WOOD-BURNING STOVES WORLDWIDE:

TECHNOLOGY, INNOVATION AND POLICY

BY
RICARDO LUÍS TELES DE CARVALHO

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AALBORG UNIVERSITY
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Ricardo Luís Teles de Carvalho

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PhD supervisor: Associate Prof. OLE MICHAEL JENSEN
Aalborg University
Assistant PhD supervisor: Associate Prof. LUÍS ANTÓNIO CRUZ TARELHO
University af Aveiro

PhD committee: Senior Researcher Henrik Nellemose Knudsen (chairman)
Energy and Environment, Danish Building Research Institute

Professor Filip Johnsson
Department of Energy and Environment
Chalmers University, Sweden

Senior Advisor Jytte Boll Illerup
Department of Chemical and Biochemical Engineering,
Technical University of Denmark

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CV

Ricardo Carvalho has been working since 2009 as a consultant at the Danish Building Research Institute/Aalborg University on the topic of residential wood combustion for heating and cooking, developing knowledge on household interventions and innovative technologies to reduce climate and health risks in Europe and overseas. His PhD work entails the design of testing methods to assess and optimize the real-life performance of wood-log and pellet stoves in modern housing across Europe and South America, through his participation in research projects in different EU countries, Norway and Brazil. He holds a MSc. in Sustainable Energy Systems and a BSc. in Environmental Engineering from the University of Aveiro, Portugal.

English summary

More than any time in our history, the wood-burning stove continues to be the most popular technology used for cooking and heating worldwide. According to the World Health Organization and recent scientific studies, the inefficient use of solid-fuels in traditional stoves constitutes the major global environmental health risk, since these sources are important contributors to fine particulate matter ($PM_{2.5}$) in the ambient air that increase climate and health risks.

This thesis explores the social-technical dimensions of both the use of wood-burning stoves (WBSs) and transition to the use of low-emission WBSs worldwide. In chapter 1, an historical view on the development of WBSs is presented taking into account the anthropological aspects associated with the control of the fire. In chapter 2, a scientific review on 9 types of stove technologies was conducted to describe traditional systems, improved efficient retrofits and advanced stove innovations. In chapter 3, four popular wood-burning practices found in five countries were singled-out to be examined closely in four case studies: “cooking in Brazil”, “cooking and heating in Peru”, “heating in Portugal” and “recreational heat in Denmark and Norway”. In each case, investigations were conducted to evaluate potential gains in the performance of WBSs by the adoption of three interventions: 1. Improved cookstoves (ICSs); 2. Efficient chimney retrofits; 3. Digital applications for a smart stove operation. In South-America, the work focused on understanding the effects of cookstove use on the indoor air quality of 20 rural houses. In Europe, qualitative interviews were conducted to study the operation of WBSs in 24 dwellings. The energy and environmental performance of a fireplace, an ordinary wood stove and an automatic stove, were determined through laboratory studies conducted at the University of Aveiro. Finally, energy simulation and indoor climate studies were carried out to analyse the influence of the operation of these types of WBSs on the heating grid of Iberian and Nordic houses. In chapter 4, international energy policies were suggested to facilitate the transition to cleaner wood-burning regimes.

Considering that 40% of the world population continues relying on traditional forms of wood-burning, the design and dissemination of cleaner technologies of WBSs constitute relevant strategies to mitigate global climate and health risks. Indeed, these measures can be especially important in places where many residential stoves are used in the same location during atmospheric inversions. Despite the considerable amount of scientific studies conducted in several developed countries to evaluate the impacts of the inefficient use of WBSs for heating on the environment and health, little attention has been paid to these issues in other parts of the world. In general, it was identified that the usage of heating stoves might cause a larger amount of $PM_{2.5}$ emissions per year (per household) than the use of cookstoves. Globally, the advanced gasifiers and automatic stoves (Digital and Forced air) were identified to be among the best performing

technologies. In spite of the fact that the thermal efficiency of the most advanced type of heating stoves (Gasifier) is around twice larger than that achieved for the most advanced type of cookstoves (Forced air), the $PM_{2.5}$ emission factors reached during the use of both kinds of stoves are within the same range of values, achieving smaller levels than the targets established for the best performing stoves established through an International Organization for Standardization consensus process. On this background, the adoption of advanced WBSs is able to reduce the $PM_{2.5}$ emission factors in, at least, 80% in relation to improved WBSs (Rocket, Cast-iron and Heavy). That means that even improved interventions applied in different parts of the world do not prevent air pollution due to the improper use of improved stoves.

In the Brazilian case study, it was observed that the kitchen concentrations of $PM_{2.5}$ monitored during wood cooking events increased by more than 10 times in relation to the background levels due to the improper use and maintenance of the studied ICSs (rocket stoves). In Southern Europe, the measured $PM_{2.5}$ emission factors from cast-iron stoves without a pre-heated secondary air-inlet were higher than the official Ecodesign requirement. The laboratory experiments showed that over 20% energy savings can be addressed by either installing heat recovery systems in the chimney or by coupling digital devices to modern cast-iron stoves in order to support users in the proper regulation of fuel loads and combustion air-inlets. The energy simulations conducted for Iberian and Nordic houses revealed that automatic WBSs can operate in an efficient way as primary heating systems in homes with low-heating demands, avoiding overheating risks. The energy and indoor climate studies conducted in Nordic houses confirmed the trends observed in the energy simulations. Here, the variations observed for the measured indoor concentrations of $PM_{2.5}$ were considered to be insignificant in relation to the background levels. However, the concentration of ultra-fine particles in some well-insulated houses increased by more than 10 times the background levels, due the improper operation of modern cast-iron stoves and old installations.

On this background, it becomes clear that energy policies can be adopted to facilitate the transition to more intelligent modes of using WBSs by: 1st training solid-fuel users to better operate and maintain existing installations, 2nd harmonizing wood-burning regulations to address the use of seasoned fuels, certified stoves and functioning chimneys; 3rd designing applications to optimize the interaction between user, stove and dwelling; 4th implementing systems of subsidies to promote the accessibility to the most advanced stoves.

As an overall conclusion, the design of future stove interventions might be based on the changes in modern society, considering each community socio-economic context. Here, the understanding of user behaviours and the empowerment of local communities might play a crucial role in the process of accelerating the transition to advanced wood-burning practices. This will be a win-win situation that will contribute to both the mitigation of climate change and protection of the human health.

Dansk resume

Mere end på noget andet tidspunkt i menneskehedens historie opretholder brændeovnen sin position som den mest populære og troværdige teknologi til opvarmning og madlavning; det gælder over alt i verden. Samtidig kan Verdenssundhedsorganisationen WHO støttet af ny forskning meddele, at ineffektiv brug af traditionelle brændeovne har skabt et alvorligt sundhedsproblem, idet store udslip af partikler ($PM_{2.5}$) til det omgivende miljø på én gang skader helbredet og forcerer klimaforandringerne.

Med denne afhandling undersøges de tekniske og sociale dimensioner som følge af brug af brændeovne samt overgangen på verdensplan til brug brændeovne med lille partikelforurening. I kapitel 1 anlægges et historisk vinkel på brændeovnens udvikling, idet der ud fra et antropologisk synsvinkel trækkes linjer til menneskets kontrol over ilden. I kapitel 2 er der gennemføres der en undersøgelse af ni forskellige brændeovnsteknologier for at beskrive forskellen mellem traditionelle brændeovnssystemer, brændeovnssystemer, der er tilføjet ny teknologi og endelig nye avancerede brændeovnssystemer. I kapitel 3 bliver der udpeget fire brændeovnspraksisser udbred i fem lande. Hver især indgår de et casestudie, hvor de bliver undersøgt nærmere: "madlavning i Brasilien", "madlavning og opvarmning i Peru", "opvarmning i Portugal" og "komfort og hygge i Danmark og Norge". I hvert tilfælde blev der gennemført undersøgelser for at vurdere gevinsten, der kan opnåse ved tre indgreb: 1. brændeovnskomfurer, der er blevet forbedret, 2. brændeovne tilført effektive skorstensløsninger og 3. brændeovne udrustet med digitale løsninger til avanceret brændeovnsstyring. I Sydamerika har arbejdet været fokuseret på at forstå virkningerne på inde luftkvaliteten ved brug af brændeovnskomfurer i 20 landhuse. I Europa er der gennemført kvalitative interviews for at studere brugernes betjening af brændeovne i 24 enfamiliehuse. På testlaboratoriet ved Universitet i Aveiro i Portugal er virkningsgrad og miljøforhold undersøgt på henholdsvis en åben pejs, en almindelig brændeovn og en automatisk brændeovn. Endelig er der udført energisimuleringer og studier af indeklima i portugisiske og nordiske huse for at undersøge virkningen på varmesystemet ved forskellig betjening af forskellige typer brændeovne. I kapitel 4 foreslås internationale energipolitikker, der kan være med til at fremme overgangen til renere brændeovnssystemer.

I betragtning af, at 40% af verdens befolkning fortsætter med at være afhængig af traditionelle former for brændeovnsfyring, vil det kunne mindske den globale klimabelastning og de globale sundhedsrisici betydeligt, hvis der blev satset på udvikling og udbredelse af renere brændeovnsteknologier. Sådanne foranstaltninger vil ikke mindst være af betydning de steder i verden, hvor der forekommer atmosfærisk inversion, og hvor boligområder er tæt besat med brændeovne. På trods af, at der i den vestlige verden er gennemført et stort antal videnskabelige undersøgelser for at vurdere konsekvenserne af ineffektive brændeovne på miljø og helbred, har der kun været lille opmærksomhed på disse forhold i andre dele af verden. Det er almindelig kendt, at brugen af brændeovne til opvarmning har været årsag til større årlige partikeludslip per husholdnig ($PM_{2.5}$) end brugen brændeovnskomfurer. Globalt set er de avancerede forgasningsovne samt automatiske ovne (digitale ovne og ovne med tvungen lufttilførsel) været set på som dem med den bedste ydende, når det gælder ny teknologi. På trods af den kendsgerning, at den termiske virkningsgrad i de mest avancerede brændeovne til opvarmning (forgasning) er ca. dobbelt så høj som den, der kan opnås med de mest avancerede brændeovnskomfurer (tvungen lufttilførsel), ligger de emissionsfaktorer, der er opnået for de to typer af ovne på samme niveau. Samtidig er der opnået mindre værdier end i de guidelines for de bedst ydende brændeovne, der er konsensus om ved den internationale organisation for standardisering, dvs. en grænseværdi på under. På den baggrund vil indførslen af avancerede brændeovne kunne bidrage til en reduktion af partikelemissionen ($PM_{2.5}$) med mindst 80% i forhold til at forbedre eksisterende brændeovne (bænkovne, støbejerns- og masseovne). Dette betyder, at selv med de forbedringer, der er implementeret rundt om i verden på eksisterende brændeovne, har dette ikke forhindret, at der indtræffer lokal og regional luftforurening alene forårsaget af forkert betjening.

I det brasilianske case studie, blev det konstateret, at partikelkoncentrationer ($PM_{2.5}$) i køkkenregionen under madlavning steg mere end 10 gange i forhold til baggrundsniveauet som følge af forkert betjening og dårligt vedligehold af de implicerede bænkovne (rocket stoves).

Målinger i Sydeuropa af partikelemissioner ($PM_{2.5}$) fra støbejernsbrændeovne uden forvarmet sekundært luftindtag viste højere værdier end de officielle Ecodesign-krav. Her viste laboratorieforsøg, at der kan opnås mere end 20% energibesparelse ved enten at installere varmegenvindingsanlæg i skorstenen eller ved at koble en digital kontrolenhed til de certificerede brændeovne for på den måde at hjælpe brugerne med at opnå korrekt tilførsel af brænde og styring af luftindtaget. Energisimuleringerne gennemført med reference til portugisiske og nordiske huse afslørede, at brændeovne med automatisk styring kan fungere effektivt som primær energikilde i hjem med lille varmebehov endog uden at risikere overophedning. Energi- og indeklima-undersøgelser gennemført i Nordiske huse kunne bekræftede resultaterne, fra energisimuleringerne. Her viste det sig, at de observerede variationer i indeklimakoncentrationen af partikler ($PM_{2.5}$) var ubetydelige i forhold til baggrundsniveauet. Dog skete der det, at koncentrationen af ultrafine partikler i nogle velisolerede huse steg mere end 10 gange baggrundsniveauet, ved forkert betjening af ellers moderne støbejernsovne samt ældre ovne.

På den baggrund kan det fastslås, at der kan anlægges en politik på området, som fremmer overgangen til mere intelligent brug af brændeovne. Det kan ske ved: 1. sætte brændeovnsbrugerne i stand til bedre at betjene og vedligeholde brændeovne,

2. harmonisere reglerne for brændehovne for at fremme brugen af tørt brænde, certificerede ovne og velfungerende skorstene, 3. fremme udviklingen af tilbehør med henblik på at optimere samspillet mellem bruger, ovn og bolig og 4. indføre støtteordninger til fremme af udbredelsen af de mest avancerede brændeovnsteknologier.

Den overordnede konklusion er, at udformningen af fremtidens brændeovne bør være baseret på de forandringer, der sker i samfundet, samtidig med at der øves respekt for den sociale og økonomiske forhold i de enkelte samfund. Her vil en forståelse af brugeradfærd og styrkelse af lokale befolkningers selvstædighed spille en afgørende rolle i processen med at fremskynde overgangen til avanceret brug af brændeovne. Dette vil være en win-win-situation, da det samtidig vil kunne bidrage til at begrænse klimaforandringerne og forbedre folkesundheden.

LIST OF PUBLICATIONS

This thesis is based on research work and findings described on the following 5 scientific papers that represent a great part of the work conducted during the PhD program:

Paper I: Carvalho R.L., Jensen O.M., Tarelho L.A. Mapping the performance of wood-burning stove installations worldwide, Energy and Buildings, Vol. 127, pp. 658-579, September, 2016. doi:10.1016/j.enbuild.2016.06.010

Paper II: Carvalho R.L., Jensen O.M., Afshari A., Bergsøe. N.C. Wood-burning stoves in low carbon dwellings, Energy and Buildings, Vol. 59, pp. 244-251, April, 2013. doi:10.1016/j.enbuild.2012.12.006

Paper III: Carvalho R.L., Jensen O.M., Skreiberg O., Seljeskog M., Goile F., Georges L. Proper indoor climate by the adoption of advanced wood-burning stoves, In the proceedings of Roomvent conference, São Paulo, 2014.

URL: http://vbn.aau.dk/en/publications/proper-indoor-climate-by-the-adoption-of-advanced-wood-burning-stoves(2c116a34-eea7-445e-a5ab-520e9977f7f3).html

Paper IV: Carvalho R.L., Jensen O.M., Tarelho L.A.C., Silva A.C. Impacts of two improved wood-burning stoves on the indoor air quality: Practices in Peru and Brazil, In the proceedings Indoor Air conference, Hong Kong, 2014.

URL: http://vbn.aau.dk/en/publications/impacts-of-two-improved-woodburning-stoves-on-the-indoor-air-quality(73ec9d77-3228-42f6-b786-035e7ca1571e).html

Paper V: Carvalho R.L., Jensen O.M., Tarelho L.A. Transition to an intelligent use of biomass stoves, Behave – 4th European conference and Behavior and Energy Efficiency, Coimbra, 2016. Accepted for publication in the proceedings, September, 2016.

URL: http://vbn.aau.dk/en/publications/transition-to-an-intelligent-use-of-cleaner-biomass-stoves(d6824bd9-a489-4758-9ea4-318bfd1a9ef4).html

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty.

Additional publications (P) and communications (C) – not included in the thesis:

P1: Carvalho R.L., Jensen O.M., Tarelho L.A. Changes of indoor climate by the adoption of retrofitted wood-burning stoves, In proceedings of Indoor Air conference, Hong Kong, 2014.

P2: Carvalho R.L., Jensen O.M., Tarelho L.A., Olesen H. R. Particulate emissions from residential wood combustion in Denmark and Portugal, 11th International Carbonaceous Particles in the Atmosphere, Lawrence National Laboratory, Berkeley, United States, August, 2015. URL: http://iccpa.lbl.gov/presentations/carvalho-abstract.pdf

P3: Jensen O.M., Afshari, A., Bergsøe, N.C., Carvalho R.L. Residential wood heating, SBi, Technical report, Danish Ministry of Environment report, 2012. URL: http://www2.mst.dk/Udgiv/publikationer/2012/07/978-87-92903-34-1.pdf

P4: Carvalho R.L., Jensen O.M., Tarelho L.A. et al. Energy performance of Portuguese and Danish wood-burning stoves. In proceedings of World Renewable Energy Congress, Linkoeping, Sweden, 2011. URL: http://www.ep.liu.se/ecp/057/vol3/040/ecp57vol3_040.pdf

P5: Alves, C., Vicente, E., Carvalho R.L., Custódio, D., Tarelho L.A. Particulate and gaseous emissions from the combustion of certified and non-certified pellets, 8th Intern. Worksh. on Sand/Duststorm, Lisbon, Portugal, May, 2016. URL: http://www.dustworkshop8.ctn.tecnico.ulisboa.pt/DUSTWorkshop8_BookAbstracts.pdf

C1: Carvalho, R. L. Biomass stoves in buildings, Pellet Stove Design Challenge workshop, Brookhaven National Laboratory, New York, United States, April 2016. URL: http://www.forgreenheat.org/decathlon/panel.html

C2: Carvalho, R. L. Wood-burning stoves in buildings worldwide, Real-world emissions from residential wood combustion seminar, Aalborg University, Copenhagen, Denmark, December 2015. URL: https://woodburningstovesblog.wordpress.com/presentations/

C3: Carvalho R.L., Jensen O.M., Tarelho L.A., Silva, A.C. Indoor air pollution caused by wood-burning in Brazilian and Danish dwellings, Environment and Health conference, Basel, Switzerland, August, 2013. URL: http://ehp.niehs.nih.gov/isee/o-1-39-02/

C4: Carvalho R.L., Jensen O.M., Tarelho L.A., Silva, A.C., Scaling housing interventions for wood-burning stoves, Environment and Health conference, Basel, Switzerland, August, 2013. URL: http://ehp.niehs.nih.gov/isee/o-4-16-01/

PREFACE

As a descendant of Portuguese explorers, I was motivated by my ancestors' stories to learn about other cultures and ways of living. After my graduation, trips to India and Mozambique called my attention to the importance of the control of fire has to people and its environmental health implications. Having come back to Europe, I started to suspect that wood-burning still remains as a universal human practice as wood is still an available resource in most of the peri-urban and rural areas in the world. From here raised the desire to study the history of wood-burning stoves (WBSs) as the most reliable technologies on earth. The development of this research was then motivated by my interest in understanding the sustainability aspects related to the usage of wood for cooking and heating. Considered by energy experts as a renewable energy source, today, environmental health specialists point out that the inefficient use of solid-fuels in open fires and traditional stoves is a major source of climate and health damaging particles. The widespread use of these energy sources can be considered not only as a regional, but also as a global issue. From this derived my inspiration to look at the development of WBSs as an opportunity to "do something" for the health of the planet. During the elaboration of this thesis emerged the question: Can advanced WBSs be considered as carbon neutral energy technologies? Another perspective discussed here is that cooking and heating with wood-fired stoves is not only an environmental health issue in developing countries, but also a traditional human practice that requires changes in the combustion technology in a wider scale. Thus, the knowledge developed here is located within the field of applied natural sciences. First, a scientific review on innovation potentials was conducted. Second, case studies aimed to investigate popular wood-burning practices in different parts: "cooking in Brazil", "heating and cooking in Peru", "heating in Portugal" and "recreation in Denmark and Norway".

As described in Figure A, a hybrid research methodology was applied to understand the influence of these energy behaviours on the performance of biomass stoves by bridging theoretical, experimental and energy simulation studies.

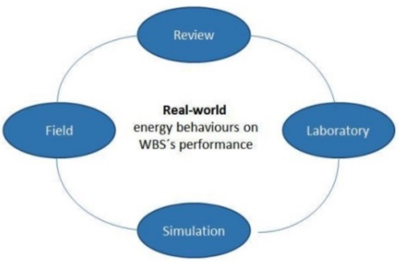

Figure A. Scheme of the PhD work methodology.

Although it involved the study of cookstoves in Brazil, this work focused on the characterization of wood-fired heating stoves in cold and temperate zones as a growing climate issue. On this background, building simulations were conducted to evaluate the thermal performance of WBSs installations in European dwellings.

The core ideas and study design presented in this thesis emerged while I was an exchange student in Denmark, a Nordic country that is part of a privileged region to study the history, culture and design of forefront technologies of WBSs. This work is a result of my involvement in research projects related to the use and performance of WBSs in both my home country, Portugal, and Denmark, having its foundations on inspiring discussions with my supervisors from both countries, namely the Senior Researcher, PhD. Ole Michael Jensen from the Aalborg University and the Associate Professor, PhD. Luís Tarelho from the University of Aveiro. The privilege of studying and working in these two countries brought me a new perspective on the technological transitions taking place in different parts of Europe, opening up other views on emerging transformations in other parts of the world. Many of the findings discussed here were also inspired by research trips to the Peru, Brazil, Norway, China and United States.

In this context, this thesis is composed of 5 chapters, where sections 2 and 3 represent a considerable part of the work (5 scientific publications) developed during the program, being organized according to the following structure:

- Chapter 1 introduces the reader to the history of wood-burning by presenting an anthropological view on the control of fire by humans;
- Chapter 2 (Paper I) presents a global scientific review on wood fuel use for cooking and heating and the performance of stove technologies, describing the characteristics of different installations found around the world;
- Chapter 3 (Papers II-V) presents the results obtained in experimental and energy modelling work on the assessment of the operating performance of forefront stove technologies in Europe and South-America;
- Chapter 4 includes a discussion of the previous chapters by suggesting measures to promote the use of low-emission stoves;
- Chapter 5 presents the overall conclusions on the advances made in the development of WBSs as a renewable heat source.

The whole structure of this thesis is based on the social-historical view presented in Chapter 1 and in the scientific review on stove technologies introduced in Chapter 2 and Paper I. The case studies presented in the other four publications were introduced and discussed in Chapter 3. The experimental and modelling work presented here is a result of research collaborations with the institutions and persons acknowledged below. Chapters 4 and 5 are based on the previous sections.

Copenhagen, June 2016, Ricardo Carvalho

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The PhD program ran from 2012-2016 through an international cooperation between the Danish Building Research Institute (SBi) at the Aalborg University (AAU) and the Centre of Environmental and Marine Studies (CESAM) at the University of Aveiro (UA) with the financial support of the Foundation of Science and Technology through the PhD grant ref. DFRH/BD/77171/2011[1].

In Nordic countries, most of the experimental work and participation in scientific meetings was funded by the SBi and the Danish Ministry of Environment through the project ref. 1435. Research collaborations were carried out with a network of Danish industrial partners, including the companies HWAM and Aduro as well as Chimney Sweepers and Retailers. The field work in Norway was conducted with the support of the Foundation for Scientific and Industrial Research SINTEF, through the project "Stablewood – New solutions and technologies for heating of buildings with low heat demand". In Southern Europe, the laboratory tests performed at the CESAM/University of Aveiro were financially supported by the EU project "AIRUSE: Testing and development of air quality mitigation measures in Southern Europe", LIFE 11 ENV/ES/000584. The field studies in South-America were carried out through two research collaborations with researchers at the Federal Institute of Ceará in Brazil (IFCE) and at the Centre for Capacity Building and Development in Peru (CECADE).

