5.9 MWh, respectively for the Danish and Portuguese models. Here, the minimum values are associated with the simulation of the operation of the automatic stoves while the maximum ones are related to the use of the fireplaces. The maximum usage of non-renewable energy through the operation of the central heating system in the Danish dwelling

was estimated for the situation where no biomass stove was used (heat supply of 3.3 MWh). On this background, the integration of certified stoves in the Danish heating grid insulated dwellings might save 57-77% of the non-renewable energy. The total thermal energy savings were estimated to range between 33% and 76% by the adoption of automatic stoves instead of the manually operated ones, respectively in the Danish and Portuguese houses. For these advanced installations, the estimated variations in the indoor temperature during a winter month were not as significant as for the manual operation of the cast-iron stoves, reflected by the smaller values of standard deviation (SD). Figure 3-3 shows how the annual CO_{2e} emissions might vary with the type of residential heating installation.

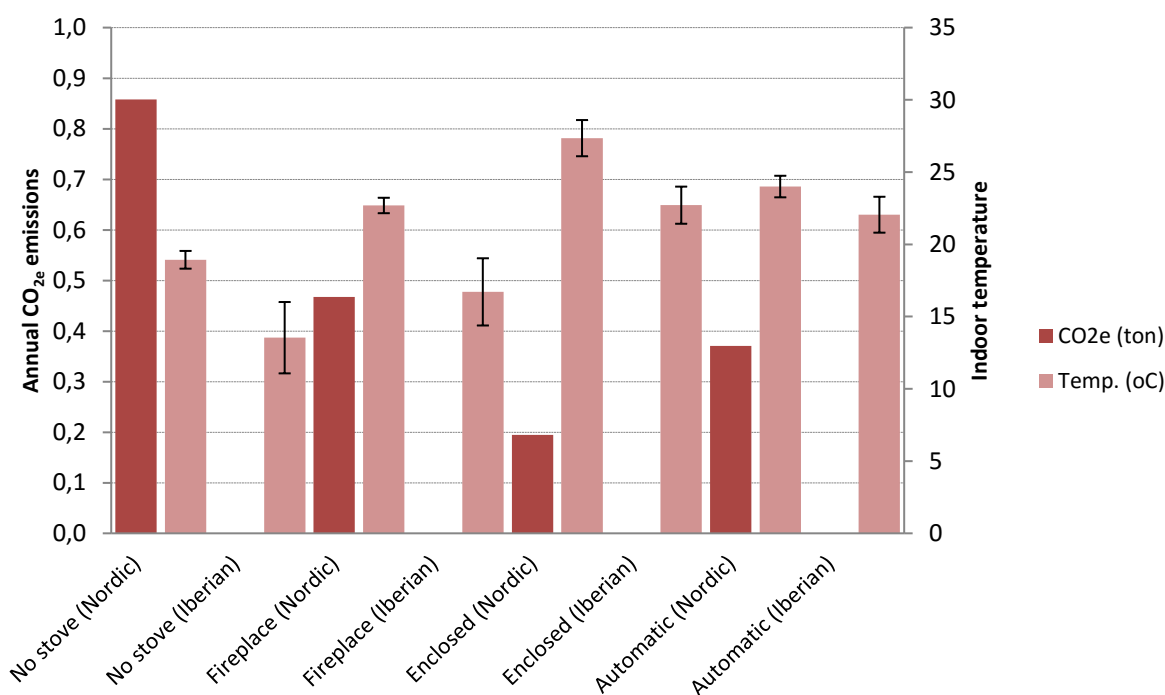


Figure 3-3. Estimated CO_{2e} emissions and indoor temperatures (\pm SD) in Portuguese and Danish dwellings. The GHG emissions were estimated by applying an energy conversion factor of 64.1 kgCO_{2e}/GJ in mass of CO_{2e} emitted to the atmosphere per unit of thermal energy released by natural gas [15].

The estimated GHG emissions achieved the maximum values over 0.8 tonnes per year for the operation of the Danish conventional heating systems without any biomass stove. The lowest CO_{2e} emissions were achieved in all Portuguese installations and when operating an enclosed (certified) cast-iron stove in the Danish dwelling. In this last case, the achieved CO_{2e} emissions were estimated to be more than 3 times lower than those reached for the situation where only a conventional heating source was operated. Although, for this condition, the energy simulation suggests that the use of this type of stoves might overheat well-insulated houses. The reduction in the GHG emissions was estimated to be around 57% by the adoption of the Danish automatic installation instead of the fireplace. Moreover, this advanced stove is

not expected to overheat the insulated dwellings. According to the indoor climate measurements, it was possible to verify that the manual operation of labelled cast-iron stoves in modern dwellings caused overheating events in Danish homes. The energy calculations and indoor climate measurements suggest that specific interventions such as the proper use of advanced applications can be combined with the installation of outdoor combustion air-intakes in new homes equipped with high-efficiency filters and functioning chimneys in order to increase the efficiency of the interplay between heating systems in order to minimize the impacts on deforestation and the undue emission of particulate matter.

4. CONCLUSIONS

In Europe, the development of advanced interplays between biomass fuels, efficient stoves and building insulations constitutes a sustainable measure to tackle climate and health risks. The transition to a more intelligent use of cleaner local-space heaters can be achieved by the adoption of low-cost retrofits and digital devices to support users in the regulation of the heat supply. This can be done by burning dried wood and pellets at low rates of 1-2 kg_{Fuel}/h, interplaying combustion air-inlets opportunely. The adoption of pre-heated secondary combustion air-inlets, chimney heat exchangers and electronic devices increases the thermal efficiency of wood stoves by at least 10%, reaching values over 80% and reducing PM_{2.5} emissions below 5 g/kg_{Fuel}. More efficient interplays between low-wattage stoves and insulated houses contribute to increase the thermal performance of the residential heating grid. The use of outdoor combustion air, heat storage reservoirs and functioning chimneys is suggested to reach similar performance levels to those achieved by modern gas boilers. As the most efficient systems, automatic stoves are costly for low-income families. Thus, public campaigns, involving sector stakeholders are suggested to incite a transition to a cleaner use of retrofitted stoves. European programs might support the adoption of advanced interplays between high-efficiency stoves and building insulation systems through financial incentives.

5. FURTHER WORK

Further research is recommended to support the design and dissemination of cleaner biomass stoves based on the knowledge about the users' interaction with residential installations. The applied scientific methods need to be refined to better study their operation in the real-world.

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