Aalborg Universitet

# Changes of indoor climate by the adoption of retrofitted wood-burning stoves

Luis Teles de Carvalho, Ricardo; Jensen, Ole Michael; Tarelho, Luis A. C.

*Published in:*
Proceedings Indoor Air 2014

*Publication date:*
2014

*Document Version*
Early version, also known as pre-print

Indoor Air 2014 conference, Hong Kong, July 2014
Topic B7: Impact of outdoor environment IAQ and energy efficiency

# CHANGES OF INDOOR CLIMATE BY THE ADOPTION OF RETROFITTED WOOD-BURNING STOVES

Ricardo L CARVALHO[1,*], Ole M JENSEN[1], Luís A C TARELHO[2]

[1]Department of Energy and Environment, Danish Building Research Institute, Aalborg University, Copenhagen, Denmark
[2]Department of Environment and Planning, Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal

[*]Corresponding email: rlc@sbi.aau.dk

**Keywords:** Improved stoves, Household interventions, Biomass savings, Indoor climate, Technological transitions

## SUMMARY

More than 3 billion people in the world rely on local solid-fuels for domestic cooking and heating through inefficient combustion, causing indoor air pollution and overheating worldwide.

Technological regimes were categorized in 18 popular stove models to describe how residential wood combustion is performed across the world. The stoves performance was traced through literature review, laboratory and field studies, according to the population´s income in 7 regions.

This technological map revealed that 92% of the wood consumption occurs in the south (cooking) while the largest share of wood heating happens in the north. The adoption of new stoves can save 15-50% of fuel and reduce 2-25 times the daily indoor concentrations of fine particles when moving from traditional to improved/advanced stoves (nanoparticles).

Ergonometric combustion chambers and proper exhausts are key-elements to delay biomass consumption, adjust heat/demand through air-staging and ensure the indoor climate performance of advanced stoves in future housing.

## INTRODUCTION

From the more than 3 billion people relying on solid-fuels worldwide, more than 1.3 billion are using traditional stoves in developing countries where firewood and charcoal are the most popular household fuels (WHO, 2010).

The indoor environmental impacts of domestic wood combustion for cooking and heating changes very much with practices, technologies and biomass fuels.

Although cooking is a widespread issue in developing countries, few attention has been given to the global inefficient regimes of household heating that cause a longer exposure to indoor contaminants during the winter season (Smith K et al, 2012).

Large indoor air pollution due to both incomplete combustion and poor ventilation conditions in low income communities are responsible for 3.5 million deaths per year (Johnson, 2013). Overheating and indoor air pollution by (ultra)fine particles caused by inappropriate matching of both heat production and demand can be a major problem for the indoor climate in low energy housing in developed countries (Carvalho, 2013; Georges, 2014).

## BIOMASS FUEL AND INDOOR CLIMATE

There is a large share of people in the world still using both traditional fuels and stove technologies. It is estimated that about 50% of the solid-fuels users in the world are located in South-east Asia and Western Pacific (*1UN, 2012; *2WHO, 2010; *3EC, 2013).

Table 1. Household biomass users in the world.

| Geographies | Population (Billion)*1 | Cooking (Million)*2 | Heating (Million) | % of world population |
|---|---|---|---|---|
| South-east Asia (SeA) | 1.8 | 1095 | ~300*1 | 16 |
| Western Pacific (WP) | 1.8 | 740 | >174*2 | 11 |
| Africa (AF) | 0.9 | 660 | - | 9 |
| Eastern Mediterranean (EM) | 0.6 | 179 | - | 3 |
| Latin America (LA) | 0.6 | 81 | >10 | 1 |
| Europe (EUR) | 0.8 | 25 | >179*3 | 3 |
| North America (NA) | 0.4 | 8 | 38*4 | 1 |
| Total | 7.1 | 2788 | 702 | >49 |

*4 assumed that 15% of the users are using heating stoves

Several aspects influence the adoption of residential energy systems due to a diversity of economical landscapes, social behaviors and environmental concerns. The use of wood stoves continues to be part of the daily life style of human kind independently of the speed of transitions taking place.

The transition to modern fuels although can be thought as a sophisticated use of biomass fuels towards the mitigation of outdoor/indoor climate effects. The current transitions in technology, biomass fuels and the relevance of its integration on the new household energy system is a core element of this research work.

Beyond the reduction of fuel consumption as a strategy to mitigate carbon emissions, variables such as the dwellings air-tightness, construction materials and the ventilation conditions might play a crucial role when designing proper low-emission stoves on the process of “changing indoor climate” (Carvalho et. al, 2013).