I would like to my supervisor Ole Michael Jensen and co-supervisor Luís Tarelho who were key elements in the construction of this thesis. I wish also to express my appreciation to my colleagues at SBi, including the Senior Researchers Alireza Afshari and Niels Bergsøe, who supported the development of part of the research work conducted in Denmark, as well as to Morten Seljeskog, Øyvind Skreiberg and their colleagues at SINTEF for their contributions in the development of the case study in Norway. My thanks to the Senior Advisor Helge Rørdam Olesen from the Aarhus University for sharing his expertize on air pollution studies and his crucial support in the organization of the seminar about residential wood combustion that took place in Copenhagen. My gratitude to Estela Vicente (CESAM) and Nuno Costa (UA) for the support in the laboratory work at the UA. I would also like to acknowledge that it was an honour to work with Adeildo Cabral Silva (IFCE) and Pedro Zanabria (CECADE), my research partners in Brazil and Peru. Thanks to Kirk Smith (U.C. Berkeley) and John Ackerly (Alliance for Green Heat) for the knowledge exchange during my research visits to the United States.

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This thesis is dedicated to:

Janaina, my soul mate, who accompanied me in several journeys around the world, my friend and brother Pedro and my parents, Alice and Artur, for their “teachings at and from home”. A special thanks to my dear friends (and also parents in law) Policarpo and Ludimilla and to our family and friends on both sides of the Atlantic Ocean, who opened “their doors” for this project. Last, but not least, it is important to point out that this thesis was also inspired in our organic farming community in Aveiro and the people who continue taking part in the dichotomic transition movements by “thinking globally and acting locally” for the health of our planet.

TABLE OF CONTENTS

CHAPTER 1. THE HISTORY OF WOOD-BURNING STOVES

This chapter presents relevant historical facts and events on the history of wood-burning that are in the origin of human evolution, being based on the collection of anthropological and social-technical information about the control of fire by humans found in scientific articles and books published around the world. This section contains two sub-chapters that immerse the reader in the sociological aspects of wood-burning as a source of human expansion (1.1), discussing the technological transitions that took place over the years (1.2).

As the most ancient and persistent energy technology worldwide, the understanding of the meaning and history of wood-burning stoves (WBSs) is essential to the explanation of the remaining forms of wood usage for cooking, heating and even lightning in homes around the planet. Along the 20th century, cooking and lightning with wood became less and less common especially in urban areas and high income regions with access to gas and electricity. However, cooking with biomass remains popular in most of the developing countries and wood heating is still a popular human practice in many cold and temperate climate zones. This first chapter presents an anthropological overview of the social and technical transformations that have been taking place since the early stages of our development. This part of the thesis presents a possible sociological explanation for the persistent regimes of residential wood combustion (RWC) that can be found worldwide.

1.1. AN ANTROPOLOGICAL VIEW

Over a million years ago, the discovery of fire ignited our development by giving rise to the genus Homo (1) through its control and the advent of cooking meals. In the book “Catching fire: How cooking made us human”, the anthropologist Richard Wrangham writes about how “cooking increased the value of our food, changing our bodies, our brains, our use of time, and our social lives”. According to the author “the transition is first signed at 2.6 million years ago when sharp flakes dug from Ethiopian rock” and between 1.9 and 1.8 million years ago some habilines (a specie of extinct humans) evolved into Homo erectus that look more like us than other previous species. According to the most popular view of anthropologists, since the 1950s, the eating of meat distinguishes Homo erectus from their ancestors. In this book (1) it is stated that in spite of the fact that some people think Homo erectus were better at hunting, they had small jaws and teeth. One of the possible explanations for that could be that “Earth has fire” where “combustible wood gives us warmth and light” where the “nights would be cold, dark and dangerous, forcing us to wait helplessly for the sun”. The author also states that without a fire “All our food will be raw. No wonder if we find comfort by a hearth". From the reading, it is also possible to understand that the human evolution was based on the fact that our ancestors handled the fire in a controlled manner. According to the Goudsblom (2), "the ability to handle the fire is, along with language", a tool of human attainment. This human skill is in the source of important changes in the morphology of mankind through new living styles like inhabiting on the ground in safer shelters protected from predators where they could gather and eat cooked food with a higher energy value. No human would survive without the control of the fire. This knowledge has strengthened our position in the biosphere by controlling and expanding the use of the territory in different ways, being at the same time related to the strengthening of social skills around the fire. The control of the fire has been essential in the emergence of agriculture during the periods of "domestication" and "agrarization", including stock rising, and later on the industrial development. The control of fire brought us both benefits and costs for the biodiversity of the planet (2). In a first stage, humans learned to extend their care and the control of fire to serve subsequent forms of care and control over other forces of nonhuman nature, such as plants and animals.

Nowadays, all of us need a fire wherever we are, for instance, like every scout might learn in survival manuals that if we are lost in the wild, one of the first things we have to do is to light a fire. Heating with a fire can also be considered as a survival issue by providing human beings with a safer and healthier environment to live in. In addition to warmth, light and hot food, fire gives us safe water, dry clothes, protection, a signal to friends and even a sense of inner comfort. Wherever we are in world today, the control of fire is embedded in the human spirit as part of our history. In modern society, fire might be hidden in other forms, like in our basement boiler, trapped in a small-combustion engine to produce electricity and hot water or confined in the power station that provides electricity to our homes, but we still completely depend on it. This represents a similar tie found in every culture in the world. With this background knowledge we might find an explanation for the fact that WBSs are still the most popular and widespread energy conversion technology in the world.

Looking at the etymology of the word "fire" (3), it is possible to realize its relationship with the home. On its origin, the Latin word "focus" meant "point of convergence" and the words "hearth, fireplace" also, figuratively meant "home, family". In the 18th century, the word was associated to the meaning of "centre of activity and energy" by Hobbes. On this background, emerged the word "stove" in the mid-15th century associated to the sense of "heated room, bath-room" from Middle Low German or Middle Dutch, originally meaning "heated room" in English. The original word in Old English "stofa" meant "bath-room". Today, the German word "stube" means "room". From the history of these words, it is possible to derive that the fireplace originated as a living space where core human activities take place (cooking, heating and lightning). In this sense, later on, the WBSs have been being the centre of activity in most of our homes. In this perspective, before the creation of stoves, open fires were handled in open sites while the emergence of stoves[2] were related to the demands for an increased control of the fire in enclosed and protected indoor spaces. This move of bringing the fire into our homes brought new health and safety issues. For that reason, the development of stoves by engineers and designers has always been associated with improvements in the control of the fire indoors in order to avoid harmful wood smoke and the danger of overheating the building. It is in this scope that this thesis explores the understanding of the human evolution and development of the interaction between people, stoves and dwellings.

1.2. A SOCIAL-TECHNOLOGICAL VIEW

This section relates the social and cultural aspects of wood-burning over the increased control of the fire in two stages. First, the technical changes, which were made in the control of the fire associated with environmental health concerns that emerged along the centuries, will be described. Second, the evolution of energy and environmental health policies along the past centuries will be presented.

During the industrial revolution, the technological development and dissemination of more efficient chimney stoves was shaped by the understanding of the danger and toxicity of burning solid-fuels in homes. For instance, indoor air pollution (IAP) generated by traditional 3-stone fires is still a major global health risk in developing countries nowadays. Beyond the health related risks, the development of WBSs is now being shaped by other social changes in modern society. In spite of being considered the main energy technology in developing regions[3], as technology progressed, modern humans living in cities lost their ability to light and control the fire. However, globally, in rural and peri-urban areas, many people are still very much spiritually connected to the use of this “survival technology”. One of the reasons that could explain that is our ancestral relation with the fire since it is still possible to find this relation in some developed countries like Finland, Norway and Denmark. Another aspect that has always been on the foundation of the creation of cleaner stove technologies has been the wish of our independence from external

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[2] Nowadays there are several definitions used to describe WBSs, depending on their operation and function. In Europe, WBSs are included in the category of solid-fuel space-heaters and cookers, depending if they are used for heating or cooking. The European Commission work on the Ecodesign framework (18,72), consider these systems as Direct heating appliances that can be operated with wood and/or pelletized fuels. Worldwide, the word “cook stove” has originated the single word “cookstove” in the context of the global environmental health concerns related to the residential usage of solid-fuels for cooking.

[3] Not necessarily located in developing countries, but located in areas similar socio-economic contexts (e.g. rural areas with limited access to natural gas).

energy sources (resilience), especially in periods of crisis. For instance, during the peak oil crisis in the 70s, families in many cold countries had to rely on wood for heating. Another example is that when there is a natural disaster or conflict and people lose their homes wood fuel can be the only available energy resource in the surrounding areas. In this view, WBSs can be considered as the most reliable technology that ever existed on earth.

The understanding of these historical aspects of the human nature and its original relation with the fire introduces the reader to the comprehension of the main forces that have been driving the development of WBSs worldwide within a single-motif: the mankind ability to control the fire, still present in our genes.

Looking at the technological evolution over the millenniums, the first evidences concerning the control of the fire by humans were found in Africa more than 1 million years ago and the oldest known hearths were discovered in Europe half a million years ago (4). Kilns with chimneys were found in the Middle East and can be dated from 4000 years ago. However, the most significant technological changes involving the development of WBSs might have occurred only around 2000 years ago when the first cast-iron stoves started to be integrated in indoor environments in cold regions of China. According to historical data, the Romans introduced the first chimney stoves that appeared to protect the indoor health around that time. Wood combustion was still at that time the sole source of energy for cooking, heating and lightning in cold nights.

In the 17th century, the Nordic iron industry demanded the clear-out of forests in Sweden to provide fuel for ironworks. During that time cast-iron stoves were produced to supply homes with heat – the oldest surviving ones are from 1632 (5). In the 18th century, in Scandinavia and other parts of the world, the amounts of wood used for heating was so great that large areas were deforested. The first significant technological transformations emerged to deal with this environmental issue when the government of Sweden commissioned two talented engineers to design and build a more efficient stove. The first drawings were made in 1767 when it was already possible to see that stoves could be designed to economize wood. With the industrial revolution, in Europe, fireplaces and cast-iron stoves started to compete with electricity and later on with centralized energy systems based on the combustion of fossil fuels. By bringing these traditional energy sources indoors a major indoor air pollution has emerged, remaining up to today as a major health risk in developing countries for people living in settings without access to modern fuels. One of the contemporary solutions to avoid the direct exposure of people to wood smoke indoors was the separation of the kitchens (e.g. outdoor cooking) or heat production units from the living rooms (e.g. separated compartments with heat boilers). This re-configuration of the household heat production sources worked only in some places. One of the reasons for that might be explained by the fact that it detached mankind from the control of the fire and its spiritual meanings and beliefs. In the 20th century, district heating and natural gas systems emerged in many parts of the developed world together with a well-developed electricity grid and RWC units started to be used, in some parts, as a backup system to supply heat in periods of energy shortage. With these transformations in the energy systems of the wealthiest countries, an interesting contradiction took place when modern WBSs re-emerged as a kind of luxurious piece of furniture and source of beautiful flames used for satisfying a feeling of comfort pleasure in Danish *"hygge"*. Nowadays, in these high-income countries, modern stoves are not so accessible to low-income people and youths due to the operational and maintenance costs associated to their proper usage. However, in some parts of these wealthy countries like in rural areas, WBSs remain as popular and reliable technologies in areas with limited access to central heating systems. Figure 1-1 illustrates the use of classical Danish WBSs found in a rural house located in Jutland where different stoves are being used for heating and cooking in different compartments of the same home.

Figure 1-1 Cast-iron stoves found in a rural home in Jutland (Denmark): classical iron stove on the left hand side in a room and cast-iron cookstove[4] *in the kitchen on the right hand side.*

Beyond its usage as a secondary heating system in urban and peri-urban of the wealthiest countries, WBSs remain as the main household energy source for many low and mid income communities located in both developing and developed

[4] Note that the word cookstove is now being spelled as one word in most of the literature and international agencies.

countries. Considering that the primary and inefficient usage of solid-fuels in these conventional installations is a major cause of ambient air pollution, innovations have been subject of public interest in many parts of Europe, the United States (US) and in some developing countries during the last few years, attracting attention from media and politicians worldwide. On this background, this thesis will focus on the forefront installations of WBSs that are being used on a small-scale, presenting a large potential to be expanded.

One of the innovations that have been attracting the interest of energy and health research communities around the world are the micro-gasification technologies of WBSs that can either operate with seasoned wood-logs (dried during a season for more than 3 months) or pelletized biomass residues. A revolutionary cookstove invention, which is applied nowadays in most of the developing countries, is the "Rocket stove" design created by Larry Winiarski in the 70s when he found out that it was possible to solve some of the household energy issues in Central America and other developing regions by creating a new and simple stove design. The Top-lit-up-draft (TLUD) stove which is nowadays being implemented in cookstove programs in Ghana and other developing countries is one of the today´s forefront innovations in the cookstove world. The first inception of this advanced combustion system occurred during the 80s by the gasification expert Dr. Thomas Reed (6) as a result from a trip to South-Africa. Later on the Norwegian Paal Wendelbo developed the model "Peko Pe" a TLUD stove that operated with natural draft. In the same decade, the North-American Dr. Paul Andersen introduced a modification to this technology that resulted in a design that is now being studied and improved by other inventors (7). In spite of the fact that cookstoves[5] are used in a different context than heating stoves, the development of the combustion technology in general has been a result of global cooperation between inventors, scientists and people using them. The last generation of WBSs combine simplicity with the principles of wood combustion, including the use of pelletized biomass fuels and the production and combustion of wood gas as a result of other biomass conversion processes (pyrolysis and gasification) occurring in these innovative stoves. Worldwide, some of the most advanced stoves being introduced in the market nowadays are the so called gasification biomass stoves that operate to produce wood gas through top-down lightning. Although technical aspects have a major importance in the reduction of the air pollution from WBSs by increasing their thermal efficiency, there is a demand for addressing behavioural aspects in the future development of these stoves.

According to the Norwegian Foundation for Industrial and Scientific Research SINTEF, a world leader in the field of combustion research, advances in the field of

[5] Note that the word cookstoves is now being spelled as one word in most of the literature and international agencies.

WBSs are directly associated to social change. In the old days, it was normal to have large households with children, parents and grandparents living together. Nowadays, in the developed regions, households tend to be smaller since the elderly live alone or in a nursing home. In modern society, households tend to be unoccupied during the daytime since people are out at work, at school, or in the nursery (5). In cold and temperate zones, the old stoves still used in low and mid-income homes burn in a relatively clean way larger amounts of wood fuel at higher burning rates than modern ones. This usually happen in old houses without insulation. These dwellings have much larger heating demands than the modern houses existing today in most of the developed countries. In these settings new stoves need to provide lower amounts of heat to avoid overheating events in well-insulated households. The development of new technologies of WBSs might be focused on adjusting the heat output from these appliances to the energy requirements of low energy houses like some Scandinavian stove producers are already doing. One of the examples on how modern stoves might look like are the appliances covered by soapstone and the new generation of automatic stoves and digital devices (8) that provide users with the information and tools to regulate the indoor temperature in the new houses. Efforts in the design of a new generation of cleaner stoves with smaller combustion chambers than the conventional ones were made to address the issues concerning the composition of the modern families, emerging work patterns, and the thermal energy performance of modern houses.

Concerning the implementation of environmental health policies associated with the combustion of solid-fuels in homes, in spite of being considered as the most ancient energy behaviour on earth, the first wood-burning regulations appeared only during past 200 years with the environmental health concerns associated to the inefficient use of solid-fuels. According to the industrial medicine scientists Brown and Thornton (9), it was during the 18th century in England that the surgeon Percivall Pott developed the first study on occupational health related to the incidence of cancer in a population of Chimney Sweepers in the city of London (9). Few years after, the first of many “Chimney Sweeper´s Act” was passed, in the sequence of Percivall´s influence on the public opinion, forcing a change to the law and establishing new regulations on personal hygiene and working conditions (10). This was a very relevant step in the scope of the history of occupational health management, considering the proximity of Chimney Sweepers with the toxic elements of wood and coal combustion. On the other hand, these happenings show that Chimney Sweepers might constitute an important population to work with in the development of cleaner WBSs and measures to control air pollution from these sources.

From the referred concerns emerged a scientific community interested in understanding not only occupational health issues related to the usage of WBSs, but also the environmental impacts associated with their inefficient operation. First, investigations were conducted on the urban atmospheric environments with a high density of conventional fireplaces and stoves. As a consequence of this scientific approach, the first wood-burning regulations were created to control the local air pollution in cities. Second, during the past decades, environmental health scientists have been focusing on investigating not only the urban air pollution scene, but also the hypothesis that traditional wood-burning systems are a major cause of global climate and regional environmental health effects. As a consequence, many studies have been pointing out that under certain atmospheric conditions and a certain landscape of solid-fuel usage these conventional systems constitute the major sources of air pollution associated with premature mortality (11). Indeed, these recent investigations have showed that the production of residential energy in inefficient stoves constitutes the major global environmental health risk worldwide, especially during atmospheric inversions and poor dispersion conditions.

CHAPTER 2. STATE OF THE ART WORLDWIDE

This chapter aims to present the state of the art concerning the global use of solid-fuels in households (2.1), existing modes of operation of different categories of wood-burning stove (WBS) installations (2.2), their performance on the environment and health (2.3), existing regulations (2.4) and emerging innovations (2.5) worldwide. This section is mainly based on the compilation of the most relevant scientific data presented in Paper I. The definition of installation of wood-burning stove (IWBS) and the method used to collect information about their energy and environmental performance is described in that paper.

As explained in Paper I, an extensive scientific review on different installations of WBSs (IWBSs) existing worldwide was conducted by compiling the most data about the energy and environmental performance of WBSs published in international reports and studies between the year 1984 and 2016, including a systematic collection of data by:

- Searching associated key-words on Science Direct, Scopus and Google. The two first are world leading web platforms in which it is possible to find the most updated and high quality peer-reviewed journals and books. The second one is the world leading web search engine in which it is possible to seek for scientific publications around the world, including academic thesis and conference articles;

- Delimiting the search to the articles published since the year 1984 up to the year 2016, giving preference to the most recent ones;

- The scientific references were searched by using “wood-burning stoves” as the main key-word and the words “energy”, “environment” and “health” as the main subject areas;

- To obtain information in scientific publications related to specific parameters used to characterize the operating performance of WBSs, the words “fuel consumption” (FC), “thermal efficiency” (EF), “emissions” (EMS), “air pollution” (AP), “indoor air quality” (IAQ), “building” (B) and “indoor climate” (IC) were used as complementary key-words.

2.1. SOLID-FUEL USE AND AIR POLLUTION

Fireplaces and WBSs are still the most popular household energy technologies used by more than 40% of the world population relying on them for cooking and heating (12). This number represents more than 2.7 billion people accounting the amount of solid-fuel users located in developing countries, mainly relying on the use of coal and biomass for cooking. According to two World Health Organization (WHO) publications (13,14) and the Global Burden Disease (GBD) Assessment report (15), the combustion of solid-fuels in open fires and conventional stoves is among the main causes of ambient air pollution, being considered today as the major global environmental health risk. This thesis aims to characterize the energy and environmental performance of the use of both wood-fired heating and cooking stoves, focusing on the issue of wood heating in cold and temperate zones. Considering this perspective, a new estimation for the users of solid-fuels worldwide is presented and discussed in this publication, being the detailed method used to estimate the residential usage of coal and biomass explained in the Paper I. Figure 2-1 illustrates the distribution of solid-fuel users worldwide where each symbol represents 20 million people relying on the combustion of coal and biomass for cooking (in orange) and heating (in blue).

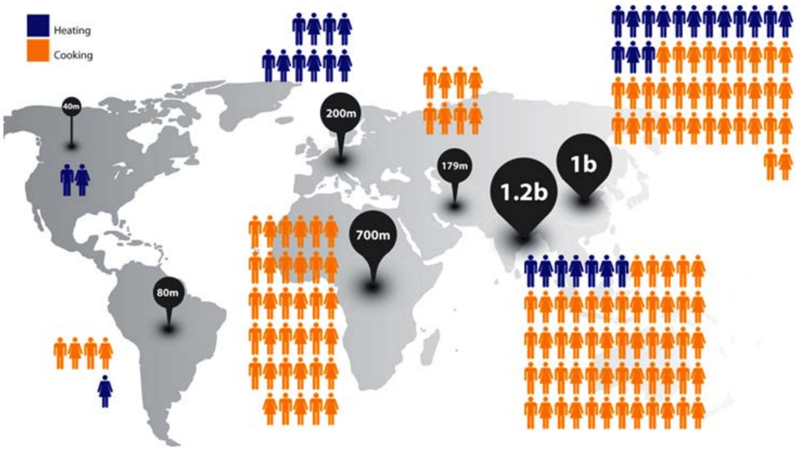


Figure 2-1 Residential use of solid-fuels for heating and cooking worldwide (Paper I).

These estimations are presented for 7 different regions in order to cover the usage of solid-fuels in open fires and stoves around the world. This world map is based on the compilation of information provided by different international databases, scientific articles and estimations made by the author of this thesis in one of his additional publications - P1 (16). This study complements one of the largest available studies related to the use of solid-fuels for cooking conducted by Bonjour et. al. (12). A new estimation on the amount of people using solid-fuels for heating in cold and temperate zones is included here. To develop this work, scientific references from Europe, North-America, China and other parts of the world where people are relying on wood fuels for space-heating were added. For instance, part of these calculations was based on working documents published by the European Commission (17) and a market analysis conducted for 15 member states of the European Union (EU) by Mudgal el al. (18). The number of users in other cold temperate climate zones was derived from scientific articles published in international journals and conferences, including several studies conducted in China like the investigations conducted by Zhuang et al. (19). Those estimates considered that in North America, Latin America, South-East Asia and other cold and temperate zones the fraction of people using solid-fuels for heating ranged between 10-25% of the total population in those regions, taking into account the world population prospects made by the United Nations (20).

Figure 2-1 illustrates that more than 85% of the total residential use of solid-fuels is associated with the usage of open fires and cookstoves in developing countries. From these estimates it is possible to state that there is still a significant amount of people using wood and coal for heating in the cold and temperate climate zones. In addition to this, globally, wood heating stoves are among the main sources of particulate matter (PM) emissions that are projected to increase in the next few years, as more households turn into burning more wood for warmth (21). In developing countries, it estimated that more than 1 billion people are relying on solid-fuels for both cooking and heating in places like India and China. In Africa, as in the Middle East, wood fuel is mostly used for cooking. For this continent, it was estimated that more than 600 million people rely on solid-fuels. In the northern hemisphere, Europe is the region with the largest numbers of users of WBSs, relying on these sources of residential heating more than 200 million people. In this and other cold and temperate zones, the use of solid-fuels for either primary or recreational heating persists as a popular practice (22). In Northern America, there are few available references concerning this, but there is an estimation that points out that in the US there are 6.5 million low-income users relying on wood heating (23). In other cold and temperate zones in Latin America in places like Chile and Peru the number of solid-fuel users is still uncertain, however, the associated environmental health issues in these countries are considered to be quite significant (24,25). In spite of the fact that the number of solid-fuel users in developing countries is much larger than in cold temperate regions of developed countries and according to Smith et al. (26), in some circumstances, it is possible to state that, globally, there is little relation between the use of wood fuel per capita and development, since this last can be more associated with the availability of biomass resources. For instance, countries like Finland and Singapore are both wealthy countries where the amount of firewood used per capita is totally different. The first country has one of the largest forests and wood consumption rates per capita in the world while the second one has almost none of both.

The intense and steady use of wood in open fires and conventional stoves is also responsible for other climate change issues associated with deforestation of sensible areas to desertification as it has been happening in some parts of Sub-Saharan Africa (27). The intense use of firewood for cooking during all year has also been a common practice in tropical (28) and semi-arid regions of South America. Here, cookstove programs were conducted in the past decades to reduce the impacts of its use on the regional biodiversity (29). On the other hand, the consumption of wood for space-heating happens only seasonally, but it can occur during larger periods of time in the day than its use for cooking. However, this practice can have a substantial contribution to deforestation when wood fuels are used inefficiently in fireplaces and conventional stoves. In rural areas people might use larger fuel loads in their heating appliances in relation to the amounts used in cookstoves in developing countries. For instance, investigations conducted in the Northern part of China (30) showed that coal and biomass heating stoves are relevant residential energy sources used most of the day during the entire winter, generating more indoor air pollution than cookstoves used in the same region (31).

Figure 2-2 Residential use of wood fuel and IAP from cooking and heating in an Andean community in Peru located in Paruro (Paper IV).

Figure 2-2 illustrates the intensive use of open and inefficient heating and cooking stoves in an Andean mountainous community of Peru. In this region, these systems are major sources of harmful particles, being the families living in these rural settings exposed to high levels of wood smoke. As it happens in some Mediterranean countries and in parts of the United States, in other cold and temperate zones in Africa and Asia in places like the Kilimanjaro and the Himalayan mountains, the inefficient use of relatively large wood-logs in open fires and old stoves during the heating season constitutes a major source of local air pollution (22). In these regions, these systems have larger combustion chambers than modern stoves used for instance in some Central and Northern European countries. Likewise, these types of traditional energy sources dominate the stock of local space-heating appliances in parts of Eastern and Southern Europe (18,32,33), North-America (23) and some regions of China (19)[6].

In many developing countries in places where people rely on traditional wood-fired cookstoves, some of the household occupants are directly exposed to wood smoke, a mix of toxic air pollutants such as Carbon Monoxide (CO) and particulate matter (PM), as a major source of household air pollution (HAP). Here, women and children are, generally, the most affected groups. Worldwide, it is estimated that every year there are around 3.5 million premature deaths (15) associated with indoor air pollution (IAP) and around 1 million deaths due to outdoor air pollution (11). In both cases, these levels of mortality are mostly associated with the residential combustion of solid-fuels in inefficient WBSs. For these reasons, the term HAP instead of IAP is now being used to better evaluate the complex effects of RWC on the local air quality in the surrounding areas of the houses where WBSs are used. Beyond the IAP, this term includes the air pollution generated by residential wood-burning that adds to the total outdoor ambient air pollution. This issue might be intensified during atmospheric inversions. The exposure to harmful concentration levels of fine particulate matter ($PM_{2.5}$) in the ambient air, mostly generated by biomass burning processes in small-scale appliances, can happen both in the indoor and outdoor environments. For instance, in parts of Chile (34) and China (30), in areas with an high density of traditional installations, when people are burning solid-fuels during periods of atmospheric inversions, the concentration levels of ambient fine particulate matter ($APM_{2.5}$) might be higher than the thresholds established by the WHO (14), mostly due to the inefficient operation of open fires and old stoves (35). Even in some developed countries, in places like Europe and the United States where all the households using solid-fuels in traditional installations are obligated to have a chimney, HAP can also be an important issue, especially in low-income settings. A study conducted in the United States by Rogasky et al. (23) has estimated that around half a million low income Americans are likely to be exposed to HAP. Despite of being considered by many energy experts as a renewable energy source, the use of conventional WBSs can be a major cause of total ambient air pollution. In regions where the daily exposure levels to $APM_{2.5}$ does not comply with the value of 35 $\mu g\ m^{-3}$, established in the WHO indoor air quality guidelines (14), the adoption of chimneys might remove air contaminants from the indoor to the outdoor atmosphere, possibly influencing (indirectly) the air quality inside the house where people stay most of their time. This issue might be even more health impacting during the atmospheric inversions occurring in cold and temperate climates, especially in homes with poor ventilation

[6] The study of biomass boilers is not the focus in this thesis.

conditions and without filtering systems for particulate matter. This particular IAP issue can be tackled by installing high-efficiency particulate air filters (HEPA), although, this technology is mainly accessible in mid and high-income settings, being these mostly located in the developed world.

Another air pollution issue caused by the incomplete combustion of solid-fuels in inefficient fireplaces and stoves is related to the emission of climate forcing aerosols that can originate the formation of atmospheric black carbon (BC) which is estimated to contribute in between 25 to 50% to global warming (21). Worldwide, in spite of the fact that the number of heating stoves is much smaller than the amount of cookstoves, heating inefficiently with solid-fuels tend to occur in regions quite closed to the cryosphere (snow and ice) regions. This situation intensifies the climate change effects by the emission of PM and BC generated by the inefficient combustion of solid-fuels in houses located in those regions. Here, the deposition of these aerosols on both the ice and snow caps decreases their reflectivity, contributing to accelerate the melting processes of land glaciers and sea ice (36).

2.2. STOVE INSTALLATIONS

The environmental health effects caused by the diverse modes of usage of WBSs vary with geography and cultural localities, reason why mapping and characterizing the performance of these energy conversion technologies according to the socio-economic context of each type of household installation is so important to support energy efficiency and mitigation measures. In general, the use of solid-fuels for cooking and heating can be either primary or secondary, depending if people rely on these sources or if they appeal to them as complementary recreational heating systems. For example, in some developing regions in the world, rural communities have been exposed to a process of transition to modern fuels like electricity, natural gas or liquefied petroleum gas (LPG). Indeed, it is a fact that a considerable part of the world population living in low-income and remote regions is still relying on wood and coal for cooking, however, in many mid and high income regions, cookstoves using solid-fuels tend to disappear as primary energy conversion systems in the home, as soon as people start to have access to the central heating grid (electricity and/or natural gas) or to LPG stoves and cylinders. Considering the energy ladder model and alternative cooking strategies pointed out by Massera et and Saatkamp (37), in many rural communities in developing countries, the use of biomass cookstoves tends to appear in parallel (in a situation of fuel) with the operation LPG and/or electric (induction) stoves as soon as the family income increases. In several mid-income developed countries, some families living in peri-urban and urban areas tend to start using their WBAs as complementary (secondary) heating sources like described in one of the case studies presented in the section 3. In wealthy regions, for instance, as it happens in Scandinavia, the use of modern high-efficiency wood stoves can be viewed as a more sophisticated practice where families seek for the feeling of comfort pleasure (“hygge” in

Danish), using the indoor wood fire as a cosy complementary source of heat and beautiful flames in dwellings equipped with central heating systems.

Globally, WBSs have different designs depending on the type of usage and energy demands. Traditional stoves are characterized by losing heat around the heated pot or space. The design of more efficient cookstove models is associated with the amount of heat transferred to the pot and might depend on the regional or even local cooking practices. For instance, cooks that require a more intensive heat transfer may use softwoods like spruce the so called "kitchen fuel" (5) and a stove that is able to transfer the heat directly to the pot in a shorter-term than those used for space-heating (seasonal use). In this last case, people might require a more stable heat release, so they can use hardwoods collected from the near forest and a stove with a thermal mass with the capacity to accumulate and release heat progressively for a certain amount of time like it happens when using Finish masonry and sauna stoves. The use of ceramic (refractory) materials around the combustion chamber (usually made of steel or cast-iron) might contribute to the adjustment of the heat supply to the actual household heat demands, by transferring smaller amounts of heat per unit of time when compared to cast-iron stoves that might release heat in a more intermittent way (38). Concerning the issue of space-heating, non-insulated dwellings might require the operation of larger biomass stoves than dwellings with lower heat demands operating with smaller wood-logs or pelletized biomass fuels.

The understanding of stove interventions in the perspective of the appliance interplay with the user operation behaviours and associated building elements (e.g. energy systems and thermal insulation components) is very important to assess energy consumption patterns and HAP events and design energy efficient retrofits and innovations with a large potential mitigate climate and health risks.

The concept of "wood-burning stove installation" was developed in this thesis during the writing process of the Paper I. This scientific article provides a categorization of WBSs in 9 types of installations by characterizing their operating performance and interplay with biomass fuels and building elements. Table 2-1 describes the existent types of installations of WBSs (IWBSs) that can be found worldwide, according to the conversion technology, fuel combustion air-flow operation as well as the associated types of building constructions and their air-tightness. Table 2-1 also describes the type of climate and health concerns related with the operation of these systems. This section presents an introduction to the characterization of 3 general categories of IWBSs where the detailed explanation of the methods and references used to develop this characterization is presented in the Paper I. Table 2-1 also presents the information on the characteristics of the interventions, respectively those that have been being used in low, mid and high-income regions. The traditional IWBSs are related to the use of open or semi-open fires in low-income regions (39). These systems operate with wood fuels with variable moisture contents and under uncontrolled venting conditions, being characterized by a poor overall thermal efficiency, being mostly used in non-insulated buildings. Most of the cookstove installations of this type do not have a chimney (40).

Table 2-1 General categories and characteristics of installations of WBSs worldwide and associated climate and health risks (Paper I).

Categories	**Conversion chamber**	**Fuel air-flow operation**	**Household elements**[7]	**Health risks**	**Climate issues**
Traditional worldwide	Open, semi-open	Solid-fuels with uncontrolled moisture and venting	Mud, brick, concrete low tight.	Direct exposure to $PM_{2.5}$	Heat losses to forest depletion and BC
Improved mid-income	Enclosed	Wood-logs moderate moisture and venting	Brick, steel concrete in moderate tightness[8]	Indirect exposure to $PM_{2.5}$	Heat losses air pollution
Advanced emerging	Enclosed	Seasoned biomass fuels with high control of venting	Cast-iron, soap stones with high tight.	Ultra-fine PM (UFPs)[9]	Overheat indoors

In spite their relatively low thermal efficiency estimated to be around 15% (41), chimney hearths are commonly used several hours day during the heating season in cold and temperate zones (22). Their intensive use has major effects on the air

[7] Building materials and stove components

[8] With and without insulation

[9] The operation of advanced stoves, with an increased air-tightness, can contribute to the generation of a significant number of UFPs per unit of air volume in dwellings where modern cast-iron stoves are used (38,93). With a larger surface area in volume than larger particles, these particles can transport large amounts of toxic pollutants (with an active surface area) that can be absorbed or condensed (94). Their high deposition efficiency in the pulmonary region make these particles very dangerous for the cardiovascular system (95), potentially inducing adverse health effects (96,97) on building occupants.

pollution and climate. The widespread usage of improved IWBSs is mostly associated with the operation of enclosed stoves in mid and high income regions. The operation of these systems is also related to the usage of wood fuels with variable moisture contents, but under more controlled venting conditions that when using traditional installations. These types of stoves are characterized by an increased overall thermal efficiency when compared to the conventional ones, being usually used in non-insulated buildings. Their inefficient use has a major influence on the air pollution. The advanced IWBSs are characterized by an optimized operation of seasoned woody fuels (dried during 3 or more months before their utilization) under controlled venting conditions in well-insulated (air-tight) dwellings. Their efficient use might contribute to the mitigation of major environmental health effects (Paper I).

According to the available literature, the use of open fires do not achieve a thermal efficiency for heating higher than 40% (42,43) and as small as 20% for cooking (44), resulting in emission factors (EFs) of inhalable particulate matter ($PM_{2.5}$) higher than 450 mg/MJ-del for both cases (44,45) as described in Figure 2-3.

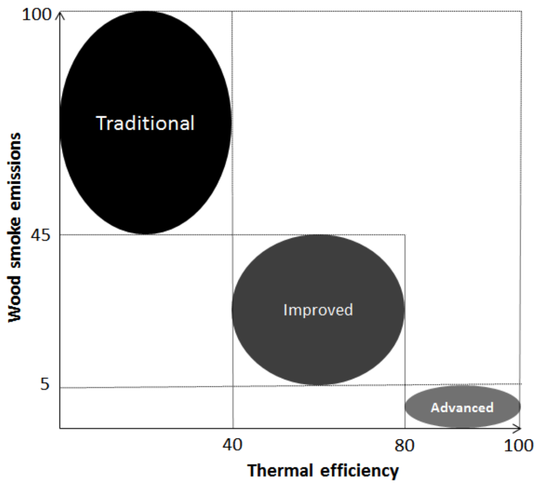


Figure 2-3 General categorization of installations of WBSs according to their thermal performance and environmental (wood smoke emissions[10]) performance (Paper I).

Here, it is also illustrated that the operation of improved type of stoves reach values of thermal efficiency that range from 40 to 80% for heating systems (42,43) and from 20 to 40% for cooking appliances (44), emitting lower amounts of $PM_{2.5}$ than the traditional settings - in the range of 45-450 mg/MJ-del (44,45). Specific

[10] Wood smoke emissions refer to the mix of toxic pollutants such as CO and $PM_{2.5}$.

retrofitting measures in improved installations of WBSs might increase their performance through a higher control of primary and secondary combustion air-inlets when compared to the previous systems. Highly-efficient IWBSs might be designed to increase the systems' environmental performance through more controlled combustion process by air-staging[11] and by introducing gasification[12] processes. In these cases, the installations might reach values of thermal efficiency higher than 80% for heating (43) and 40% for cooking with the emission of very low amounts of $PM_{2.5}$ lower than 150 mg/MJ-del for the most efficient local-space heaters and 45 mg/MJ-del for the most advanced cookstoves (44,46). Beyond the high values of thermal efficiency achieved during the operation of these types of installations, the most recent advances in these technologies are associated with the optimization of their interplay building elements (e.g. ventilation systems and construction materials). In some developed regions, a new generation of WBSs have been being designed to satisfy the low heat requirements of modern insulated dwellings. The design of low-wattage stoves has been being based on a more intelligent control of primary and secondary combustion air-inlets by the adoption of intelligent user behaviours, digital (electronic) sensors (that open and close appurtenant[5] valves) or powered fans (that control the combustion air rate[13]). Figure 2-3 also illustrates how the wood smoke[14] emissions vary in function of the thermal efficiency. The horizontal scale represents the actual values of thermal efficiency for heating stove installations. For cookstove installations, this axis represents the percentage of the maximum value of thermal efficiency that is possible to reach for this kind of appliances. According to the available literature on the most clean biomass cookstoves (47), it was considered this value to be 50%. The scale on the vertical axis is related to the percentage of the maximum value of $PM_{2.5}$ emission factors achieved by WBSs, considered to be 100% for local-space heaters and 50% for cookstoves. According to the scientific review this value was around 1125 mg/MJ-del (Paper I).

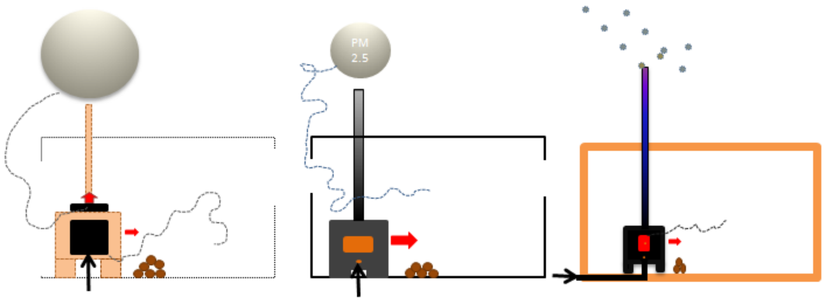
[11] Opening and closing valves of the combustion air-inlets during the different stages of the biomass combustion process.

[12] Gasification stoves are designed to produce wood gas that results from the pyrolysis of the wood fuel and then these gaseous products are burnt through the use of secondary combustion air-inlets.

[13] Fans are usually used to increase the velocity of the combustion air-jets, being used, for instance, to burn pelletized fuels.

[14] Fine particulate matter as a part of wood smoke (a mix of toxic pollutants generated by wood combustion) is considered in this thesis as the best single indicator of environmental health impacts associated with residential wood combustion.

Figure 2-4 illustrates typical improved household installations[15] that can be used for heating and cooking worldwide, concerning their associated air-tightness, aerosol formation and dispersion conditions that can be related with different types of exposure to particulate matter (outdoor, indoor or both). On the left hand side of Figure 2-4 (a), is represented a typical configuration of an improved wood-burning stove installation (WBSI), commonly found in low-income households in developing countries. In the centre of Figure 2-4 (b), is represented a typical improved installation. This type of installation is mostly found in mid-income dwellings (with natural ventilation) located in temperate zones where WBSs are used for both heating and cooking. Here, the houses are usually equipped with a mid-size combustion chamber (smaller than for traditional stoves and larger than for advanced stoves) that operates with higher fuel loads than most of the cookstoves found in developing countries. On the right hand side of Figure 2-4 (c), is represented an advanced installation found in high-income settings where the stove, with a smaller combustion chamber than that found in traditional and improved stoves, operates with an outdoor combustion air-intake and lower fuel loads than most of the stoves found worldwide. This type of installation works mostly as a secondary heating source in well-insulated dwellings.



(a) *(b)* *(c)*

Figure 2-4 Traditional (a), improved (b) and advanced (c) wood-burning installations (and particle emissions) found worldwide in cold and temperate zones[16] *(Paper I).*

The dwellings with uncontrolled ventilation conditions are susceptible to the transport of fine particles from the outdoor to the indoor environment, since their

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[15] This thesis characterizes the usage and performance of WBSs used for both heating and cooking, focusing on the issue of wood heating worldwide.

[16] The orange color symbolizes the usage of thermal mass materials for increasing either the heat storage around the stove or the energy savings in the house (by the adoption of thermal insulation).

dispersion can be influenced by both external meteorological and indoor climate conditions. In these cases, the users are still vulnerable to be exposed to direct indoor emissions due to the inefficient operation of fuel loads, combustion air-inlets and non-functioning chimneys. Here, the chimney draft might be regulated to extract the particles from the indoor spaces. However, if the energy conversion efficiency of these stoves is still moderate, the flame temperature might be too low to promote a proper dispersion of particulate pollutants. In these cases, the outdoor pollution can return to the houses, mainly when the ventilation system does not have any high efficiency particulate filters (HEPA). In the case of the advanced installation that presents the highest air-tightness (c), built in dwellings equipped with mechanical ventilation and HEPA filtering systems, it is possible to control the air-flows in the house to ensure the reduction of particle emission at the source and better dispersion conditions than those found in the improved traditional (a) and installations (b). The high conversion efficiency of this type of advanced applications promotes the reduction of the mass of particles emitted to the outdoor air at high flame temperatures over 600^{o}C. In these cases, the installation of the most advanced stoves might be properly interplayed with well-insulated dwellings with low-heating requirements (16). The IWBSs found in the scientific review were categorized in 9 specific systems (Paper I) to explain the patterns of solid-fuel and stove usage in different regions around the world, according to the following 7 key-geographies: Africa, Eastern-Mediterranean, Europe, Latin America, North-America, South-East Asia, and Western Pacific. This task was done according to their origin and popularity in each region. Table 2-2 describes the installations of WBSs according to a categorization based on their most relevant characteristics such as the fuels used, associated construction materials, and design of the combustion technology and air-inlets.

The use of solid-fuels in traditional cookstoves remains in open fireplaces (unvented[17]) like the 3-stone fire (Fig. 2-5 a) and semi-opened cookstoves (Fig. 2-5 b) or the models using a chimney like the Indian Chulla (vented[18]). Due the effects caused by the operation of these types of traditional stoves on HAP, simple designs of improved cookstoves (ICSs) like the widely used rocket stove, a stove with a higher thermal efficiency than an open fire, constitute low-cost energy solutions to mitigate IAP and associated health risks. These types of installations work either as primary cooking systems like it happens in some developing regions of Ghana, Peru and Northern India or as secondary cooking devices, functioning in a condition of “fuel-stacking” (37) with the simultaneous use of Liquefied Petroleum Gas (LPG) stoves (or induction stoves) in places like Mexico and Southern India.

[17] Without a chimney.

[18] With a chimney.

Table 2-2 Dominant categories and sub-categories of installations of WBSs according to different designs[19] *and geographies (Paper I).*

Categories	**Combustion air-inlets**	**Heaters**	**Cookers**	**Geographies**
Traditonal Open (OP)	Opened (48–50)	Open fire (50)	3-stone (48) Improved open (49)	Developing regions
Traditonal Semi-open (SO)	Semi-opened (25,48)	Mud saw dust (48)	Simple rocket (48), Ghana wood (48), Chulla (25)	Developing regions
Traditional Hearth (HTH)	Largely opened with chimney (50,51)	Fireplaces (51) Hearth (50)	Kitchen hearths (50)	Europe, North America and Australia
Improved Rocket (RK)	Mildly opened (39,52–54)	Old stoves, Bukhari (52) Chimney rocket (53)	Rocket (54), Ecostove (39), Uganda 2-pot (39)	Europe, US, Nepal, China, India, Africa, Latin America
Improved Heavy (HVY)	1-2 air-inlets (39,48,55–59)	Masonry (56), Sauna (57), Chinese Kang (59), Thermal mass (58)	Patsari (39), Plancha (48), Chinese Kang (55)	Europe, America, China
Improved Cast-iron (CI)	2-3 air-inlets (32,60,61)	Cast-iron (32) modern stove (61), Hydronic (60)	Kitchen stoves (62);(33)	Europe and North America
Advanced Gasifier (GF)	3 tiny air-lets (63,64)	Double-chamber gasifier (64)	Semi-gasifier (65), TLUD (63), Sampada (63)	Germany, US, Norway, India
Advanced Digital (DIG)	3 controlled air-inlets (60)	Auto-piloted stove (60)	Biolite	Nordic countries, US
Advanced Forced air (FA)	2-3 forced air-inlets (25,39,48,56,64)	Pellet stove (56)	Wood gas (39), Fan (48), Philips (63), Oorja (25)	Europe, North America and India

[19] Design of the combustion chamber, materials used and combustion air-inlets, based on the type of venting system (with – vented - or without a chimney - unvented).

Figure 2-5 illustrates WBSs that can be found around the world, namely the traditional (a,b,c), improved (d,e,f) and advanced types of installations (g,h,i).

(a) 3-stone fire in Nepal, credits to Christoph Messinger GIZ (66).

(b) Indigenous cookstove in Brazil.

(c) Chimney hearth.

(d) Rocket stove in Tajikistan, credits to Heike Volkmer GIZ (66).

(e) Heavy Kang stove in China.

(f) Hydronic stove in Norway.

(g) Twinfire from Germany, credits to Alliance for Grean Heat (67).

(h) Automatic (Digital application) stove from Denmark.

(i) Pellet stove (Digital application) in Portugal.

Figure 2-5 Illustrations of different types of wood-burning stove (WBS) installations that can be found worldwide (Paper 1).

Situations of fuel stacking are more likely to happen in developing countries with a more developed energy infrastructure like it happens in parts of Brazil (68) and China where there is a larger fraction of the population with access to LPG cylinders and the electricity grid. Some cookstoves can also work as heating stoves, such as the thermal mass stoves (Kangs) found in Northern China (Fig. 2-5 e).

Heating systems such as fireplaces (Fig. 2-5 c), enclosed cast-iron and tiled stoves can also be used as charcoal biomass cookers (33). In Europe, North-America and other cold and temperate climate zones, cast-iron WBSs (either room heaters or inserts) are designed in function of their type of use. Many of these types of stoves are already certified according to either the European (69,70) or the North-American standards (71). Here, two main modes of RWC were identified, namely the primary use of wood fuels in space-heating stoves and their secondary use in either cast-iron appliances[20] or masonry heaters (thermal mass stoves) that are used as either primary or recreational heating sources. In some parts of Finland and Russia, masonry (or sauna) stoves are also used as primary heating systems. The use of fireplaces or conventional WBSs as sole energy sources for space-heating is a more common practice in Southern and Eastern Europe, as well as in different parts of the North America and Asia. There, WBSs are designed to operate with larger wood fuel loads at higher burning rates than, for instance, when using modern (certified) cast-iron stoves in Nordic countries (Fig. 2-5 d-e). When WBSs are used as secondary heating sources, like in most of parts of Nordic countries and Central Europe, it is necessary to design smaller and more efficient combustion chambers to provide a lower wattage output (Fig. 2-5 d-e) than the appliances used in other parts of Europe and in the US. The usage of smaller and cleaner WBSs in a significant amount of homes is now becoming a trend in many parts of Scandinavia. In spite of the fact that there is still a considerable fraction of old dwellings in these regions, these technological changes and the trends towards the adoption of cleaner stoves can be associated with both the low-heat requirements of the new Nordic dwellings and cultural aspects. These factors might explain why Scandinavia is an important region concerning the development and implementation of cleaner technologies of WBSs that can be combined with other devices and building elements (e.g. water jackets, solar energy systems) in order to optimize their integration in dwellings (Fig. 2-5 f). Worldwide, there have been other emerging advances that combine combustion technologies with gasification processes. These advanced stove applications can also be operated with different biomass fuels (hybrid solutions[21]) – including, for instance, a more automatic[22] use of pelletized

[20] It refers to WBSs.