### Developing countries

In China it is estimated that 174 million people are heating their households with mass bed stoves which accounts more than 2% of the world population – twice larger amount of people than in Latin America (Li et al, 2009; United Nations, 2010).

In Latin America we can find cooking/heating regimes with either open fires or traditional stoves typical from the Andean regions while in Africa residential wood combustion is mainly used for cooking in 3-stone fires during the all year. In Africa, where the speed of transition to modern fuels is slower, 75% of the population in the continent rely on domestic solid-fuels as a primary system in single-family houses (WHO, 2010; Bonjour et al., 2013).

The amount of people exposed to inefficient wood heating stoves can be higher during 10-12 hours per day in the winter season in high altitudes of China, South-East Asia and South America and in many developed countries (Smith K et al, 2012).

In developing countries, domestic wood-burning is a major issue for women and children exposed to very high concentrations of fine particles over 150 µg m-3 (24-hour average) and the overheating of the stove can become a safety issue in rural households.

**Developed countries**

In Europe and North America, considering previous inventories, it is possible to presume that about 18% percent of the population in those regions is using wood combustion during the heating season corresponding to 4-6 months/year for 4-8 hours/day (European Commission, 2013). This together represents around 5% of the world share of residential biomass in stoves.

Deforestation and regional air pollution (fine particle emission to the outdoor environment) has been being object of public debate (Gonçalves  et al, 2012). The concentrations of fine particles $PM_{2.5}$ can reach 150 µg $m^{-3}$ (24-hour average) found in rural backgrounds where there is an high density of wood-burning stove installations.

In modern households for instance, previous field studies revealed that 3-air intake stoves ($\eta>75\%$) generate indoor emissions of ultra-fine particles. This happens when lightning and operating the stove in air-tight houses where the concentration of ultra-fine can reach $10^{11}$ particles/$m^3$, 7-90 times the background level concentration (Afshari et.al, 2011).

Combined with the intensive exposure to indoor nanoparticles during the wood combustion cycles, overheating might cause discomfort when the temperatures are over 26°C during the mild winters as experienced before in Danish single-family households (Carvalho, 2013).

**Transitions to modern fuels and change of indoor climate**

In most of the developed countries there has been an increase in the last decades in the use of biomass stoves for as either a primary or secondary heating, due to the current high prices of natural gas and electricity – “a seek” for home heat and cosiness (Salthammer et al, 2013).

Mid-income countries such as India, China, Brazil and Mexico are facing rapid household energy transitions to LPG and access to electricity, using biomass as a secondary household energy source. Fuel stacking is less common in Africa, reason why large cook stove programmes are stressing the importance of improved cook stoves and fuels.

Medium-term strategies to mitigate outdoor and indoor air pollution depend on both the adoption of high quality biomass fuels (pellets, briquettes, biogas and ethanol) and in the improvement of the energy conversion ($\eta>75\%$ through air-staging, gasification and pyrolysis). These new technologies can increase the retention time of the flue gas and thus, burning particles that are no longer released into the ambient air (Musil-Schläffer, 2012).

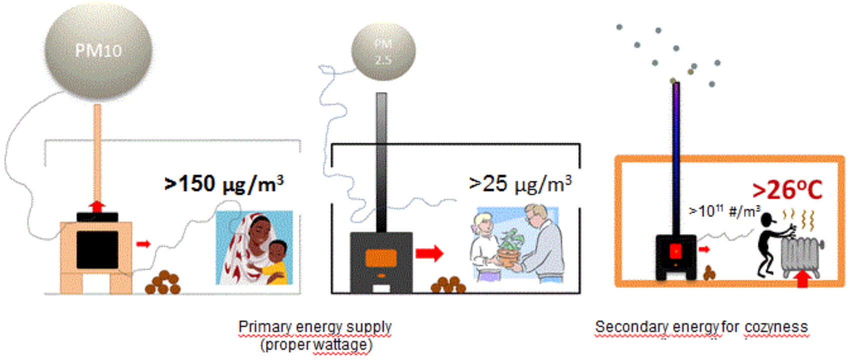

Figure 1. Change in particle emission with stove/envelope from low to high performance

The adoption of forced draft technologies can reduce the emission of fine particles and black carbon by 50-90% in improved combustion chambers (Anenberg et al., 2013). Advanced combustion is now more and more popular in developed countries, although producing ultra-fine particles in the lack of proper chimney draft during operation (Salthammer et al, 2014).