[21] Under development by some producers and designers in order to increase the flexibility of the operation of different fuels (e.g. wood and pellets) between the manual and automatic modes.

[22] Usually involving the operation of digital (electronic) applications.

fuels when people have less time available for tending the fire (Fig. 2-5 g). Other automatic stove technologies[23] (Digital and Forced air) using wood-logs to control combustion air valves (Fig. 2-5 h) were developed in Denmark. Moreover, systems using forced air to burn pelletized biomass residues (wood and residues) were invented in the US, being already used in many European households (Fig. 2-5 i).

2.3. REGULATIONS

Beyond the presented technological developments, wood-burning regulations can be crucial to guide a transition to cleaner and more intelligent wood-burning behaviours through energy efficient and social-technical innovations in order to avoid the emission of climate forcing and health damaging PM. Energy efficiency and mitigation measures, for instance through the adoption of certified stoves, might be addressed regionally or at the country level through the establishment of wood-burning regulations that incite the adoption of innovative tools and modern technologies towards more efficient and cleaner biomass combustion practices.

The WHO indoor air quality guidelines (14), dedicated to present mitigation strategies to control HAP from the combustion of solid-fuels and the International Workshop Agreement (IWA), establish the requirements on 4 different tiers of performance (46), concerning the thermal efficiency and the emission factors of CO and $PM_{2.5}$ of cookstoves using solid-fuels. The testing methods used to regulate the global impacts of wood smoke through an increased energy performance of WBSs are several. The Water Boiling Test (WBT) can be used to determine the thermal performance and wood smoke emissions from solid-fuel cookstoves[24] under standard laboratory conditions. Other protocols can be applied to test the influence of real-world user behaviours on the energy and environmental performance of cookstove interventions, namely the Kitchen Performance Test (KPT) used to determine the fuel savings by the adoption of more efficient biomass stoves and the Controlled Cooking Test (CCT) applied to evaluate the thermal efficiency and the CO and $PM_{2.5}$ emissions that might happen during certain cooking events[25]. The main wood-burning regulations established for heating stoves are those applied in some developed countries, including the New Source Performance Standards (NSPS) developed by the US Environmental Protection Agency (USEPA),

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[23] Using electronic devices to control the admission of combustion air either by opening and closing valves (Digital), by controlling the operation of a fan (Forced air) or by combining both modes of operation.

[24] Operating with coal, charcoal, wood fuels and biomass residues.

[25] In this case, the performance tests are conducted during cooking activities that are typical from a certain region or location. The cooking events are performed by an operator that simulates local cooking processes.

legislation that establishes thresholds for $PM_{2.5}$ emissions in the order of 2g/h for WBSs (71). Recently, the European Commission established the framework on Ecodesign requirements (72) for different types of local space-heating appliances (fireplaces and enclosed stoves using wood and pelletized fuels) in order to regulate the thermal efficiency and $PM_{2.5}$ emissions from these sources, establishing emission limits in order of 2-5 g/kg_F[26]. Currently, the testing methods and certification systems applied for heating appliances used in many cold and temperate zones is done either by applying the EU (69,70,73) or USEPA (71) standards. The European framework also defines the requirements for testing methods that can be applied by different EU member states to determine gaseous[27] and $PM_{2.5}$ emissions from WBSs, to be implemented by 2022 (72). Following these trends, other measures are being recommended in developed countries. For instance, Chile has been one of the few developing countries leading research and political processes in this domain towards implementation of mitigation measures to control air pollution from residential heating stoves operating with solid-fuels. According to Schueftan et al. (24), the promotion of household thermal energy refurbishments and the introduction of high-efficiency WBSs using certified fuels constitute issues of major importance that need to be addressed in Chile.

Considering that biomass combustion stoves are major sources of climate forcing BC, the Climate and Clean Air Coalition (CCAC) is now looking at reducing climate forcing BC emissions from WBSs, being in a process of elaborating emission standards and testing protocols to evaluate the emissions of carbonaceous aerosols from both biomass cookstoves and heating stoves worldwide. According to the CCAC, improving residential wood heating processes is a relevant way to reduce the impacts of BC emissions on the global climate (21).

2.4. INSTALLATIONS´ PERFORMANCE

Worldwide, the investigations carried out on the energy and environmental performance of WBSs in dwellings include the determination of their thermal efficiency, heat transfer conditions and gaseous and $PM_{2.5}$ emissions in association with the people´s exposure to $APM_{2.5}$. This section presents a scientific review on the performance of the 9 installations of WBSs categorized in section 2.2 in order to represent the technologies available worldwide. The scientific review presented in detail in the Paper I considered both laboratory and field measurements conducted in different countries. Some laboratory experiments, considered here and presented in section 3 (Paper V), were developed through the simulation of typical wood-burning behaviours on operation of the WBSs in Europe. Field data was also obtained to characterize the performance of IWBSs on the IAQ (Paper I-V).

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[26] Mass of $PM_{2.5}$ emitted by fuel burnt in dry basis (g/kg_F).

[27] CO and Organic Gaseous Compounds (OGCs).

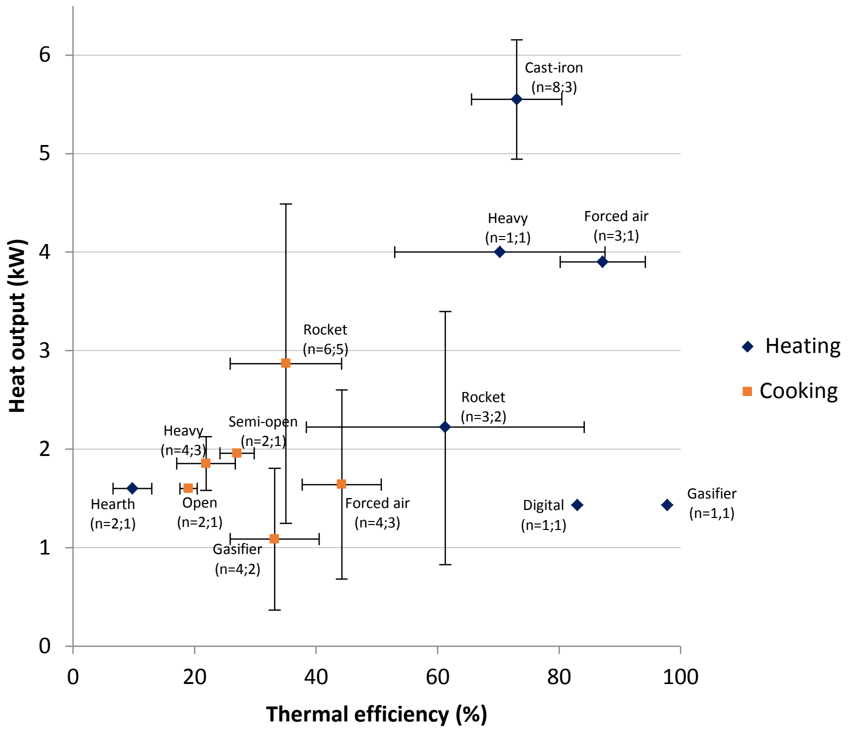

Figure 2-6 Energy performance of WBS installations worldwide. Heat supply in function of thermal efficiency – for seasoned wood 5-20 %wt.[28]*, where n (n=nEf;nHo), respectively represents the number of studies considered to obtain the mean values (±SD) obtained for the thermal efficiency (nEf) and heat output (nHo) for each category of WBS installation. The blue squares represent the heating installations and the orange squares illustrate the cooking installations (Figure 5 in Paper 1).*

Figure 2-6 illustrates the results obtained for the energy performance of the 9 categories of IWBSs covered by the scientific review, presenting the mean value of the heat output for each category (±SD) in function of the mean value of the thermal efficiency obtained for each installation. Here, it is possible to observe the higher thermal efficiency of heating stove installations (blue squares) in relation to the thermal efficiency of cookstove installations (orange squares). This situation can be explained by the fact that cookstoves usually loose at least more than 15% of heat to the living spaces through the stove/chimney surfaces. Traditional local-space heaters with chimneys (e.g. fireplaces, hearths) transfer small amounts of heat into the house, due their inefficient operation (sometimes an overall negative space-

[28] Moisture content.

heating efficiency[29]) in dwellings without insulation. This can happen due to uncontrolled venting and infiltration conditions in these dwellings.

Figure 2-6 also illustrates the relatively high heat output obtained for the usage of cast-iron stoves that, in some circumstances, cause overheating events while being operated in houses with low heat requirements (38,74). Thus, the new generation of WBSs are more sophisticated and smaller than the old stoves designed to achieve the highest thermal efficiency and the lowest emissions of PM through the operation of seasoned wood-logs[30] and pelletized biomass fuels[31]. The cleanest available WBSs are those which may better transfer and adjust the heat to the heat demands of cooking pots (depending on the cooking practices) or, in the case of heating appliances, those that better integrate the stove use with the building insulation (higher energy savings) and other heating systems. Thus, here, it is possible to state that the more adjusted is the wattage output to the actual heat requirements, the larger is the installation´s flexibility to interplay with other sustainable energy systems in the house, including both solar energy and responsive ventilation systems[32]. The more controlled the biomass combustion processes through the operation of relatively small fuel loads at low-burning rates[33] are, the more efficient is their integration in the built environment. For instance, the adoption of digital (electronic) devices that can be coupled with improved stoves to manage the heat transfer might increase the adjustment of the heat supply to the actual heat demands. When used for residential heating, these advanced technologies can actually achieve very high net-thermal efficiencies while operating in dwellings with low wattage requirements. Moreover, these types of IWBSs can be interplayed with heat exchangers in the house (e.g. floor heating systems, combustion air-inlets and pipes from the outdoor environment, heat storage reservoirs) by releasing heat progressively in the dwellings through a more stable release that can be manually or digitally adjusted to the daily life demands (for heating and/or cooking).

Beyond the overall thermal efficiency in the heat transfer processes in dwellings, the emission factors of CO and $PM_{2.5}$ are presented in this thesis to characterize the environmental performance for each stove installation in relation to the impacts of

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[29] In these cases, the fireplaces remove heat from the house.

[30] Chopped and dried during an entire season for more than 3 months.

[31] Preferably certified by a proper regulatory body in relation to their ash and moisture contents as well as other parameters.

[32] Intelligent ventilation systems (usually using automatic devices and sensors) able to adjust the air exchange rate in function of the energy consumption and IAQ.

[33] In relation to the operation of conventional WBSs.

their operation on the ambient air quality. These two parameters are considered to be the most relevant general toxic elements present in wood smoke that are used in policy making processes.

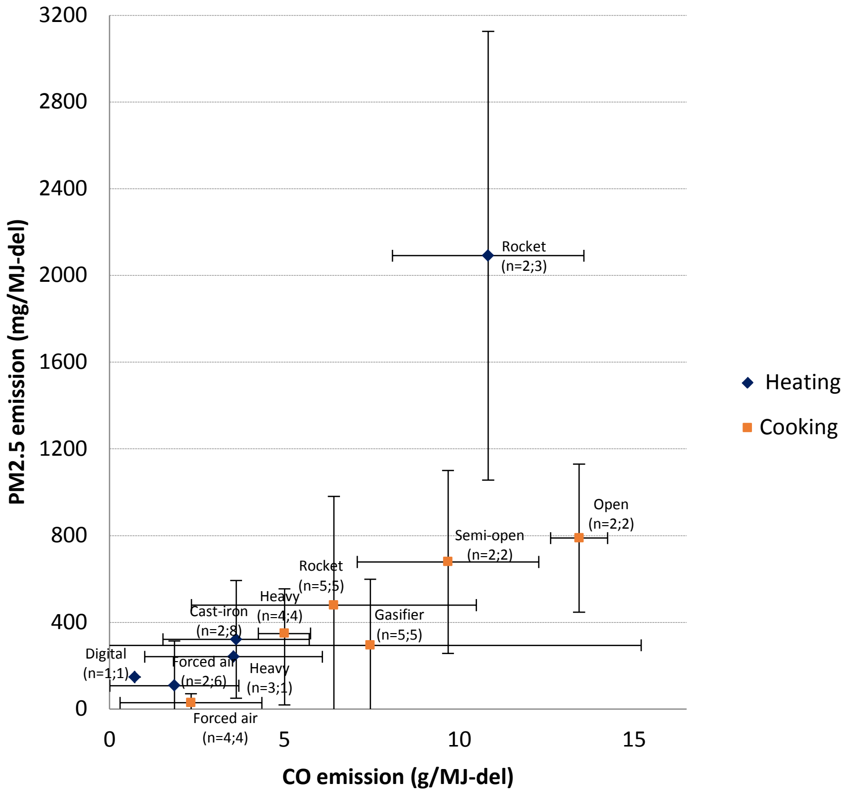

Figure 2-7 Environmental performance of different WBS installations found worldwide in relation to their influence on the air pollution. Emissions of mass of $PM_{2.5}$ (mg) and CO (g) per unit of delivered energy (MJ-del) by WBS installation – for seasoned wood 5-20 %wt.[34], where n (n=nCO;n$PM_{2.5}$), respectively represents the number of studies considered to obtain the mean values (±SD) for the CO (nCO) and PM2.5 (n$PM_{2.5}$) emission factors (EFs) for each category of installation. The blue squares represent the heating installations and the orange squares illustrate the cooking installations (Figure 7 in Paper 1).

Figure 2-7 describes the emission factors of $PM_{2.5}$ in function of the emission factors of CO for the 9 categories of IWBSs. Figure 2-7 presents a compilation of all the data collected in the scientific review, being the specific references presented

[34] Moisture content.

in Table A.3 in the Appendix of Paper I. In Figure 2-7, it is possible to observe the mean values and standard deviation (error bars) for the values obtained for the emission factors of $PM_{2.5}$ ($EF_{PM2.5}$), presented here in function of the values obtained for the emission factors of CO (EF_{CO}). On one hand, the chimney hearths are not shown in this chart due to the relatively higher $EF_{PM2.5}$ when compared with the other categories of IWBSs analysed in this scientific review (>2000 mg/MJ-del) which would make it difficult the comparation between the emission factors of the different types of installations presented here. According to the available studies, the hearths with a chimney might emit the largest ammounts of $PM_{2.5}$ even when compared with open fires without a chimney, a fact that might be related to distinct testing conditions applied to quantify the EFs. On the other hand, the modern cast-iron heating installations seem to be able to mitigate both the emissions of CO and $PM_{2.5}$ in more than 50% in relation to the emissions caused by chimney hearths (see Table A.3. in Paper I). The adoption of advanced IWBSs, instead of the adoption of improved IWBSs, would reduce the $PM_{2.5}$ emissions in more than 30% to values below 150 mg/MJ-del through the usage of automatic applications (instead of manual systems)[35] to properly ensure optimized air-staging processes while burning proper loads of seasoned biomass fuels and by regulating combustion air-inlets automatically.

Concerning the use of some types of improved wood-fired cookstove installations, the rocket stoves designed for cooking still reveal high variations on both the EF_{CO} and $EF_{PM2.5}$ which might be related to the lower air-tightness of these kind of low-cost applications when compared with other improved types of installations, namely the heavy mass (e.g. Masonry, Kang) or modern cast-iron WBSs. The rocket stoves used for heating were characterized by higher EFs than most of the other categories of WBS installations, since they generaly have a lower air-tighness when compared to the other WBSs and also due to the fact that most of the wood heating stoves operate with larger ammounts of fuel than most of the wood-fired cookstoves. As a consequence, it is important to point out that only the most advanced heating installations of WBSs (e.g. Gasifier, Digital and Forced air) might be able to fulfill the $PM_{2.5}$ emission thershold of 2.5 g/h[36] established in the NSPS for new wood heating stoves[37] (67,75). However, currently, these types of advanced installations, equiped with a functioning chimney, are mostly operated in high income settings. In the context of global regulations and considering the IWA system of tiers of performance, some advanced cookstoves (e.g. gasifiers) might not achieve the

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[35] The automatic operation of cleaner biomass stoves (fuel loads and combustion air-inlets) instead of the manual control of combustion air valves during the usage of the modern stoves.

[36] If emissions tested using wood-logs (cord wood is the word used in the US).

[37] Necessary to be sold in the US.

maximum level of performance (tier 4) concerning the emission of $PM_{2.5}$ (46). Being the WHO guidelines and IWA system global regulatory instruments that aim to promote cleaner wood-burning conditions in households, they are, however, mostly applied to regulate the usage of solid-fuel cookstoves (mostly in developing countries), presenting tighter and more ambicious emission targets than those demanded by the European or North-American standards. These global regulatory instruments are focused on reducing emissions to very low-levels at the source[38]. Indeed, the orientations provided by the WHO are based on the fact that even the unvented cookstoves (without a chimney) might be able to achieve very low levels of CO and $PM_{2.5}$ emissions. On this background, modern gasifiers and forced-air cookstoves without a chimeney emit less than 400 mg/MJ-del of $PM_{2.5}$ (tier 2) to the kitchen. In fact, in tropical climate zones, the cookstoves are mostly located outside the home or in a different compartment of the house from that where people stay most of the time. Even thouth the EFs are more than 60% lower for these categories of advanced cookstoves when compared to traditional systems, the improper use of such forefront applications without a functioning chimney installation might still, in some circunstances, contribute to local air pollution events in the regions where these advanced stoves are used. Further research should be addressed to test the influence of the operation of these types of unvented installations on the local ambient air quality[39].

2.5. EMERGING TECHNOLOGIES

In the past 20 years there has been an effort to promote WBS innovations that could increase the thermal efficiency of heating and cooking stoves, respectively over 80% and 40% for heating and cooking stoves, targeting the reduction of the emission of climate and health damaging $PM_{2.5}$ to near-zero levels, which means below the levels recommended by the WHO indoor air quality guidelines and other international standards. In short, among the most efficient (not commonly used) available energy conversion technologies in the world are the stoves that apply and optimize (in combination) the following biomass conversion processes, including:

- An intelligent combustion of biomass through air-staging by either using digital devices[40] or through a proper interplay between the manual control of primary and secondary air-inlets;
- A controlled pyrolysis, gasification and combustion of the biomass fuel in small-scale appliances[41] by increasing the mixing and residence time of the

[38] Independently of being unvented or vented.

[39] Both indoor and outdoor air quality.

[40] Digital devices can support users in the operation of fuel loads and primary and secondary air-inlets, as well as giving recommendations for the proper maintenance of chimneys.

combustion gases in the chamber, for instance, in stoves with two distinct chambers (e.g. Twinfire) or in cookstoves with a Top-lit-up-draft (e.g. TLUD – several models[42]) design;

- An appurtenant usage of electronic devices that integrate fans to regulate the combustion air-flow and velocity into the stove (necessary for the combustion of pelletized fuels).

These types of emerging innovations are considered as forefront technologies of WBSs since they are slowly being enlightened and adopted worldwide, constituting promising solutions towards the transition to cleaner household biomass combustion regimes.

Figure 2-8 illustrates the performance of the most advanced stoves and associated innovations found on earth, describing wood smoke emissions (in terms of $PM_{2.5}$[43]) in function of the thermal efficiency of the energy conversion systems. From this chart, it is possible to grasp the idea that there is a significant gap between the thermal efficiency of cookstoves and heating stoves. Here, it is also clear that the WBSs that use a fan to regulate (forced air) the combustion air-flow rate (and associated velocity of combustion air-jets[44]) are among the most promising innovations to be considered in the design of advanced stoves. On the other hand, the combustion systems that involve a previous gasification stage (Gasifiers) are the most efficient systems used for heating and cooking that do not require electrical power, emitting very low amounts of $PM_{2.5}$.

According to recent exploratory investigations conducted during the “Pellet Stove Design Challenge workshop” that took place at the Brookhaven National Laboratory (New York) in April 2016 (76), a model of multi-fuel gasification heating stove (Gasifier) using a catalyst developed in Germany by researchers at the Deutsches Biomasseforschungszentrum (DBFZ)[45] seems to release the lowest

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[41] Stoves can be design to promote a first process of pyrolysis through the regulation of the primary air, generating gaseous compounds that can be burnt in the upper part of the combustion chamber through the injection of secondary air.

[42] As explained in the section 1.2, after the invention of the TLUD design in 80s, upgrades to the first inception by Dr. Reed, Wendelbo and other designers have been being conducted by Anderson, Roth, Winter, Harris and other designers involved in development projects (6,47).

[43] As the most studied indicator of the environmental health effects caused by the emission and formation of wood smoke in the atmosphere.

[44] Velocity of the combustion air that flows into the stove.

[45] Among them are Dr. Ingo Hartmann and René Binding and other developers (98).

amount of $PM_{2.5}$, performing even better than the most advanced models of gasifier cookstoves that use an electric fan (Forced air).

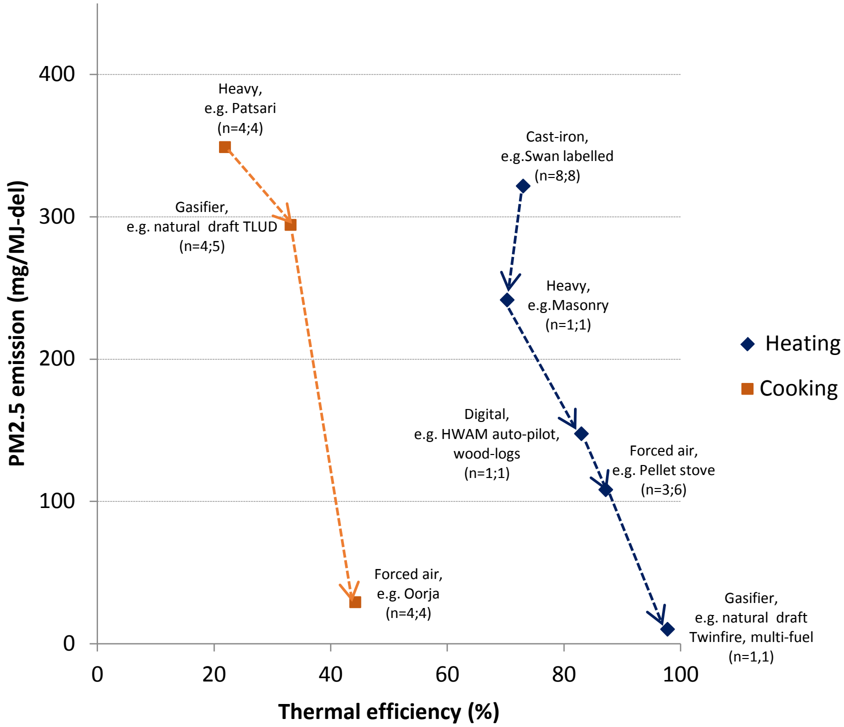


Figure 2-8 Performance of emerging stove technologies (14) and example of a stove name[46]. Mean value of the emission of mass of $PM_{2.5}$ (mg) per unit of delivered energy (MJ-del) in function of the mean value of the thermal efficiency for each WBS installation – for seasoned wood 5-20 %wt.[47], where n (n=nEf;n$PM_{2.5}$), respectively represents the number of studies considered to obtain the mean values (±SD), concerning the thermal efficiency (nEf) and the $PM_{2.5}$ (n$PM_{2.5}$) EFs for each category of installation. The blue squares represent the heating installations and the orange squares illustrate the cooking installations.

Concerning the natural draft gasifiers, new cooking applications are currently under development where designers such as Mr. Kirk Harris at the Aprovecho Research

[46] Stove model or type included in each category (References in the Paper I).

[47] Moisture content.

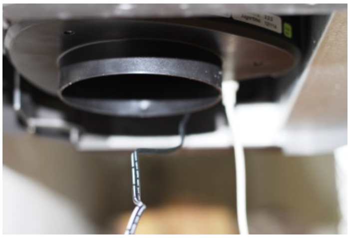
Centre (ARC) are working on the increasing the regulation of the firepower by controlling the amount of primary air supplied into the batch of fuel[48].