This study aims to map the use of biomass fuels in stoves and the relevance of the improvements towards the implementation of near-zero emission appliances.

## TECHNOLOGICAL MAPPING AND BIOMASS CONVERSION

Eighteen biomass stove technologies were categorized by type (traditional, improved and advanced), function (cooking and heating) and heat capacity (low, medium, high), as shown on the Table 2 in order to compare the distribution in the domestic use of biomass worldwide.

Table 2. Categorization of biomass stove models according to its performance.

| Stove type (St) | Traditional (T) | | Improved (I) | | Advanced (A) | |
|---|---|---|---|---|---|---|
| Power (P)/ Use (U) | Cooking η<30% | Heating η<30% | Cooking 30≤η≤40% | Heating 30≤η≤75% | Cooking η>40% | Heating η>75% |
| Low (L) 2/8 kW | Wood Tripod | Wood Mud | Pellet rocket | Wood Masonry | Waste to Biogas | Digital multi-stage |
| Medium (M) 3/10 kW | Wood 3-stone | Wood Steel | W/Briquette 3-chamber rocket | Wood rocket steel | Wood Gasifier TLUD | Pellet Auto |
| High (H) 4/13 kW | Wood Open fire | Wood Open fire | Wood 2-chamber Rocket | Wood 2-air intake | Wood Fan | Wood 3-air |

Traditional appliances were defined as those with energy efficiency lower than 30%, including open and 3-stone fires, commonly used in low-income regions. Improved technologies considered as a closed fire appliances with a cast-iron combustion chamber and sometimes covered with a mass brick layer (low-wattage stoves).

Advanced wood-burning stoves incorporate an even better control of the combustion process maximizing the burning rate by using secondary and sometimes tertiary air injection (3-air) and through the use of pellets in heating stoves or by introducing pyrolysis or gasification (TLUD in cooking stoves) in order to reach combustion rates of less than 1.5 kg/h. The use of domestic waste in for bio digestion can be a low cost technology as well in the households in developing countries (Waste to Biogas).

The heat output depends on the usage and the values pointed out in Table 2 are mean values varying from low (eg. heating low energy houses) to high heat output (eg. heating houses without insulation), considering a floor heated area ranging from 100-250 $m^2$.

The calculation considered a current regime of household energy use with more than 3 billion people in the world still relying on solid-fuels with a global population over its 7.1 billion inhabitants (UN, 2012), with more than 2.7 billion users living in developing countries and approximately 250 million of wood heating users in developed countries (European Commission, 2013).

The consumption of biomass in small scale appliances was estimated according to the equations 1 and 2, respectively, taking into account the shares of the 18 categories of stove models (Table 2) used across the 7 regions: SeA, WP, AF, EM, LA, EUR, NA (Table 1). The daily biomass use rates (obtained from the literature review and field studies in Europe and Latin America) were considered to vary between 1-10 kg/person in heating stoves and 0.9-2.6 kg/person in cooking stoves (from traditional to advanced, respectively).

The world biomass consumption in stoves in the domestic sector was estimated by the sum of the biomass consumption in the 7 regions. It was considered that 60-90% of the people in developing countries and 40-60% of the people in developed countries use traditional stoves.

$$\dot{BC}_j = \sum_{i=1}^{18} (N_i \cdot st_i \cdot tu_i \cdot p_i) \cdot \dot{B}_i \cdot 10^{-3} \cdot hy_i \quad (1)$$

$$\dot{BC}_w = \sum_{j=1}^{7} \dot{BC}_j \quad (2)$$

where $BC_j$ is the regional household biomass consumption in tonnes per share of type of stove $st_i$, use $tu_i$ and power capacity $p_i$, $B_i$ is the rate of biomass use in kg/hour; $hy_i$ is the number of hours of use per year, $N_i$ is the number of units installed in each region, while $BC_w$ is the household biomass consumption worldwide in tonnes with r=7 regions. The calculation of the regional CO emissions (stove performance indicator) for each stove model per region was carried out considering the emission factors varying between 10-100 gCO/kg.

## BIOMASS CONSUMPTION AND CO EMISSIONS

The current consumption of biomass in 2012 was estimated to be 2239 Mton/year, 92% of this occurring in developing countries in wood cooking/heating stoves, while about 207 Mton is consumed in developed countries in heating stoves.