Figure 2-8 also illustrates that, except for the cast-iron stove, the increase in the thermal efficiency of the most advanced WBSs is associated with a reduction of the $PM_{2.5}$ emissions. The gains in both the energy and environmental performance of the most advanced WBSs (e.g. Forced air and Gasifier stoves) might be correlated with the higher flame temperatures achieved during the operation of this type of installations when comparing them with systems with a lower air-tightness (e.g. masonry and cast-iron stoves). Figure 2-8 also shows that the most efficient technologies are those using forced air and pelletized fuels (at the same time, e.g. Oorja) reaching very low emission factors of $PM_{2.5}$ when comparing with the other types of stoves. In this case, the $PM_{2.5}$ emission factors are lower than 120 mg/MJ-del (<50 mg/MJ-del for the forced air type of cookstoves). The level of reduction of the impacts of WBSs on air pollution by the adoption of a fan and pelletized fuels (forced air) is higher for cookstoves than for heating appliances. This might be explained by the fact that the most of the forced air heating stoves (e.g. pellet stoves) operate at higher biomass burning rates than the same type of cookstoves (using the same type of pelletized fuels). As a consequence, the cleanest pellet stoves generate more $PM_{2.5}$ per unit of delivered energy than the most efficient forced air cookstoves, being the emissions from the local-space heaters more than 4 times higher than 7 mg/min (the intermediate recommendation established in the WHO guidelines). In certain external circumstances (e.g. fuel moisture, downwind), and considering that even the most advanced energy conversion technologies might not be able to achieve this emission targets, innovative electronic applications can be integrated in the stoves to fulfil this recommendation. For instance, digital devices can be installed in modern cast-iron stoves to ensure a thermal efficiency for space-heating over 85%. In this case, the new applications will comply with the EPA emission targets for $PM_{2.5}$ of less than 2g/h, considering a biomass burning rate of $2kg_F$/h and the use of seasoned or pelletized wood fuels. Several of the most advanced biomass conversion principles can be combined in a single technology[49] like it happens in some multi-fuel stoves that burn wood-logs and pellets (e.g. Biolite, new version of the Twinfire[50]).

[48] In this case, a secondary combustion unit on top of the primary combustion chamber swirls the air/flame/gas/ smoke mixture and seems to reduce emissions (47).

[49] For instance, pyrolysis, gasification and combustion through proper designs and automatic air-staging techniques using a fan and/or appurtenant valves controlled by a digital device.

[50] Still under development by the DBFZ.

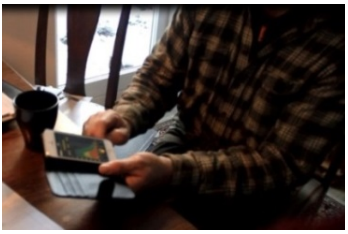


Hwam auto-pilot – automatic stove with digital application[51] *(a)*

Biolite - gasifier[52] *cookstove (b)*

Solar – cast-iron hydronic heater (c)

Paladium - catalyst (d)



Aduro smart – digital device and app (e)

Burn ban (f); credits to pscleanair[53] (77)

Figure 2-9 Advanced biomass combustion systems: energy conversion systems (source), heat and emission control devices (exhaust) and end-user digital applications (behaviours).

Figure 2-9 illustrates some of the emerging innovations that are already available in the market. Beyond the fact that some of the automatic air-staging solutions are already available in the market like the HWAM auto-pilot (Fig. 2-9a), this type of

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[51] Controls the admission of combustion air during different stages of the wood combustion process – ignition, combustion and re-ignition, indicating the best time for refilling the stove.

[52] Gasifier and a forced air cookstove.

[53] Image collected from the official webpage of pscleanair (77).

advanced applications have a large potential to be further developed in order to optimize the stove interplay with ventilation systems and other end-user applications connected to smart phone applications and the internet.

Some of the intelligent devices illustrated in Figure 2-9 can also assist users on the best lightning and operating behaviours that should be applied on a certain day, depending on the local meteorological conditions. Among the most advanced energy conversion systems are also the gasifier cookstoves using pelletized biomass residues that are able to regulate the velocity of the combustion air through forced air-jets or to reuse extra heat to produce electric power in a small generator to supply the fan or to recharge other electronic devices like the Biolite[54] (Figure 2-9b). In spite of being significantly cleaner than other stoves, the installation of functioning chimneys in these types of advanced stoves is considered to be a very important intervention in order to avoid particles and other pollutants indoors[55]. In the case of the local-space heaters, further retrofits can be applied to recover heat that would be lost through the exhaust by installing heat exchangers around the chimney pipe that can be used to pre-heat combustion air-inlets as shown in the Portuguese case study analysed in section 3. Moreover, in this case, thermal mass materials and water jackets can also be coupled to heating stoves with high energy conversion efficiency over 75% to provide a more efficient and stable heat release across the different compartments of the house. These hydronic heating stoves can also interact with solar thermal systems as described in the Norwegian case study presented in section 3 (Figure 2-9c). Beyond the primary mitigation measures, catalytic converters (Figure 2-9d), extra draft pumps, smart ventilation sensors that provide a better stove interplay with the exhausts in the house as well as high-efficiency filters are among some of the possible secondary measures to reduce particulate emissions to levels below 7 mg/min (emission target recommended by the WHO). However, these additional measures might be expensive for most of the people, requiring extra attention and maintenance. Other emerging technologies of WBSs are the smart applications connected to the web. These applications can be important tools to manage ambient air pollution in both a local and regional scale. Wireless apps such as the one developed the Aduro Smart Response system (Figure 2-9e) and the air quality app developed by the Purge Sound Clean Air Agency (Figure 2-9f) can support users to operate their stoves in a more efficient way, indicating when is the best time to light and operate their stoves, chimneys and appurtenant combustion air-intakes. These types of applications have a potential to guide the users to deal with undesired and adverse meteorological conditions (e.g. atmospheric inversions and strong winds).

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[54] Electricity production in a small electric generator (through a gradient of temperature).

[55] Especially relevant during the lightning phase when a considerable part of the PM emissions occur under shouldering conditions.

Some of the applications presented in this section are still under development in the US and Europe and might constitute relevant solutions to support the transition to a more intelligent use of cleaner WBSs in low-carbon dwellings[56]. In spite of the fact that some of these innovations are only accessible for high-income families, political efforts should be addressed to facilitate the accessibility to them. Moreover, some of the forefront stove innovations used today in few developed countries, for instance in places like Scandinavia, can be re-designed to accomplish the requirements and socio-economic conditions found in other regions of the world. For example, some digital applications used in Nordic countries to improve the control of fuel loads and combustion air-inlets could be appropriated to users of wood-fired cookstoves living in developing countries. Such actions of technology transfer and appropriation could give an important contribution to the mitigation of global climate and health risks.

Another issue that could be addressed in developing countries is related with the re-utilization of the heat that is usually lost around the pot on the top of biomass cookstoves. These energy losses could be avoided by using heat storage reservoirs (e.g. to produce domestic hot water, improving hygiene and health conditions) or thermal mass materials in order to develop systems that would reach values of thermal efficiency close to those achieved by heating stoves.

The last, but not the least, despite the fact most advanced cookstoves generate a very low mass of $PM_{2.5}$ and CO per unit of delivered energy, some of these applications are installed without any chimney. Here, functioning chimney interventions are recommended to avoid indoor air pollution events, especially during the start-up and refilling of the stove.

[56] Dwellings with low energy requirements, including those buildings with a low carbon footprint (e.g. built with local and proper materials).

CHAPTER 3. CASE STUDIES: INNOVATIONS POTENTIALS

This chapter explores the practical aspects concerning the use of forefront stove improvements worldwide through experimental and energy simulation studies, presenting results on the energy and environmental performance of stove retrofits and innovations (2.6). The case studies described here cover 4 relevant wood-burning practices happening worldwide, namely the cases of: heating in cold and temperate zones of Europe and Peru and cooking in tropical climates of Brazil. Field and laboratory experiments were conducted to evaluate the performance of the usage of installations of WBSs in 5 countries, according to the following practices: “cooking in a situation of fuel stacking in Brazil”, “primary cooking and heating in Peru”, “primary heating in Portugal” and “recreational wood-burning in Denmark and Norway”. The investigated regions and locations represent places in the world where biomass fuels are being used in households in a daily basis mostly in peri-urban and rural areas where there is an on-going transition to cleaner wood-burning practices and modern fuels. In Europe, the 2 case studies involved the analysis of the performance of both dominant and emerging stove technologies on the heating grid of 24 dwellings. In Southern-America, the other two case studies were conducted to investigate the effects of the usage of ICSs on the IAQ of 20 rural houses. Here, the studies were conducted in communities benefitted by cookstove programs. In all the investigated regions, the experimental work was conducted to evaluate the energy and environmental performance of forefront stove technologies that have been installed in those regions during the last 10 years.

For the case studies conducted in the Iberian and Scandinavian dwellings, energy simulations were carried to estimate the typical stove operating performance in heating grid of building envelopes existing respectively in the Mediterranean and Nordic regions. This chapter is mainly based on the compilation of the most relevant scientific data presented in 4 of the scientific papers included in this thesis (Papers II-V). The overall study design and explanation about the parameters analysed in each case study is presented in section 3.1. The methods applied to study the interventions in the European dwellings are described in section 3.2 while the method used to perform laboratory tests is presented in section 3.3. In section 3.4 are presented the methods used to conduct the building simulations on the energy performance of 3 different types of WBSs in the heating grid of typical Portuguese and Danish single-family houses. In section 3.5 (Paper IV) are presented the results of the case studies conducted in South-America to analyse the infield performance of cookstoves on the IAQ in two rural communities, respectively located in a mountainous region of Peru and in a semi-arid region in Northeast Brazil. In section 3.6 (Papers II-V) are described the results obtained in the experimental (field and laboratory) and modelling (energy simulations) studies. Section 3.8 presents a general analysis on the innovation potentials investigated in the 4 case studies.

The methodological approach applied in these case studies combined infield and laboratory studies in order to include the analysis of typical user behaviours and stove operating conditions observed in the real-world. The studies aimed to evaluate the effects of stove interventions on the household energy usage, thermal efficiency and emission of gaseous and particulate pollutants from wood combustion.

3.1. STUDY DESIGN

The experimental and modelling studies presented in this section show the results of the evaluation of the operating performance of emerging stove retrofits and more advanced applications used to improve the interplay between user behaviours, seasoned biomass fuels and combustion air-inlets.

The studied areas in the European countries are places with a well-established energy grid where families living in rural and peri-urban areas are using WBSs for either primary or secondary heating, respectively in Portugal and Denmark. In the first case, the stock of RWC appliances is dominated by fireplaces and conventional stoves. In the second case, enclosed modern stoves are the most common types of wood-burning systems. Figure 3-1 illustrates the appliance stock in Portugal (32) and Denmark (78), respectively estimated to be around 1.5 and 0.7 million units.

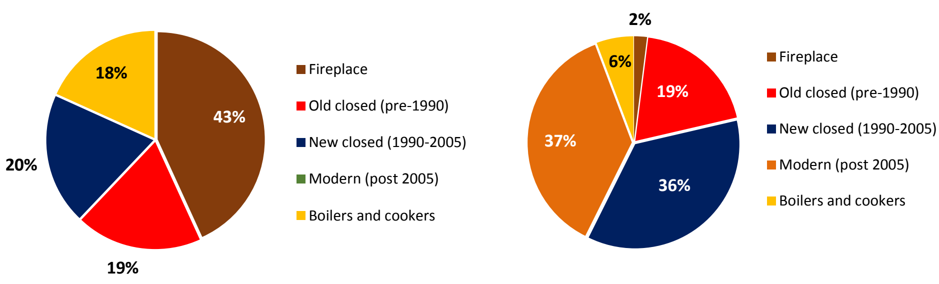


Figure 3-1 Stock of residential wood combustion appliances in Portugal (32) on the left hand side and Denmark (78) on the right hand side (Paper V).

In both cases, the $PM_{2.5}$ emissions from RWC are estimated to represent more than 30% of the total emissions in each of the two countries. It is estimated that the highest levels of $PM_{2.5}$ emissions might occur in the peri-urban areas of Aveiro and in the outskirts of the cities of Copenhagen, Aarhus and Oslo.

The two countries in South America were selected as developing regions in different climate zones where there is a great variability of situations in the access to the energy grid. It is important to point out that during the past decade substantial incentives have been provided by the governments of Brazil and Peru to facilitate the transition to gas and improved wood-fired cookstoves in rural areas of those two countries. According to the WHO report on the household cooking fuel sector, it is still estimated that there are more than 10 million wood fuel users in each developing country, being these sensitive regions concerning deforestation and local air pollution.

(a) Hydronic stove and solar panels in low energy house in Norway

(b) Use of pellet stove in a rural house in Portugal

(c) Use of improved cookstove for heating in a rural house in Peru

(d) Use of an improved cookstove in a rural house in Brazil

Figure 3-2 Experiments conducted in rural dwellings using WBSs in cold (Norway), temperate (Portugal and Peru) and tropical climate zones (Brazil).

On this background, the operating performance of wood-fired stoves in the studied regions was determined through the application of reference and equivalent measurement methods. Figure 3-2 illustrates some of the tested IWBSs.

In Europe, the thermal efficiency, gaseous and particulate emissions of 3 types of heating stoves was analysed in a laboratory installation in Portugal (3.3). In Denmark and Norway, indoor climate studies were conducted to evaluate the risks of overheating and particulate emissions. In South-America, the effects of the operation of two models of ICSs (Peruvian Nina – Fig.2-2 - and Brazilian IDER – Fig.3-2.d.) on the indoor temperature and concentrations of CO and $PM_{2.5}$ were analysed.

First, field interviews were conducted to collect information concerning the use of household energy and typical user behaviours on the operation of biomass fuels and stoves in 24 households in Portugal, Denmark and Norway. Second, laboratory experiments were conducted to determine the energy and environmental performance of three wood-burning installations used in Europe under typical operating conditions. These experiments were carried out in a laboratory setting at the University of Aveiro to determine the thermal efficiency and gaseous and $PM_{2.5}$ emissions from each type of installation. Third, building simulations were conducted to analyse the influence of the operation of 3 types of stove installations (traditional, improved and advanced) on the heating grid of Iberian and Nordic single-family houses. Fourth, field measurements were performed to evaluate the effects of stove operation on the indoor climate of 12 dwellings located in Scandinavia and 10 rural houses located in South-America. The experiments conducted in Peru and Brazil had an exploratory character, targeting the understanding of variations on the IAQ in households benefited by the installation of ICSs and not the determination of the users´ exposure to wood smoke. In both cases, the studied communities were benefited by relevant programs developed by local Non-governmental Organizations (NGOs) between 2006 and 2012. The Peruvian cookstove program was implemented by the Centre for Capacity Building and Development (CECADE) in thousands of households located in mountainous regions of the country. The Brazilian cookstove program was conducted by the Institute of Sustainable Development and Renewable Energy (IDER) selected as the largest program ever implemented in the country.

The laboratory experiments were designed in function of the information collected on typical user behaviours on the operation of European stove installations. The study parameters considered in the design of each case study are presented on Table 3-1, describing the testing conditions adopted to conduct each case study. The parameters presented here were selected to evaluate the performance of different stove interventions. Table 3-1 presents information on the sampling periods, stove interventions, emerging innovations, the number of samples collected and parameters analysed in each case study.

Table 3-1 Case studies, interventions and experiments carried out in European and South-American countries.

Case studies	**Denmark & Norway**	**Portugal/ Spain**[57]	**Brazil**	**Peru**
Climate	Cold/ temperate	Temperate Mediterranean	Tropical	Cold/temperate
Testing periods	3 weeks in 3 winters	3 months in 3 winters	2 weeks in 2 years	1 week in 1 winter
Mainstream interventions	Masonry, cast-iron stoves	Fireplace, cast-iron insert	Rocket cookstove	Rocket stove
Innovations	Digital device hydronic	Stove retrofits automation	None	None
Interviews, experiments	12 interviews, 3x12 samples	12 interviews and 3x6 lab. tests	10 interviews, 7 samples (exploratory)	10 interviews, 3 samples (exploratory)
Energy performance	Flame temp, 4 energy simulations	Exhaust temp, combustion air-flows, 4 energy simulations	Thermal energy use	Thermal energy use
Flue gas emissions	O_2 infield	$PM_{2.5}$, CO, TOCs	None	None
Indoor air quality	Temp, RH[58], PM, UFPs, CO, TVOCs	None	Temp, RH, $PM_{2.5}$, CO, TVOCs	Temp, CO

[57] The types of stove installations used in Portugal and Southern-Europe might be similar to the systems used in other cold and temperate climates worldwide.

[58] Relative Humidity

Table 3-1 also describes the information about the building simulations conducted to estimate the energy performance of the total system (energy consumption, indoor climate and CO_{2e} emissions) during the operation of traditional, improved and advanced stove installations in both well-insulated and non-insulated dwellings, typically found in Denmark and Portugal.

In Europe, the laboratory work aimed to test the typical operating performance of a fireplace and an enclosed wood stove. The experiments conducted for a pellet stove were carried out to analyse the potential performance gains that can be achieved by the adoption of this emerging technology. In Scandinavia, the performance of the operation of masonry and certified cast-iron stoves (43) on the indoor climate of Danish and Norwegian dwellings was analysed, including the assisted operation with digital devices of appliances with a Swan label. In South-America two different models of rocket stoves with a steel combustion chamber covered by thermal mass materials, respectively using clay and concrete, were analysed. It is important to point out that different parameters and instrumentation were used to perform the tests due to distinct testing conditions and environmental health risks observed in the different studied regions (Figure 2-4). In developing countries, the two case studies aimed to understand variations on the IAQ during the usage of wood-fired ICSs that still operate under smouldering conditions, the reason why this work focused on IAP issues. In the developed countries, the two case studies were concentrated on the development of stove retrofits and advanced applications in order to increase the energy performance of conventional installations by reducing associated gaseous and particulate emissions at the source.

3.2. FIELD INTERVIEWS

For all case studies field interviews were carried out to wood fuel users by selecting and collecting qualitative information from the typical operation practices applied in their IWBSs. The interviewees were persons using WBSs on a daily basis during the winter in Nordic, Iberian and Andean settings. In Brazil, the interviews were conducted to people using improved wood-fired cookstoves during the whole year in rural households located in the North-East part of the country.

The selection of the study areas was based on the literature review on wood-burning activities and the dwellings were found with the help of local stakeholders from the stove sector like non-governmental associations and companies. The regions with where the highest annual $PM_{2.5}$ emissions from RWC are expected to occur were chosen to conduct the field studies. Thus, the field work was performed in the locations with a significant number of WBSs. In Portugal, the peri-urban areas of Aveiro (32) were chosen due to the fact that this is the region of the country where the highest annual $PM_{2.5}$ emissions from RWC were estimated as described in section 3.1. In Denmark, the outskirts of Copenhagen and Aarhus were selected as the regions with the highest annual $PM_{2.5}$ emissions from RWC in the country as referred in section 3.1. In Norway, a low energy house located near Oslo was selected to study the usage of a hydronic stove in its residential heating grid as a site where there is a high density of wood heating stoves.

Table 3-2 Household energy sources and stove installations used for heating and cooking in Europe and South-America.

Site	Usage	House	Stove	Ventilation	Heat sources
Iberian rural (N=8)	Primary heating	Adobe, concrete	Fireplace, stove	Natural	Wood
Iberian peri-urban (N=2)	Secondary heating	Concrete, brick, insulated	Manual and automatic stove[59]	Natural	Wood, electric, solar
Nordic (N=2)	Primary heating	Concrete, brick, insulated	Stoves and digital devices	Natural, mechanical	Heat pump, solar
Nordic (N=10)	Recreational heating	Concrete, brick, insulated	Stoves and digital devices	Natural, mechanical	Gas, district heating
Andean (N=2)	Cooking, heating	Mud	Traditional	Natural	Wood
Andean (N=8)	Cooking, heating	Mud	Improved rocket	Natural	Wood
Northeast Brazil (N=2)	Cooking	Adobe	Traditional	Natural	Wood, LPG
Northeast Brazil (N=8)	Cooking	Adobe, concrete	Improved rocket	Natural	Wood, LPG

[59] Pellet stove (Forced air).

In South-America, the qualitative interviews were conducted in a mountainous community near the city of Cusco (Peru) and in a village located in the state of Ceará (Brazil). The interviews were carried out in 20 households to demarcate existing wood-burning practices in rural communities relying on wood-fired cookstoves benefited by ICSs programs.

The qualitative interviews revealed 8 main types of stove installations, according to the interplay between fuel use and building elements in 4 regions with different climates: Iberian Mediterranean, Nordic cold and temperate, Andean mountainous and Northeast Brazil semi-arid. Table 3-2 presents general information concerning the types of application, construction materials used, stove design, type of ventilation and thermal energy sources used in the houses. Moreover, the thermal energy supply from the heat sources in the houses was calculated multiplying the primary fuel consumption by the energy conversion factors associated with their operation, including the low heating value of the fuels used and thermal efficiency of each of thermal energy system found in each of the studied dwellings. These calculations were conducted to evaluate the influence of the stove operation on the heating grid of each of the investigated houses.

3.3. LABORATORY WORK

After the collection of data about the use of WBSs in European houses, laboratory tests were conducted to evaluate the performance of three categories of WBSs commonly used in Southern Europe and other cold and temperate climates. The studies were performed at the laboratory installation at the University of Aveiro.

Considered as one of the most common types of wood fuel used in Mediterranean dwellings, the pine softwood specie "*Pinus Pinaster*" was selected to perform all the tests conducted to evaluate the thermal performance of a fireplace and a certified wood stove in order to compare different operating conditions (including stove three retrofits). Moreover, experiments were also conducted to evaluate the operating performance of a pellet stove. Here, two different types of wood pellets, the certified pellet fuel I (EN-plus) and the non-certified pellet fuel II, were chosen to perform the experiments for which it was considered that typically these automatic stoves operate between the maximum (level 5) and mid (level 3) levels of heat output when operating the fan at mid-power (level 3). The laboratory work aimed to understand the effects of the adoption of stove retrofits and innovations on the thermal efficiency, heat output and emissions of CO, $PM_{2.5}$ and Total Organic Compounds (TOCs) for the three installations. Figure 3-3 illustrates the studied IWBSs tested in Europe, namely a fireplace (a), certified wood stove (b) and an automatic pellet stove (c).

(a) Fireplace *(b) Wood stove* *(c) Pellet stove*

Figure 3-3 Experimental setting used to evaluate the thermal performance of three types of IWBSs typically used in Europe: a fireplace (a), a wood stove (b) and a pellet stove (c).

First, the operating conditions and thermal performance of a certified wood stove was tested taking into account the European testing method established by the standard EN13229 (70). Second, three retrofits were designed and integrated in that wood stove and then their operating performance was tested in order to evaluate the impact of these mitigation measures on the thermal efficiency and emissions of pollutants resulting from the wood combustion processes. These retrofits correspond to the installation of secondary air inlets (single and multiple) and an annular chimney used to pre-heat the primary combustion air (Fig. 3-4.a.). In this case, a heat exchanger was installed in the chimney (Fig. 3-4.c.) able to use outdoor air. Here, the air between the two chimneys was vacuumed through a flexible pipe connected to the stove operating with natural convection. The retrofit for multiple air-inlets was designed to be installed in the same opening (Figure 3-4.b.) of the single secondary air-inlet, providing 18 nozzles that admitted secondary combustion air in between the middle and top part of the combustion chamber.

Figure 3-4 illustrates the retrofits, namely the pre-heating primary air pipe (a) and air exchange system in an annular chimney (b).

The experiments conducted for the wood stove were also carried out for both a fireplace and a certified pellet stove that controls the air-supply through a digital device. This automatic stove was certified according to the standard EN14785 (73). All of the results obtained in these laboratory experiments were then analysed according to the framework of Ecodesign requirements established by the European Commission (72).

(a) Pre-heated primary air-inlet

(b) Opening for secondary air-inlet

(c) Annular chimney

Figure 3-4 Experiments on the wood stove and its retrofits: certified wood stove and pre-heating system (a), secondary air-inlet (b) and heat exchanger in an annular chimney (c).

The laboratory experiments were designed taking into account the typical user behaviours on the operation of biomass fuel loads and combustion air-inlets in the studied Iberian dwellings (Paper V). After pre-heating the stove (hot start), three wood combustion cycles (N=3 replicates) were considered to determine the mean thermal efficiency and heat output for each of the 6 studied conditions, according to the equations 1-4. For the fireplace and wood stove, the flue gas temperature and composition used to calculate the energy losses in the dwelling were collected in intervals of 20 seconds during 40-60 minutes, depending on the biomass conversion process (operating conditions) in each of the tested conditions. For the pellet stove, the same type of data was also obtained for each 20 seconds. However, here, the sampling period was 10 minutes due to the fact that the automatic stove operated under more controlled biomass combustion conditions (almost under steady-state). Each wood-burning replicate was performed considering the typical regional fuel operating behaviours in each type of installation by burning:

- 2 kg of seasoned pine wood in the fireplace;
- 2 kg of seasoned pine wood in the certified wood stove. The same tests were conducted for each of the 3 retrofits;
- 0.8 to 1.2 kg/h of wood pellets in the certified automatic stove using wood pellets type I with the European quality label EN-plus (79) and wood pellets type II produced in the Aveiro region.

Considering the goal of this comparative study, fuel loads with the same number of wood-logs or amount of wood pellets as well as with a similar kind of geometry were fed into the stoves. Equations 1-4 were used to determine the energy performance of each installation by applying the calculation method presented as one of the additional publications and included in the list of references (80):

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

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

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

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

Where η (%) is the thermal efficiency of the combustion system, $\dot{Q}_{in}$ (kW) is the heat generated from wood-burning, $\dot{Q}_{lost}$ (kW) are the energy losses by the dwellings during each wood combustion cycle, LHV_b (kJ/kgF) is the low heating value of the biomass fuel, $\dot{m}_b$ (kg_F/s) is the biomass burning rate, $\dot{m}_{ca}$ (kgF/s) is the mass flow rate of the combustion air, h_{ca} (kJ/kg_F) is the specific enthalpy of ambient air, $\dot{n}_i$ (mole/s) is the molar flow rate of the gaseous compound i, $\overline{cp}_i$ (kJ $mol^{-1}K^{-1}$) 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 mean reference temperature considered to be 273K, w_{wF} (%) is the moisture content of 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 interior of the house, being n the number of combustion products. Equation 4 considers that all the thermal energy produced by the appliance and chimney pipe (inside the house) is transferred to the interior of the dwelling. Taking this into consideration, the temperature and composition of the flue gas were measured at 3.5 meters considered to be the interior height of a typical European single-family house[60]. A mean value of the wood-burning rate was used to determine the heat generated from wood-burning process for each testing condition. The low heating values considered to calculate the thermal efficiency and heat output for each testing condition were determined at an external laboratory. 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).

[60] Considering that the interior height of the European single-family houses varies between 2.7-5 meters.

Figure 3-5 presents the detailed drawing of the laboratory installation where the experiments were conducted. The gas flow rate of the flue gas 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 operating conditions in each type of stove (A) installation were analysed by measuring the flame (B) and exhaust (G) temperatures using K-type thermocouples, among other parameters.

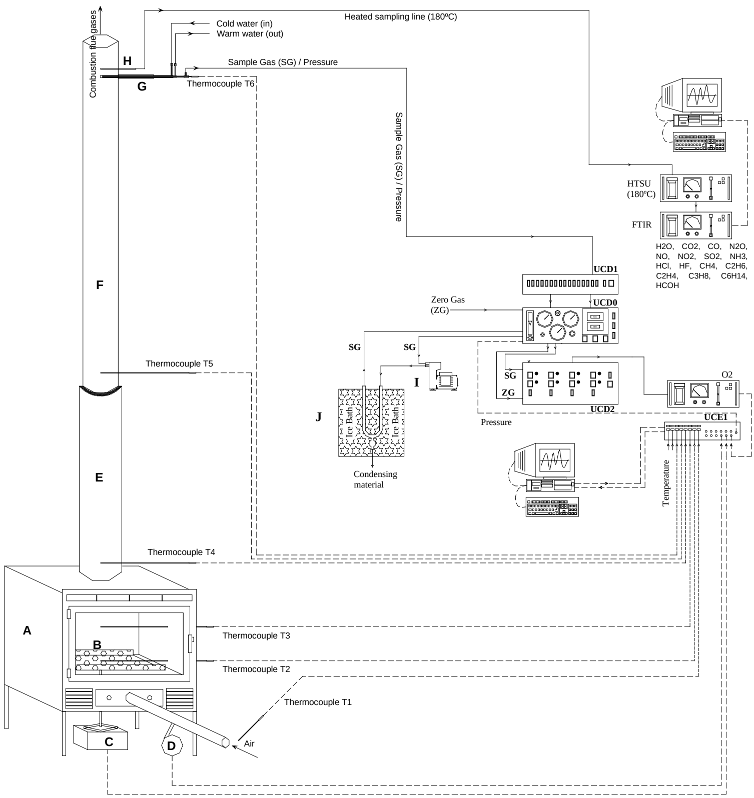
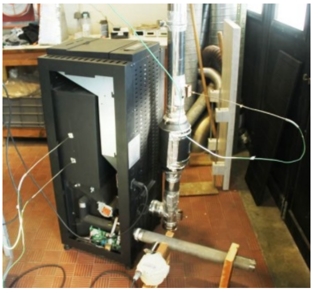


Figure 3-5 Schematic representation of the laboratory installation at the University of Aveiro. A – Stove; B - Combustion chamber; C – Weight sensor; D – Air flow meter; E – Chimney exhaust; F – Chimney duct; G – Water cooled gas sampling probe; H – Gas (hot) sampling line; I – Gas sampling pump; J – Gas condensation unit.

The real-time wood-burning rate in the fireplace and wood stove was monitored by using a wood fuel weight sensor DS-Europe Model 535QD-A5 (C) that measured the weight of the fuel in the grate of each combustion system. This equipment was not installed in the pellet stove due to the small size of the combustion chamber. For both the wood stove and pellet stove, the combustion air flow rate was measured using an air flow rate meter model KURZ Model 500-2.0-P40 (D) installed at the primary combustion air intake. 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 flue gas composition in terms of H_2O, CO, CO_2 and TOCs (wet basis) was measured in a heated sampling line at 180^oC (H) connected to a Fourier Transform Infrared Spectroscopy (FTIR Gasmet, CX4000) analyser. The O_2 concentration (dry basis) was measured in a gas analyser ADC Model O_2-700 with a Servomex Module by sampling the flue gas in a water-cooled probe (G). In this case, the flue gas passed through a set of gas conditioning (sampling probe with a filter for particulate matter and with an external water quenching sleeve for condensing the water vapour in the flue gas) and distribution units (J).

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.

Figure 3-6 illustrates the experimental setting and instrumentation used for the measurement of the real-time values of operating temperatures, combustion air-flow rate and composition of the flue gas.



(a) Thermocouples and air-flow meter in the pellet stove

(b) O_2 and FTIR analyser

Figure 3-6 Laboratory installation at the University of Aveiro (Portugal): measurement of operating conditions through the use of K-type thermocouples, air-flow meter Kurz 155 (a) and gas analysers Gasmet and Servomex (b).

The $PM_{2.5}$ emission factor of the fireplace was obtained from a previous study conducted at the same laboratory facility by Gonçalves et al. (32). The $PM_{2.5}$ emission factors obtained for the wood stove 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 fibre filters) for gravimetric analysis using a TCR TECORA (model 2.004.01) instrument operated at a flow rate of 2.3 Nm^3h^{-1}. The filters were prebaked at 500^{o}C during 6 hours. The sampling was located 10 m in the downstream of the dilution tunnel entrance as described in previous studies conducted at this laboratory (81,82). The filters were prepared and weighted before and after the sampling in a room under controlled conditions of temperature and relative humidity. This part of the laboratory work was conducted in collaboration with a research fellow at the CESAM.

(a) Dilution tunnel under isokinetic conditions

(b) TCR Tecora, sampling probes and filter heads for $PM_{2.5}$

Figure 3-7 Laboratory installation located at the Department of Environment and Planning at the University of Aveiro (Portugal).

Figure 3-7 illustrates the dilution tunnel and filter heads used to sample the $PM_{2.5}$. After sampling the PM, the Teflon fibre filters were dried and weighted in a micro-balance. The $PM_{2.5}$ emission factors determined for the pellet stove were derived from the determination of the emission factors of thoracic particulate matter (PM_{10}) by considering 85% of the mass of PM_{10} corresponds to the mass of $PM_{2.5}$. The same protocol used to determine the $PM_{2.5}$ emission factors was applied to determine the PM_{10} emission factors for the two experiments conducted for the pellet stove, however, using another sampling filter head, proper to sample PM_{10}.

3.4. BUILDING SIMULATIONS

This section aims at presenting the methodology used to conduct building simulations on the operation of the studied installations of WBSs used in cold and temperate zones. The energy simulations presented here are based on the information provided by both field and laboratory studies conducted in Portugal and Denmark, reflecting the typical patterns of household energy use, stove operating conditions and their influence on the indoor climate of both non-insulated (Iberian) and well-insulated (Scandinavian) dwellings. The simulations were performed using the well-established Building Simulation Modelling (BSim) tool. The software was downloaded from the BSim SBi/Aalborg University website (83). Afterwards, two construction models were applied to simulate the operation of WBSs, respectively in modern and old houses. The energy models considered the operation of 3 different types of WBSs (open fireplace, enclosed wood stove and automatic stove[61]) used in the two regions.

Table 3-3 Building models and simulations conducted to compare different regimes of operation of IWBSs in Portugal and Denmark (Paper V).

Model	**Heating systems**	**U-val. (W/m^2)**	**Stove**	**Power (kW)**	**Winter season**	**Time in day**
Portugal	Thermal loads[62]	0.7	None	0.0	Nov-Apr.	18-23
			Open	2.0		
			Enclosed	4.8 (8,80)		
			Automatic	3.0 (8)		
Denmark insulated (mineral wool)	District heating, Natural gas, Heat pump, thermal loads[7]	0.2	None	0.0	Oct-Mar.	6-8; 18-22
			Open	2.0		
			Enclosed	6.5		
			Automatic	6.0		

[61] Digital (modern wood stove in Denmark) and Forced air (pellet stove with a digital application in Portugal).

[62] Thermal loads due to the usage of electric devices and the occupation, considered to be the same for both the Portuguese and Danish houses.

The building models were based on the characteristics of the single-family houses found in Southern and Northern Europe. Initially, a building model with a total net volume of 322.4 m^3 and floor area of 114.3 m^2 was considered. Here, information on the construction elements (e.g. materials, thickness of the walls, windows) and energy systems (e.g. thermal loads[7], electricity, ventilation) that are part of a typical Danish dwelling (insulated) were included in the first model provided by the SBi/Aalborg University and then redefined to represent the use of the different types of WBSs during the winter.

The same geometrical construction was then used to design a typical building model representative of the construction materials and energy systems used in a typical Portuguese dwelling (non-insulated).

Climate data from the cities of Copenhagen and Coimbra were respectively downloaded from the BSim and Energy plus websites. The two selected cities were considered to represent the weather conditions for a Typical Reference Year (TRY) in Denmark and Portugal. To use the Portuguese climate data from Energy Plus™ it was necessary to download and apply a conversion tool to create a file format that could be used in the BSim software (84). Afterwards, the input data concerning the typical stove operating practices for the associated 3 types of installations was introduced in each of the energy simulation models (insulated the non-insulated houses). In most of the cases, the heat output used to simulate the operation of the different stoves was obtained from the laboratory experiments. For the Portuguese stove, an averaged value of the heat output for the wood stove and retrofits was considered to perform a single simulation for this kind of appliance. The same thing was done for the pellet stove where an averaged value of the heat output for the use of two different types of fuels was considered. For the Danish stoves, data on this parameter was obtained from scientific publications (8,80). It is important to point out that the Danish model considered that a conventional heating system was programmed to achieve an indoor set point temperature of 19°C in the insulated house. For the Portuguese model, no central heating system was considered to operate in the house, being the stove considered as the only source of heat in the non-insulated dwelling. The information concerning the heat output of the different WBSs was based on the scientific review presented in Chapter 3 and the laboratory work conducted in Portugal presented in the section 3.3.

Table 3-3 provides information about the characteristics of the buildings, including information about the thermal characteristics of their elements such as the U-value of the external walls and heating systems using in the houses. The heat output supplied by the stoves to the dwellings is also described for each stove installation (e.g. fireplace, wood stove and automatic stove), including their typical periods and hours of operation during the heating season.

Considering the information described on Table 3-3, a set of 6 energy simulations were performed to study the influence of each stove installation on the residential heating grid on their interaction with two different types of European dwellings located in two distinct regions. From the simulations it was possible to extract information on the total thermal energy consumption and associated Greenhouse gas (CO_{2e}) emissions for each of the interplays between stoves and dwellings. The energy simulations were also used to predict the indoor climate conditions associated with the operation of each installation. In general, it was possible to estimate potential energy savings and the contribution of the most efficient installations to mitigate climate change in relation to the use of fireplaces.

3.5. INDOOR CLIMATE MEASUREMENTS

This section presents the results obtained in indoor climate measurements conducted in the households where qualitative interviews were applied, except for the case of Portugal where no field measurements were conducted. This last case study focused on the laboratory measurements presented in section 3.3.

Considering the uncertainty associated with the results obtained in the building simulations, field measurements were conducted in Danish and Norwegian houses (Paper II-III) to analyse the effects of different wood-burning behaviours on the indoor climate and the risks of overheating and particles. The indoor climate measurements here were conducted during 3 heating seasons for 12 dwellings. The measurements of the indoor temperatures and concentration of PM (e.g. PM_{10}, $PM_{2.5}$ and ultra-fine particles) were carried out during the usage of masonry and certified stoves according to the standard EN13240 (69) operating either manually or using a digital device. For all experiments, the sampling started half an hour before lightning the fire in order to determine the background levels for each parameter. In Peru and Brazil, IAQ measurements were conducted to evaluate the variations in the kitchen temperature and concentration of CO and $PM_{2.5}$ during the operation of the studied wood-fired cookstoves (Paper IV), also starting the measurements at least half an hour before lightning the fire. The case studies in this region are considered as exploratory due to the fact that the IAQ measurements were conducted for short-periods of time for few samples. This can be explained by the fact that these studies were conducted in remote places with a limited access to proper instrumentation to perform reliable measurements, allowing only the development of the exploratory characterization of variations occurring on the air quality in kitchens using vented cookstoves[63].

[63] Refers to the improved stoves in relation to the traditional models that have a chimney.

In this case study, buildings erected in different years (1977-2011) and using other heating sources such as natural gas boilers, district heating, heat pumps and solar collectors were selected to conduct the indoor climate measurements.

Table 3-4 Data concerning the indoor climate study on Nordic IWBSs in dwellings located in the outskirts of Copenhagen (CPH), Aarhus (AAR) and Oslo (OSL).

Building (location)	Age (class)	Stove	Label	Device	Heating systems	City
Espergærde A	1977(D)	Masonry	-	None	Gas	CPH
Værløse II B	1985	Cast-iron	DS	Auto	Gas	CPH
Bagsværd C	1998	Cast-iron	DS	Auto	Heat pump	CPH
Hillerød D	2001(C)	Cast-iron	DS	None	Gas	CPH
Ringsted E	2006(B)	Masonry	-	None	Distr. heat	CPH
Virum F	2007(B)	Cast-iron	DS	None	Gas	CPH
Værløse I G	2008(A)	Cast-iron	DS	None	Heat pump	CPH
Lasby H	2008(C)	Cast-iron	DS	Smart	Heat pump	AAR
Esrum I I	2009(A)	Cast-iron	DS	None	Heat pump	CPH
Esrum II J	2008(B)	Cast-iron	DS	None	Gas	CPH
Skandenborg L	2011(A)	Cast-iron	DS	Auto	Heat pump	ARR
Langhus M	2011(A)	Cast-iron	NS	Hydronic	Solar	OSL

The influence of the operation of masonry and cast-iron stoves on the indoor climate, certified either according to the Danish (DS) or Norwegian (NO) version of the European standard EN13240, was tested twice under controlled operating conditions (manual use by an expert or automatic operation) in the 12 dwellings by performing 3 wood combustion cycles using seasoned wood-logs (usually Beech). Here, the experiments were conducted according to the following burning rates and conditions:

- 2 kg of wood per hour in masonry and certified cast-iron stoves with the support of an expert on their operation through top-down lightning (7);
- 1 kg of wood per hour in certified cast-iron stoves using two different types of computer added devices, namely the HWAM Auto-pilot (N=4) and the Aduro Smart Response system (N=1).

Table 3-4 presents the detailed information about each of the studied dwellings and stove installations analysed in Scandinavia. As described in detail on the papers II-III, tiny tags recorded the real-time temperature and relative humidity indoors and outdoors. Two condensation particle counters (CPCs) were used to measure the real-time concentration of ultra-fine particles (UFPs) in the same sampling points, by installing the TSI model CPC3007 (indoors) and P-track 8025 (outdoors), recording data with an aerodynamic diameter ranging between 0.01 and 1 µm.

Figure 3-8 illustrates the field experiments and instrumentation used to measure the indoor climate parameters. The instruments used outdoors were installed in sites distant from the chimney of the stove and the building ventilation system. Inside the house, a gas analyser was used to sample and measure the real-time concentration of CO and Total Volatile Organic Compounds (TVOCs). A Laser II particle counter was used to measure the real-time concentration of particles within different size ranges varying, allowing the calculation of the $PM_{0.3}$ and PM_{10}. All the samplings conducted indoors were carried out in the centre of the living room where people stay most of their time. The samples were collected at the breathing zone at 1 meter height, considering that building occupants tend to remain sited in the couch or at the dining table when they come back from work. The sampling time had the duration of 4 hours considered to be representative of the daily use of the stove during the afternoon when people come back from work. A passive tracer gas technique, the so-called PFT technique (Per Fluorocarbon Tracer), was used to measure the air change rate, air infiltration and air exfiltration in the houses. The technique is a multiple tracer-gas method based on passive sampling (85).

Figure 3-8 Field measurements in a Danish house on the left hand side (a) and in a Norwegian setting on the right hand side (b) during the use of advanced stove applications.

Table 3-5 presents the general specifications of the interventions implemented and analysed in the two South-American countries (Paper IV), presenting information on the thermal efficiency of the low-cost wood-fired ICSs.

Table 3-5 Information concerning the stove interventions in South-America: general specifications regarding the operation of ICSs in Peru and Brazil.

Case study	Wood species	Thermal efficiency (%)	Energy savings (%)	Cost (€)	Benefited families
Nina (Paruro/Peru)	*Eucalytus Escallonia*	5-30[64]	30	15	>2000
IDER (Ceará/Brazil)	*Eucalyptus Mimosa*	5-35	40	20	>26 000

In Peru, the study was conducted in the Andean community of Yaurisque in Paruro. In Brazil, the field experiments were carried out in the village of Km60 located in the semi-arid region of Limoeiro do Norte in Ceará. The development of the field measurements had the support of both local universities and NGOs that facilitated the accessibility to the studied locations and instrumentation, the reason why these two communities were selected for conducting the IAQ experiments, excluding other villages located in more remote places.

In total, the measurements were performed under uncontrolled conditions in 10 dwellings during the operation of the ICSs by the users for a typical cooking period of 2-3 hours. Due to the limited access to calibrated portable instruments that could be transported to the remote villages, only 5 dwellings will be analysed in more detail in section 3.6.

Among the portable monitors and sensors used in these IAQ measurement campaigns are the HOBO sensors used to record real-time kitchen concentrations of CO during all day in Peru. HOBO temperature sensors were installed in the households to record the indoor temperature and relative humidity. In Brazil, the kitchen concentrations of $PM_{2.5}$ were measured using a DustTrack™ Aerosol Monitor 8530 (Figure 3-9.a.). The gaseous concentrations of CO and TVOCs were measured using a Graywolf sensor and monitor.

[64] More than 35% when used for space-heating during the winter season.

Figure 3-9 Field measurements in a Brazilian house on the left hand side (a) and in a Peruvian setting on the right hand side (b) during the use of ICSs.

All the instruments were placed in the centre of the kitchen at the breathing zone of the cooks while they were preparing the meals. The experiments started to be carried out 30 minutes before the local users lightened the cookstove.

3.6. COOKSTOVES AND INDOOR AIR

This section presents the results concerning both qualitative and quantitative information on the operating performance of wood-fired cookstoves, being focused on the study of the usage of ICSs. This section focuses on the performance of low-cost technological systems that were made locally (non-industrial applications). Some of these systems were already illustrated in Figure 2-2. Thus, this section presents a compilation of the most relevant results concerning their influence on the IAQ.

The qualitative interviews conducted in the studied communities show that in South-America the families adopted the ICSs as either their primary or secondary energy system for cooking. In Peru, the wood-fired cookstoves worked mainly as primary cooking and heating systems. Figure 3-10 presents an overview chart concerning the adoption of the ICSs in the two communities. In Figure 3-10 it is also possible to observe that the new stoves were fully accepted by the Peruvian community and partially adopted by the Brazilian one. This fact might be explained by social changes in the Brazilian cooking habits. Another reason could be explained by economic aspects concerning the access to LPG, higher in the Brazilian village than in the Peruvian one.

In fact, in the field visits it was possible to verify that some of the Brazilian families have reframed their cookstove to satisfy their local cooking habits, which require the usage of larger wood-logs.

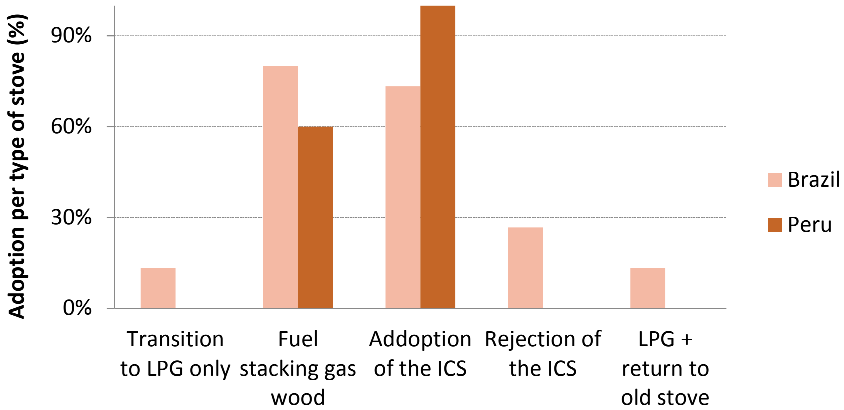


Figure 3-10 Use of wood-fired[65] and LPG cookstoves in the studied communities in Peru and Brazil (Paper IV).

Some of the women interviewed in this study complained that the size of the combustion chamber was too small or improper to serve their local cooking practices, the reason why more than 1/5 of the families in the Brazilian village rejected the IDER cookstove. Figure 3-11 illustrates the re-framed stoves by the local users in Brazil. On its left hand side the reutilization of an LPG stove for cooking with coal and wood is represented while on its right hand side, a changed version of the IDER cookstove is illustrated.


Figure 3-11 Cookstoves in Brazilian houses: reutilization of an LPG stove on the left hand side (a) and a reframed version of the IDER cookstove on the right hand side (b).

[65] Includes the use of a traditional (old) open or semi-open fire and/or the operation of an improved cookstove (ICS).