With the largest amount of users, Asia is the continent with the largest amount of residential biomass and coal users with 1629 Mton (60% of the world users) while Africa with fewer users presents a fairly high consumption of 538 Mton/year only for cooking, due to the use of larger share of traditional appliances.

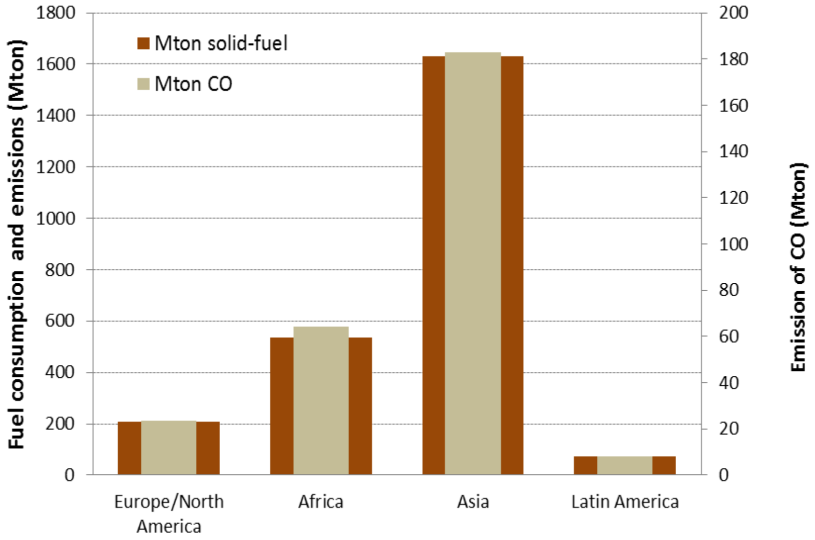

Figure 2. Solid-fuel consumption and CO emission by region (Mton in 2012).

In Europe, where traditional appliances have still been being used for residential heating during the last few years, the share of biomass consumption in the region is about twice higher than in Latin America where traditional stoves are still popular for domestic cooking in rural areas.

The large emission rate of CO per capita in Africa and even in the developed countries can be explained by the incomplete combustion in traditional 3-stone fires which are very popular in Africa and the remaining use of open fire places for all day during the heating season in Europe and North America. Changes occurred in the recent years towards the usage of new biomass cook stoves and fuels in Asia and that is one of the reasons for the lower emission rate of CO per capita in this continent when comparing with Africa.

## CHANGE OF INDOOR CLIMATE

This study shows how outdoor/indoor emissions might change within the different patterns of domestic wood consumption by the adoption of proper improvements for stoves depending on the climate and social environment: how it these changes may influence particle emissions?

Household air pollution (HAP) associated to wood cooking activities are mostly influenced by fine particle concentration ratios Indoor/Outdoor>1 in rural dwellings with natural ventilation. This ratio might be higher when we talk about heating activities in dwellings with a high air-tightness and natural ventilation: lower air-change rates during the winter season in cold climates. The air-intake from indoors might be insufficient to sustain a complete combustion in the combustion chamber on this cases.

In the south hemisphere we have the largest consumption of solid-fuels and the higher emissions of particles and CO in traditional appliances. In the north hemisphere, direct indoor emissions of (ultra)fine particles and overheating in houses with thick insulation is a new critical issue created by the use of modern cast-iron stoves (intermittent heat outputs).

Heating stoves also cause a longer and intensive human exposure to particles in most of the developed countries during 4-6 months per year, reason why it is imperative to move towards advanced wood combustion chambers where indoor emission of unburned gases might be easily mitigated by reducing the users interaction with the appliances and the use of pelletized wood seems to be a key strategy to cut down the daily human exposure to levels of $PM_{2.5}$ concentrations under 25 µg/m$^3$ (10 times lower than the level found in developing countries) and promote proper indoor comfort temperatures between 20-26 $^{o}$C by reaching a near-zero amount of ultra-fine particles (≤1µm) on the indoor air.

The global change of indoor climate depends not only on the design of ergonomic slow heat release, insulated combustion chambers (flame temperature above 400$^{o}$C) and air-staging technologies (regulated heat output through a complete combustion), but also on efficient household interventions, such as proper chimney height and draft designs in order to avoid nanoparticles (<300 nm) to escape into the living room. The stove is no longer seen as an isolated system.

## CONCLUSIONS

The implementation of advanced combustion is a key-strategy towards the transition to high quality biomass combustion in homes. The shift to new fuels and technologies can save half of the wood per house by increasing the conversion rate of wood progressively depending on the heat demands per area (heating) and per number of users (cooking).