In the studied Brazilian community, almost none of the users have returned to the old stove, although some people have reshaped the available cookstoves adapting them to use local wood fuels according to their cooking needs.

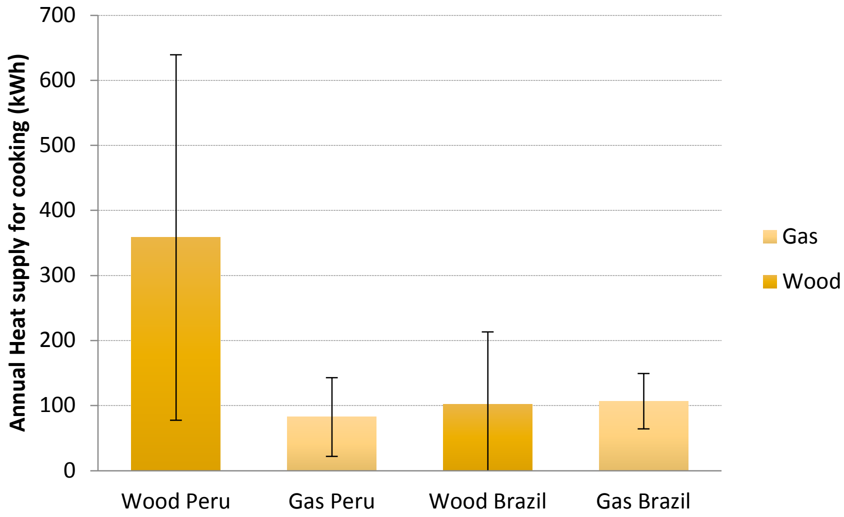


Figure 3-12 Heat supply to the cooking pots (±SD) by wood-fired and LPG cookstoves in the Peruvian and Brazilian communities (Paper IV).

Anyway, most of the families in Brazil remained in a situation of fuel stacking, using the LPG and wood-fired cookstove at the same time as is described in Figure 3-12. In Peru, more than a half of the users were using wood and LPG simultaneously, too. Figure 3-12 illustrates the annual heat supply by cookstove type in each community, reflecting that the contribution from wood-fired cookstoves used for cooking processes in Peru is more than 3 times higher in this case (primary system) when compared to the energy supplied by gas stoves in both countries or even when comparing it with the contribution of the usage of wood-fired cookstoves in Brazil. However, in this case the reported wood fuel consumption varied quite significantly from house to house. In the case of the Brazilian community, the energy supplied by the wood-fired cookstoves to the cooking pots (either work as primary or secondary cooking systems) is almost the same as for the amount of heat transferred by the LPG stoves (fuel stacking).

The real-time CO concentration measurements conducted in one of the Peruvian houses during a week day during the winter show that in this case, typically 3 cooking events occur during the all day. Figure 3-13 shows that the peaks in the kitchen concentration of CO occur during the morning breakfast, lunch and dinner times. As a consequence, these ICSs are mainly working when people want to cook their meals, using the residual heat for warmth during the time they sit in the kitchen to have their meals and socialize. From these real-time measurements, it is possible to observe that the CO concentration during cookstove use never exceeded the value of 45 ppm.

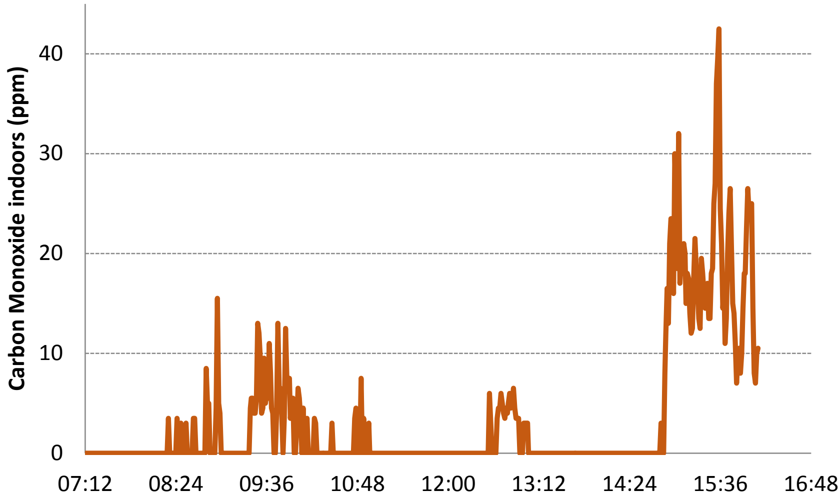


Figure 3-13 Carbon Monoxide concentrations during a week day in the winter in a Peruvian household using a Nina cookstove (Paper IV).

The most relevant variations in the CO concentration occurred in the end of the day when the entire family was home after work during the dinner time. For the Brazilian settings the kitchen concentration of CO never exceeded the values achieved in this Peruvian setting. The measurements of $APM_{2.5}$ in the Brazilian kitchens revealed significant variations during the operation of the cookstoves A-E where the installations E and D were reframed by the users.

Figure 3-14 illustrates that in the intact installations A and B (original ICSs) the kitchen concentration of $PM_{2.5}$ reached values over 1000 µg/m^3 approximately 25 minutes after lightning the fire in the stove. This fact might be explained by the position of these cookstoves in the kitchen balcony, a situation that might explain why the pollutants took some time to be transported from the balcony to the main part of the kitchen.

From the exploratory field studies in South-America, it was possible to confirm that in this developing region wood-fired cookstoves are not only being used for cooking like in rural areas in Brazil, but also for space-heating like in mountainous areas of Peru.

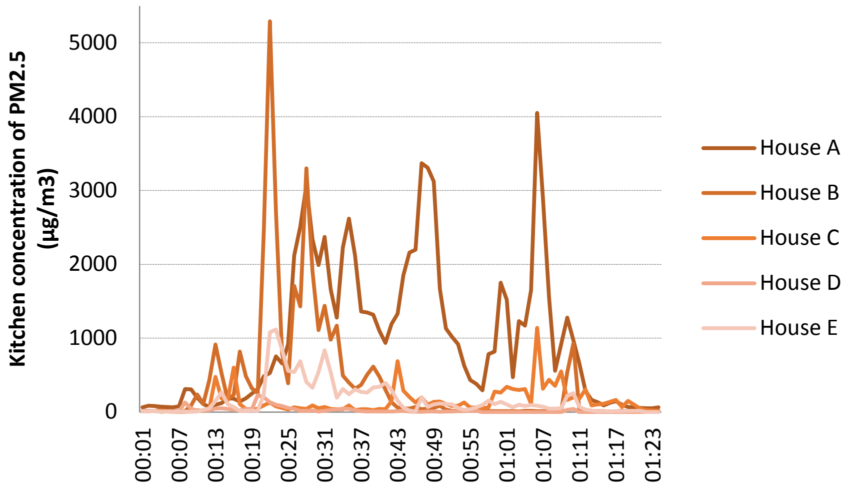


Figure 3-14 Influence of cookstove use on the IAQ in the Brazilian houses A-E (Paper IV).

Both of the studied models of ICSs revealed to have larger performance in terms of wood savings rather than on improving the IAQ, since the second issue is strongly correlated with the household interventions and cooking behaviours. The IAP issues observed in this exploratory study showed that there are other factors rather than the installation of more efficient technologies of cookstoves and chimneys that influence on the IAQ (e.g. resistance of the materials used to produce the stoves, chimney maintenance). In general, the users were satisfied in having more efficient stoves than those used before, since the new stoves used in average 40% less wood than the traditional ones. Moreover, the use of the ICSs could also be combined with the operation of LPG stoves in short-term cooking events such as water boiling for making coffee or tea. The stoves used for both cooking and space-heating in Peru revealed to have a wood consumption more than two times larger than the Brazilian ICSs. In this last case, even the operation of ICSs can cause higher concentration levels of $PM_{2.5}$ than the Canadian Alberta air quality objectives for short-term exposure times of 1-3 hours (86). Thus, improvements are recommended towards the development of these low-cost models of ICSs by increasing their air-tightness in order to avoid the leakage of pollutant particles from the stoves to the local ambient air. In this context, functioning stove/chimney installations might be considered in order to improve the exhaust draft towards a better dispersion of the PM in the atmosphere, avoiding outdoor-indoor transport and backdrafts from the combustion chambers. Further developments of the energy conversion technologies might be based on the user behaviours in order to tackle the WHO indoor air quality guidelines. IAP monitoring campaigns on future interventions might constitute relevant tools to support the adoption of cleaner cooking and heating stoves in these regions of South-America.

3.7. HEATING STOVES AND PERFORMANCE

This section presents the results on the operating conditions concerning the usage of biomass heating stoves in Peru as well as in the studied European countries, being focused on exploring opportunities for the adoption of more advanced user behaviours and energy conversion technologies. This part of thesis suggests that energy efficiency measures can be applied to mitigate greenhouse gas (GHG) and $PM_{2.5}$ emissions from the inefficient usage of traditional wood stoves in these cold and temperate zones. First, information on the typical user behaviours and biomass stove installations found in Peru as well as in Iberian and Nordic countries will be presented. Second, the results from the laboratory experiments on the operating performance of 3 typical European installations of biomass local-space heating systems will be analysed. Third, the influence of the operation of these types of installations on the heating grid will be discussed taking into account the estimations made for the total Carbon Dioxide equivalent (CO_{2e}) emissions occurring in typical Portuguese and Danish dwellings where wood heating is a common practice during the winter season (Paper V). Fourth, the results of the indoor climate measurements conducted in Nordic dwellings will be analysed.

Table 3-6 describes typical modes of using wood fuels in the studied installations of heating stoves as either a primary or secondary energy source used for space-heating and domestic hot water (DHW) production in different socio-economic contexts. For instance, traditional fireplaces, thermal mass or cast-iron stoves without secondary air-inlets (improved) using different types of biomass fuels (e.g. wood and pelletized fuels) were found in non-insulated and insulated households located in rural and peri-urban areas of Peru, Portugal, Denmark and Norway.

According to Table 3-6 it is possible to state that the more modern the stove installations are, the higher is the reduction in the fuel consumption and GHG emissions. This tendency is accompanied by an increased duration of the wood combustion cycle (batch). The use of hardwoods like Beech is common in Nordic countries. The use of this type of fuels in modern installations provides more stable heat-release conditions.

In Peru and Portugal, it was found that hardwoods like Eucalyptus are usually used as a primary heating system in either traditional fireplaces or improved stove installations, also used for cooking in Peru. According to the field studies conducted in these two countries, HAP related issues were observed and reported by some of the house owners relying on wood heating during the winter.

Figure 3-15 illustrates the contribution of WBSs to the residential heating grid either as a primary heating system in Portugal or as a secondary heat source in most of the investigated Danish dwellings. This information was obtained for 22 dwellings in total (11 in Portugal and 11 in Denmark).

Table 3-6 Operating conditions during the usage of the studied heating stove installations used in Peru as well as in Iberian and Scandinavian countries.

Installation	**Design**	**Fuel load (kg_F/h)**	**Wood fuel and batches**	**Duration of a cycle**	**Chimney**
Traditional Andean (N=2)	Open semi-open	2.5-4.0	Wood-logs variable batches	30-45 minutes	Variable conditions
Improved Andean (N=8)	Improved rocket	1.5-2.5	Wood-logs mid batches	30-45 minutes	Variable conditions
Traditional improved Iberian (N=10)	Fireplace old stove	1.5-4.0	Wood-logs variable batches	30-45 minutes	Variable conditions
Advanced Iberian (N=2)	Pellet stove digital device	0.8-1.5	Wood pellets	Several hours	Variable conditions
Improved Nordic (N=8)	Masonry modern stove	1.5-2.5	Hard wood variable batches	40-50 minutes	Variable conditions
Advanced Nordic (N=4)	Modern stove digital device	1-1.5	Mostly hard wood small batches	40 minutes to several hours	Functioning

In Figure 3-15 it is possible to observe that the annual thermal energy supply from wood-burning in dwellings (A-L) in the Aveiro region ranged between 0.8 MWh for the new house J (constructed after 2000) and 10.1 MWh for the old house D (prior to 2000). In the region of Copenhagen, these values ranged between 1.0 MWh for the old new home F (2000-2008) and 8.1 MWh for the old dwelling A. The annual total thermal energy supply from all heating sources in the Aveiro region ranged between 1.1 MWh for the new house J and 10.4 MWh for the old house D. In the region of Copenhagen, these values ranged between 7.3 MWh for the new home L and 39.7 MWh for the old dwelling A. In Portugal, the contribution of wood stoves for the heating grid was secondary for the old new dwelling E equipped with solar collectors and erected in 1990 (renovated) and in the new building L also using solar panels built in 2011. In Denmark, it was possible to observe that two different advanced wood stove applications (Aduro smart response and HWAM auto-pilot) were used as primary heating sources in the new houses H constructed in 2008 and L erected in 2011.

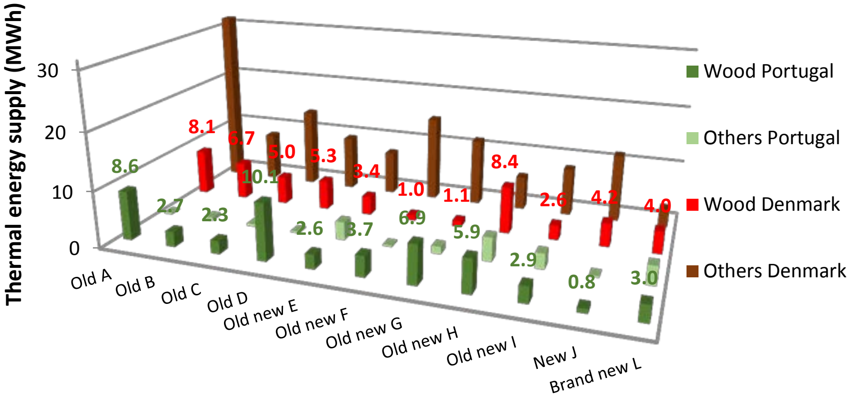


Figure 3-15 Thermal energy supply from wood heating (Wood) and other heating (Others) systems in old and brand new Portuguese (PT) and Danish (DK) dwellings (Paper V).

Considering the collected field data in European installations of biomass stoves (Table 3-6), the experimental studies present results on the performance of heating stoves in the following two parts by:

- First, analysing the operating performance of a fireplace (A), a certified wood stove (B) and an automatic stove[66] (C) typically used in Europe by comparing their thermal efficiency and associated gaseous and particulate emissions determined in a laboratory installation in Portugal;

[66] In this case a pellet stove using a digital application to control the fuel loads and the combustion air flow.

- Second, by studying the indoor climate performance of the operation of masonry, certified and advanced stoves used in old, renovated and brand new dwellings located in the outskirts of Copenhagen, Aarhus and Oslo.

Figure 3-16 reflects the overall results obtained in the laboratory measurements, confirming the hypothesis that the use of digital (electronic) devices could assist the users in controlling the fuel loads in a more efficient and automatic way through an optimized interplay between multiple combustion air-inlets in the pellet stove (C). The automatic operation of this stove resulted in a thermal efficiency more than 30% higher than that obtained during the manual operation of the certified wood stove (B), being around 3 times higher than when using the fireplace (A). Indeed, the thermal efficiency of the pellet stove reached values close to 90% at low burning rates of 1.0-1.7 kg_F/h being the thermal efficiency of this stove in the same range of values as that obtained for the most efficient gas boilers. In this case, the energy losses through the chimney are lower than that obtained for the operation of the other stoves. This situation can also be explained by the relatively low mean values of temperature (less than 100°C) achieved in the flue gas during the combustion of wood pellets. This relatively high efficiency means that the part of the chimney pipe that is inside the house[67] still releases heat to the indoor space. Another study conducted at the same laboratory facility by Kruse (87) showed that the thermal efficiency of the same pellet stove ranged between 78-83% under similar operating conditions, but in this case the temperature in exhaust considered to calculate the energy losses in the flue gas was measured at a lower height. From the laboratory experiments it was possible to confirm that the adoption of such advanced technologies might contribute to a decrease in the emission of $PM_{2.5}$. Figure 3-16 shows that the operation of the pellet stove reduced the $PM_{2.5}$ emission factors for this appliance in more than 20% in relation to the use of the certified stove by achieving the requirements established by the Ecodesign framework (72). For this case, the $PM_{2.5}$ emission factors were more than 40% below the Ecodesign requirement of 2.4 g/kg_F for this type of appliance (Annex III 4.i.a.2.). Figure 3-16 also illustrates that the use of the certified (EN-plus) wood pellets I (79) - in the pellet stove caused two times less emissions of $PM_{2.5}$ per mass unit of fuel burnt than for the usage of the locally produced wood pellets II without any certification.

Moreover, the experiments on the development of low-cost retrofits in the wood stove showed that the thermal efficiency of around 65% obtained for the operation of the certified stove can be increased by more than 10%, more than two times the value obtained during the use of the fireplace, by the adoption of the chimney pre-heating retrofit (Fig. 3-4.a.). The adoption of the pre-heating system also caused a reduction in the fuel consumption of more than 40% for a lower heat output in the

[67] Considering that typical internal height of a European single-family house varies between 2.7-5 meters.

order of 5.5 kW in the same range of the values obtained for the pellet stove using the certified pellet fuel I. In this case, the heat-release conditions along the wood combustion cycle were more stable than for the reference condition without any retrofit. However, for this improved condition as for the fireplace and the wood stove the $PM_{2.5}$ emission factor determined for the operation of this condition did not comply with the requirements established by the Ecodesign framework, except when adding a single secondary air-inlet (Fig. 3-4.b.) to the wood stove. In spite of causing a reduction in the thermal efficiency to levels below 60%, in this last case the $PM_{2.5}$ emission factor was reduced to levels below 5 g/kg_F. At the same time, the use of a single secondary in-let provided a reduction in the heat output from 7.8 kW (reference condition without any retrofits) to 6.2 kW, a lower wattage output that might be more suitable for insulated dwellings.

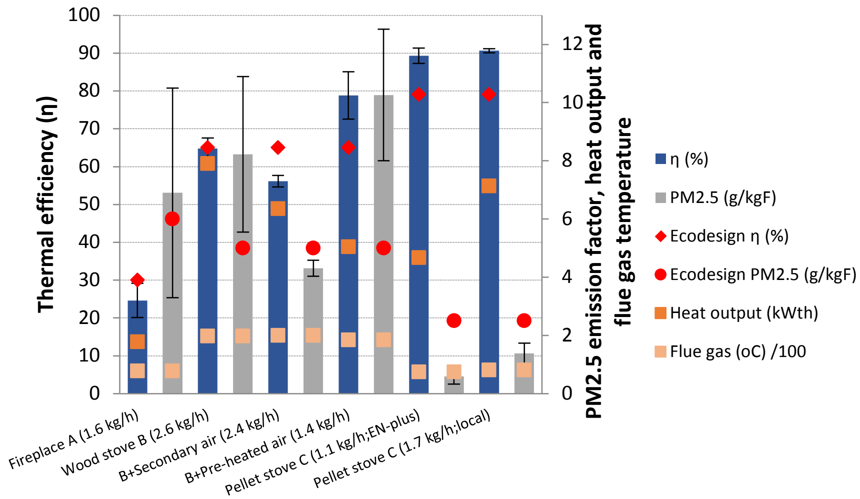


Figure 3-16 Thermal efficiency (±SD) and $PM_{2.5}$ emission factor (±SD) achieved during the typical operation of biomass heating stoves, including retrofits and digital applications. The value of the $PM_{2.5}$ emission factor (±SD) indicated for the fireplace was obtained from a published study conducted by Gonçalves et al. (32) at the same laboratory facility (Paper V).

Generally, the use of certified pellets in the automatic stove revealed to achieve the best operating performance when comparing to the other 5 situations. However, Figure 3-17 shows that the emissions of CO and TOCs caused by the combustion of non-certified pellets in the automatic stove are more than twice lower than for the situation when wood pellets with an EN-plus label were burnt in the pellet stove. This was the only condition in which the Ecodesign requirements for the gaseous emissions of CO and TOCs were achieved.

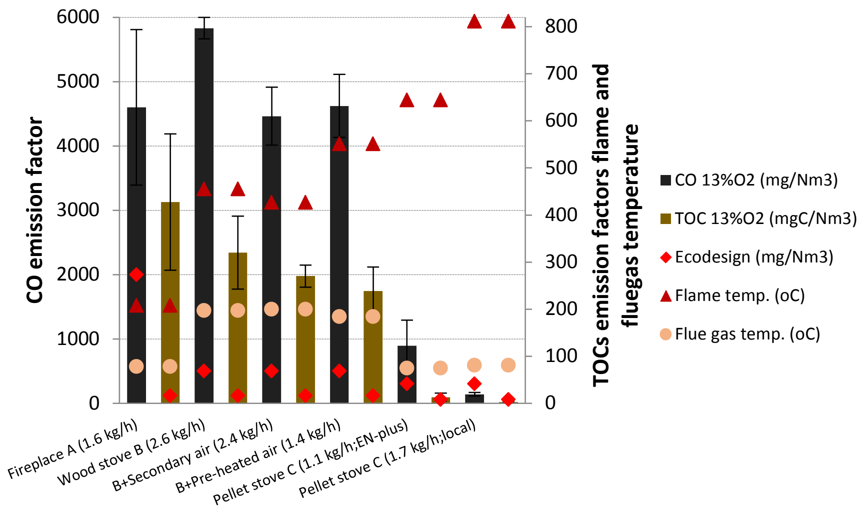


Figure 3-17 Gaseous emissions of CO and TOCs caused by the operation of biomass heating stoves, including retrofits and digital applications.

This fact might be explained by the higher mean value of the flame temperature achieved when using this type of biofuels which was also reflected in a substantial increase of the mean fuel consumption by around 54% at the burning rate of 1.7 kg_F/h in relation to the use of the certified pellets I. In spite of the fact that the adoption of the wood stove retrofits decreased the emission factors of gaseous pollutants in relation to the reference condition, major improvements are required for all the associated conditions to meet the upcoming Ecodesign requirements, respectively concerning the emission factors of CO and TOCs.

The next paragraphs describe the typical operating conditions observed during the use of the wood stove (reference condition) and the operation of the same stove with the chimney pre-heating retrofit (with multiple secondary air-inlets). Figure 3-18 describes the wood-burning rate as well as the variations in the flame and flue gas temperatures along the combustion cycle when using wood stove (reference condition). Figure 3-19 represents the variations in the same operating parameters for a typical wood-burning cycle using the wood stove with the pre-heating retrofit. Figure 3-18 illustrates the significant changes in the flame temperature associated to the intermittent heat transfer conditions in the reference situation (no retrofits). When comparing these variations in the reference condition with the changes presented in Figure 3-19 for the stove retrofit, it is possible to observe that the new condition reflects less variations in the flame temperature that was over 450°C for more than 30 minutes. In this case, there was also a 20% increase in the flame temperature during the operation of the new system in relation to the reference condition (less stable heat-release). In this case, the CO emission remained at very low levels during a longer period of time (in relation to the reference condition) when the system of multiple secondary combustion air-inlets was opened. Indeed, this laboratory experiment revealed that the adoption of a system of secondary air inlets in conjunction with the installation of an heat-exchanger in the chimney that pre-heats the primary combustion air-intake significantly reduced the mean wood-burning rate by more than 40%, decreasing the mean temperature in the exhaust along the combustion cycle by 7% (less energy losses than for the reference condition).