The concentration of (ultra)fine particles can change by 2-25 times to levels below 25 µg/m$^3$ through a proper stove/chimney interplay in the house including its regular maintenance and by disseminating air cleaning technologies (extra draft pumps) and catalytic filters. The main concern here is not only the conversion efficiency but also its indoor climate performance looking at the stove/chimney as only one system to be integrated in the building envelope.

The improvements of indoor climate can be six times larger when moving from traditional to improved stoves, comparing with the possibility to move from improved to advanced stoves.

Three different scenarios for 2030 could assess the potential speed of transitions (policy making) in future work. International standards should include guidelines for proper stove integration (indoor climate performance in either regional kitchens or living rooms), essential to promote the demanded speed of transition depending on the social and cultural context.

ACKNOWLEDGEMENT

This research work was funded by the Portuguese Science and Technology Foundation (FCT) through the PhD grant with reference DFRH/BD/77171/2011 and the Danish Building Research Institute – Aalborg University.

## REFERENCES

Anenberg S C, Balakrishnan K, Jetter J et al. (2013) Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits. *Environmental Science and Technology*, April 2013.
Accessed on the 22nd January 2014: dx.doi.org/10.1021/es304942e

Afshari A, Jensen O, Bergsøe N, Carvalho R (2011) Impact of operating woodburning stoves on indoor air quality. In: Proceedings of: Indoor Air Quality and Climate, The 12th Conference of Indoor Air 2011, Austin, Texas, United States, 2011.

Berkeley Air Monitoring Group (2012) Stove Performance Inventory Report, Prepared for the Global Alliance for Clean Cookstoves, United Nations Foundation, Berkeley, October 2012.

Bonjour S, Adair-Rohani H, Wolf J et al. (2013) Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980–2010, *Environmental Health Perspectives*, 121, 784-790, May 2013.
Accessed on the 22nd January 2014: http://dx.doi.org/10.1289/ehp.1205987

Carvalho R, Jensen O, Afshari A, Bergsøe N (2013) Wood-burning stoves in low carbon dwellings. Energy and Buildings, 59, 244-251, April 2013.
doi: http://dx.doi.org/10.1016/j.enbuild.2012.12.006

European Commission (2013). Working Document on Possible Ecodesign and Energy Labelling Requirements for Local Space Heaters, Lot 15 Local Heaters and Lot 20 Combined, 2013.

Georges L, Skreiberg Ø, Novakovic V (2014) On the proper integration of wood stoves in passive houses undercold climates. Energy and Buildings, 72, 87-95, April 2014.
doi: http://dx.doi.org/10.1016/j.enbuild.2013.12.023

Gonçalves C, Alves C, Pio C (2012) Inventory of fine particulate organic compound emissions from residential wood combustion in Portugal. Atmospheric Environment, 50, 297-306, 2012.

Johnson M, Pilco V, Torres R et al. (2013) Impacts on household fuel consumption from biomass stove programs in India, Nepal, and Peru. Energy for Sustainable Development, April 2013.
Accessed on the 20th January 2014: http://dx.doi.org/10.1016/j.esd.2013.04.004

Musil-Schläffer B, McCarry A, Schmidl C et al. (2010) European Wood-heating Technology Survey: An Overview of Combustion Principles and the Energy and Emissions Performance Characteristics of Comercial Available Systems in Austria, Germany, Denmark, and Sweden. Prepared by: Bioenergy2020+GmBH, April 2010.
Accessed on the 27th January 2014: www.bioenergy2020.eu

Salthammer T, Schripp T, Wientzek S, Wensing M (2013) Impact of operating wood-burning fireplace ovens on indoor air quality. Chemosphere, December 2013.
Accessed on the 21st February 2014: http://dx.doi.org/10.1016/j.chemosphere.2013.11.067

Smith K, Pillarisetti A (2012) A Short History of Woodsmoke and Implications for Chile. In: Proceedings of: Estudios Públicos Conference, Santiago, Chile, 2012.
Accessed on the 28th January 2014: www.cepchile.cl

Li Y, Zhuang Z, Liu J (2009) Chinese kangs and building energy consumption. Chinese Science Bulletin, Springer, 54, January 2009.

United Nations, Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision, DVD Edition., Population Division, United Nations, Geneva, June 2013.

World Health Organization (2010) WHO Household Energy Database, Department of Public Health and Environment, United Nations, Geneva, July 2010.