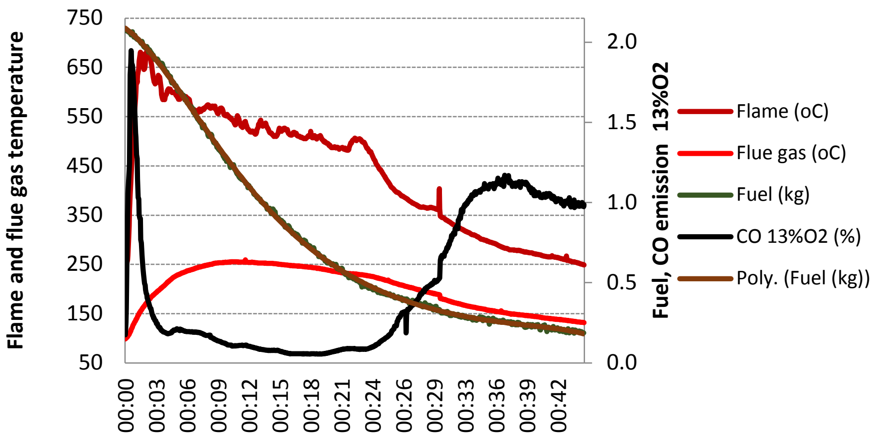


Figure 3-18 Operating conditions during the use of the wood stove (reference condition).

On this background, the stable heat transfer process to the dwelling provided by the adoption of the low-cost pre-heating system might contribute to increase the energy savings in insulated houses with lower heat requirements by avoiding potential overheating risks. The retrofitted configuration presented for the wood stove approaches the thermal energy performance of automatic appliances by providing a more uniform heat-release to the room in the range of 4.8-7.2 kW verified for the operation of the pellet stove using the two tested types of pelletized wood fuels. Although, the results obtained for the $PM_{2.5}$ emission factors showed that these retrofits need to be improved in order to optimize the interplay between the primary and secondary admission of combustion air. In this case, a better interplay between the operation of different combustion air-inlets will provide optimal wood combustion conditions (residence time, flame temperature and turbulence) towards the reduction of the $PM_{2.5}$ emission factors below the Ecodesign requirement of $5g/kg_F$. One of possibilities might be to increase the residence time and mixture of the combustion gases in the combustion chamber through the development and installation of an improved system of pre-heated secondary air-inlets at a lower height in the combustion chamber than the tested system. This could be done in order to decrease the heat losses through the chimney.

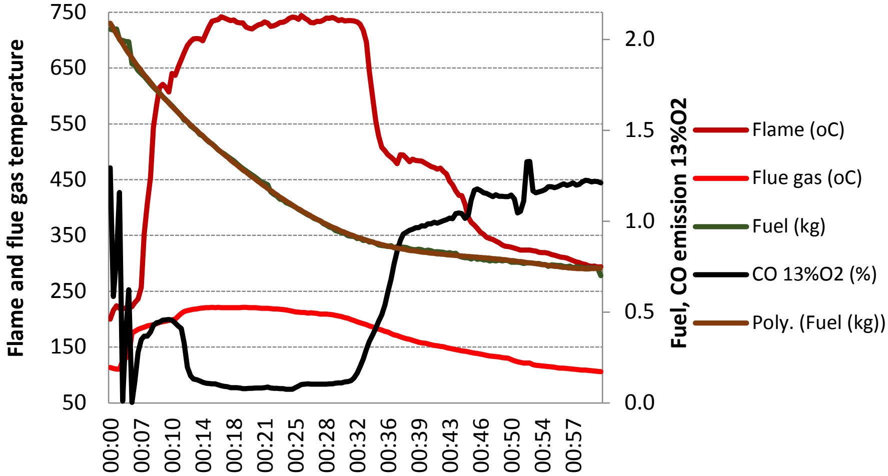


Figure 3-19 Operating conditions during the use of the wood stove equipped with the chimney retrofit by using a pre-heating system and multiple-secondary air inlets.

In the case of the tests conducted for the pellet stove, it was possible to observe that, after lightning the fire, the real-time values obtained for each of the studied operating parameters did not vary so much as for the manual retrofitted wood stove. Figure 3-20 illustrates the mild variations in the flame and in the exhaust temperatures as well as in the emission of CO (13% O_2) observed during the operation of the automatic stove using the certified wood pellets I. In this chart, these operating conditions are only represented for a period of 10 minutes, assuming that the stove operates under steady-state conditions over the time it was operated at the same power level. Figure 3-20 also shows that the flame temperature is kept at higher values (over 400^{o}C) than those observed during the operation of the wood stove. In this case, the flame temperature ranged 400-800^{o}C due to the automatic fed of pellets that fell down from the storage container to the combustion chamber in small batches. Figure 3-20 also illustrates the relatively low temperature of the exhaust in relation to the values observed during the operation of the wood stove. Moreover, in this case, the CO emission remained always lower than 0.4%. Here, the variations in the emission of CO might be related to the variations of the automatic batches over the biomass combustion process. However, in this case, the biomass burning rate was determined for an entire period of one hour, since this stove was not equipped with the weight sensor.

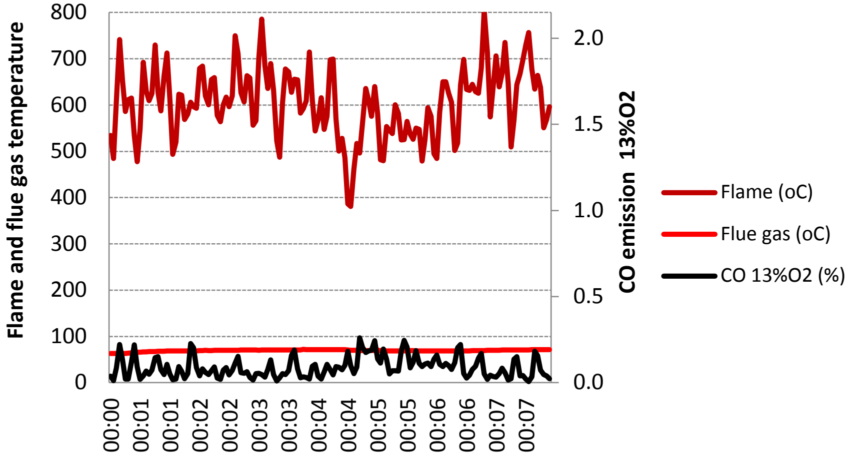


Figure 3-20 Operating conditions during the use of the pellet stove using the certified pellets at the mid-power level.

The results obtained in both the field interviews and laboratory measurements were used to simulate the performance of the operation of fireplaces, wood stoves and automatic appliances in the heating grid of non-insulated (Portuguese) and insulated (Danish) houses.

Table 3-7 provides an overview on the results obtained from the energy simulations. Here, it is presented the estimations on the energy supply for heating through the operation of primary and secondary heating sources and information used to calculate the GHG emissions from the total residential heating system as well as information used to estimate the mean indoor temperature achieved in the building envelopes during the coldest winter months (February and March) for each of the studied types of installation. Table 3-7 describes the mean values of the amount of thermal energy supply to the dwellings provided by both the wood heating sources and conventional heating systems, including the results of the estimation of the total CO_{2e} emissions by each installation. In fact, this calculation considers that the WBSs work as primary heating systems situation which might not be so common in Scandinavia where the accessibility to the district heating grid is higher than in other parts of Europe. In this context, the Danish houses that operate a certified stove during the winter might cause the lowest amount of GHG emissions among the Scandinavian settings reaching annual wood consumption values of around 190 kg. However, this installation is expected to overheat the living-room of well-insulated houses during one of the coldest months in the winter. The calculation of the CO_{2e} emissions assumed that all WBSs operate with excess air (complete combustion), being wood heating considered as a carbon neutral process as it is possible to observe in the Portuguese settings (with no GHG emissions from wood heating sources).

Table 3-7 Energy simulation outputs: Annual energy use and supply, maximum indoor temperature achieved in the day during a winter month and annual GHG emissions from the use of stoves and conventional systems in non-insulated and insulated houses (Paper V).

Installation (house)	Wood use[68] (ton)	Wood heat (MWh)	Other heat (MWh)	Heat supply (%)	Room temp. ±SD (°C)	CO_{2e} [69] emission (ton)
None (insulated)	0.0	0.0	3.3	3.3	18.9±0.6	0.90
None (non-insulated)	0.0	0.0	0.0	0.0	13.5±2.5	0.00
Fireplace (insulated)	3.2	3.4	1.8	5.2	22.7±0.5	0.50
Fireplace (non-insulated)	1.9	1.8	0.0	1.8	16.7±2.3	0.00
Stove (non-insulated)	1.9	8.1	0.8	8.9	27.4±1.3	0.19
Stove (non-insulated)	1.5	5.9	0.0	5.9	22.7±1.3	0.00
Auto-stove[70] (insulated)	1.3	5.1	1.4	6.5	24.0±0.7	0.37
Auto-stove[71] (non-insulated)	0.8	5.4	0.0	5.4	22.1±1.2	0.00

[68] The annual use of wood fuels was calculated considering the results presented on Table 3-6 on the wood-burning rate and patterns of wood use during the year.

[69] Based on the energy conversion factor for natural gas of 64.1 $kgCO_{2e}/GJ$ in mass of CO_{2e} emitted to the atmosphere per unit of thermal energy released by natural gas (99).

[70] Wood-log stove using a digital application (emerging technology in Denmark).

[71] Pellet stove using a digital application (emerging technology in Portugal).

The results obtained from the building simulations point out that the integration of advanced WBSs (instead of the full use of a gas boiler) as a primary heating system in the household heating grid of both insulated and non-insulated dwellings might reduce the impacts of the residential energy production on the indoor climate by more than 50% for optimal indoor temperature conditions. The transition to an intelligent use of advanced stove applications might reduce the wood fuel consumption by more than 30%. Indeed, the use of automatic stoves might reduce the total CO_{2e} emissions associated to the space-heating demands, avoiding overheating the living room as it is expected to happen in well-insulated dwellings using certified stoves. However, the building simulations indicate that even the most advanced applications could be further developed to improve the heat transfer conditions to the other rooms in the Iberian houses through the adoption of water jackets integrated with solar thermal energy systems that could distribute the heat all over the dwellings. This measure would increase the renewable energy supply by reducing the use of wood fuels and other conventional heating systems.

On one hand, the energy simulations considered wood-burning in efficient stoves as a carbon neutral process, assuming that all the energy present in the biofuel is converted into CO_2 and that this energy can be absorbed by the ecosystem. This perspective does not include potential environmental health effects associated to the emission of health damaging aerosols and other by-products resulting from biomass combustion under smouldering conditions. In fact, the emission of PM is a common fact in real-world situations, for instance, when burning wood with significant moisture content (over 20%) or ash. On the other hand, the energy simulations were based on assumptions and generalizations concerning the operation of the wood heating appliances in dwellings that did not cover in detail the variability of user behaviours, stove operating conditions, building characteristics and ventilation conditions that were observed in the field studies.

Figure 3-21 illustrates in more detail the variability in the net heat supply observed through the interviews conducted in 12 Scandinavian houses, including information about a Norwegian low-energy house (N=1) located in Langhus near Oslo. In this case, the building age increases from the left hand side (oldest house from the 70s) to the right hand side (brand new house from 2011) of the chart. Figure 3-21 shows that the fraction of wood heating in the residential grid is in most of the real cases lower (2-60%) than the share of wood heat estimated to be supplied to the building by the energy simulations (76-91%). In fact, the energy simulations present a condition that is more similar to what happened in the modern dwellings H and L where the advanced wood heating applications contribute to more than 50% of the heat supply in these houses. One of the reasons that might explain this exception is the fact that both of the houses were not connected to the central heating grid.

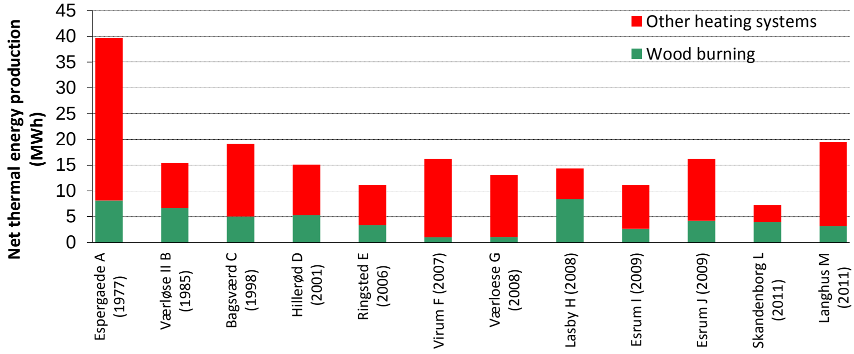


Figure 3-21 Net thermal energy production in Nordic single-family houses using masonry (Espergæde and Ringsted) and certified and cast-iron stoves.

One of the reasons for the overestimation of the contribution of wood heating by the energy simulations is that, here, the energy losses by infiltrations were not considered. However, in the calculation of the net-energy production presented above it was considered that the operation of indoor combustion air-inlets caused extra infiltrations in the dwellings, causing heat losses that ranged between 1-10% of the total heat supplied by the use wood heating systems, depending on the ventilation conditions.

Figure 3-21 illustrates that the amount of heat released to the dwellings was in general associated with the heat requirements and year of construction of each house. The single-family house that was erected earlier, i.e. built according to building regulations in force in 1977 presented the highest energy consumption for heating. From the stated heat balances, one can clearly see how the oldest house presents the largest levels of heat consumption where more than 70% of the thermal energy supply was provided by a natural gas boiler. The largest contribution of wood heating appliances was reached in the houses H and L, respectively located in Skadenborg (Denmark) and Langhus (Norway), where the advanced applications of WBSs worked as primary heating systems. By comparison, the contribution of wood for the residential heating grid in the oldest house A in Espergaerde only reached 20% of the heat supply. In this case, the annual used amount of wood was estimated to be 2500 kg, a value more than two times higher than that used in the houses H and L.

Moreover, in the modern house I, the indoor temperature measurements conducted during 3-weeks in February revealed substantial variations in the living-room temperature during the operation of a modern cast-iron stove. Here, the temperature exceeded 25°C two or three times a day as illustrated in Figure 3-22.

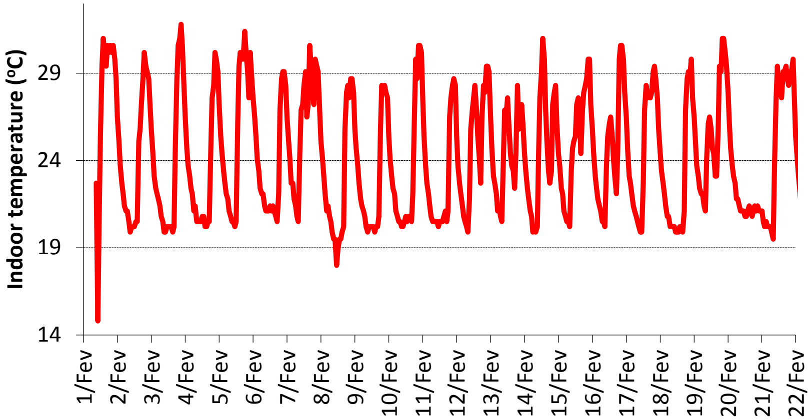


Figure 3-22 Overheating conditions during the operation of a modern cast-iron stove in the brand new house I (Paper II).

In spite of these overheating events, this issue was not observed when operating masonry stoves in an energy-efficient house E where the living-room temperature varied between 20 and 23°C during the day over the same month.

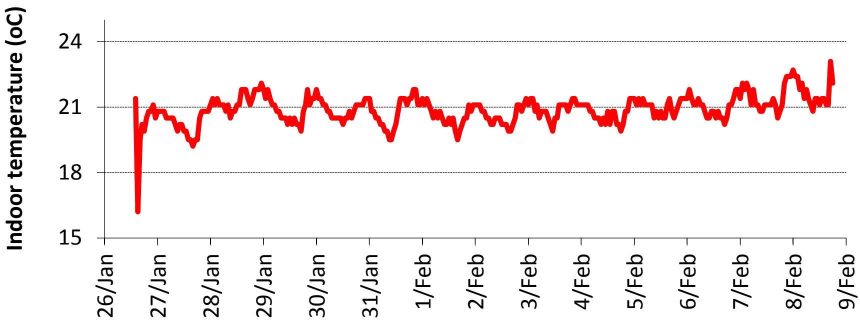


Figure 3-23 Stable heating conditions during the operation of masonry stove in the new house E (Paper II).

Figure 3-23 illustrates the stable heating conditions observed in the new house E where the temperature typically ranged between 19 and 23 °C. Differently from the operation of the modern cast-iron stove in Esrum, which released heat in an intermittent way, the stable-heat release provided during the use of this masonry stove in the home in Ringsted suggests the importance of the thermal mass around the combustion chamber as a slow and low wattage heat release component that can improve the interplay between both modern stoves and new building envelopes.

One of the main outcomes of this field study is that the development of future technologies might address the aspects related to the heat requirements of modern buildings. In this sense, the measurement campaign conducted to evaluate the indoor climate performance of certified stoves that operate with automatic devices showed that these sources might work well as primary heating systems in low-energy houses without overheating them. As for central heating systems, these advanced applications give to users the possibility to regulate the indoor temperature in the living-room for a certain set point temperature.

Another aspect that was not addressed in the laboratory tests and energy simulations was the possible emissions of gaseous and particulate pollutants to the indoor environment. Thus, in the Nordic field studies, no significant variations in the concentrations of CO and TVOCs were observed in the indoor air. However, considerable variations in the indoor mass concentrations of PM_{10} were observed for the modern houses I and J located in Esrum. Here, these concentrations reached values over 150 µg/m^3 after lightning the fire. However, in most of the studied houses, the variations in the indoor concentrations of $PM_{2.5}$ observed during the use of the certified stoves were quite insignificant. These facts might be explained by the high thermal efficiency of the tested WBSs, ensuring quite clean wood combustion conditions. Although, as explained in Chapter 2 (Figure 2-4), in air-tight and high-efficient combustion stoves of this kind the flame temperature is kept at quite high values, reason why this might promote the production of a significant number of UFPs with an aerodynamic diameter typically less than 0.1 µm.

The IAQ measurement campaigns conducted to evaluate the influence of the operation of certified stoves on the indoor concentrations of UFPs showed that, in some circumstances, these concentrations increased after opening the doors of the stove for refilling it. Thus, the frequency of wood-log batches in the interaction of users with the modern cast-iron stoves might influence the IAQ in modern dwellings such as the house in Esrum, which had a smaller air-change rate than the older dwellings. Figure 3-24 illustrates the significant variations on the indoor concentration of UFPs that occurred after refilling a modern cast-iron stove with wood-logs 30 minutes after lightning the fire (minute 60 in the Figure 3-24) in the modern house Esrum I.

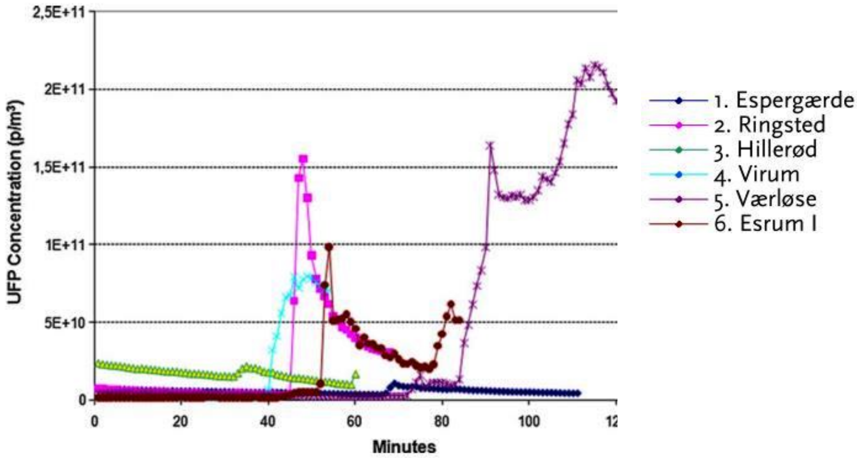


Figure 3-24 Real-time indoor concentration in number of ultra-fine particles (UFPs) per unit of air volume (#/m^3) in old and modern dwellings during the operation of thermal mass and cast-iron stoves (Paper II).

Beyond this explanation, the indoor emissions of UFPs can be related with the negative pressure in the dwelling when the combustion air-openings are in competition with the ventilation systems in the house, for instance when kitchen and toilet fans are operating at the same time as the stove or during periods of adverse meteorological conditions. As a consequence there are other factors, other than the user interaction with the combustion chamber that might influence the indoor emissions of UFPs. Thus, the use of combustion air from outdoors instead of using it from indoors and the design and maintenance of the chimney are among potential mitigation measures that can be adopted to avoid the emission of UFPs to the living-room. In some cases, even though the pollutants are exhausted from the indoor spaces to the outdoor air, they can return to the house during periods of atmospheric inversions. In this case, the installation of high-efficiency particulate arrestance filters (HEPA) consists in an important measure to avoid the transport of these particles to the house.

Table 3-8 shows that in most of the houses using advanced stove applications there were less variations in the indoor concentrations of UFPs in relation to the background levels.

Table 3-8 Indoor concentrations in number of UFPs per unit of air volume (#/m^3) and associated variations in relation to the background values.

Location installation	*Air-change rate (h^{-1})*	*Background conc. (#/m^3)*	*Max. conc. (#/m^3) series 1*	*Max. conc. (#/m^3) series 2*	*Increase (times)*
Espergærde Masonry A	0.61	5.82E+09	3.00E+09	2.40E+10	4
Værløse II Automatic B[73]	>0.4	5.06E+09	1.43E+11	-	28
Bagsværd Automatic C[73]	>0.4	1.02E+10	1.85E+11	-	18
Hillerød Cast-iron D	0.58	5.86E+09	-	1.55E+11	26
Ringsted Masonry E	0.55	5.86E+09	5.00E+09	1.10E+10	2
Virum Cast-iron F	0.55	5.86E+09	-	9.90E+10	17
Værløse I Cast-iron G	0.40	5.86E+09	2.20E+10	8.00E+10	14
Lasby Digital H[72]	>0.4	9.92E+09	2.78E+10	-	3
Esrum I Cast-iron I	0.33	5.93E+09	2.23E+11	2.16E+11	38
Esrum II Cast-iron J	0.58	5.84E+09	2.36E+11	-	40
Skandenborg Automatic L[73]	0.35	6.33E+09	7.12E+09	-	1
Langhus Hydronic M	0.50	1.72E+09	4.94E+10	-	29

As shown in Table 3-8, the indoor concentration of UFPs did not change significantly in the brand new houses H (3 times) and L (no increase) using digital devices, respectively the Aduro Smart Response[72] and the HWAM auto-pilot[73] systems. In these two brand new houses the combustion air was taken from the outdoor environment. In these cases, it was observed that the chimneys were well maintained. These improved levels of the IAQ presented in Table 3-8 can be related to the fact that the digital devices supported the users to perform a better wood combustion process that required less tending of the fire by reducing the frequency of the associated batches, extending the wood combustion cycles.

Although the more intelligent use of stove retrofits and electronic devices can optimize to a certain extent the energy conversion processes in the stoves, in some cases, the increase in the energy efficiency of the total heating grid and indoor climate conditions is also dependent on the interaction between the combustion air-intakes, thermal mass materials and the ventilation systems in the houses.

3.8. INNOVATION POTENTIALS

According to the results presented in the sections 3.6 and 3.7, it is possible to point out 3 relevant mitigation strategies towards the development of cleaner user behaviours on the operation of high-efficient stove retrofits and innovations worldwide by:

- 1st Designing functioning stove and chimney retrofits for ICSs in South-America based on local cooking practices to ensure a better dispersion of PM in order to avoid local air pollution that can return back to the household;
- 2nd Optimizing low-cost stove retrofits and the use of biofuels in pellet stoves considering typical wood-burning behaviours in Southern-European countries. In this case, the use of new designs of certified local-space heaters is recommended by combining chimney heat exchangers and improved interplays between primary and secondary in-lets. These systems can be integrated with the adoption of insulation, solar thermal collectors and heat storage reservoirs to supply the heat in function of the household heating demands;

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[72] Modern wood stove using a digital application to support users in the manual operation of the stove (fuel loads and combustion air-inlets).

[73] Modern wood stove using a digital application to support users in the operation of the stove, controlling automatically the operation of combustion air valves.

- 3rd Developing and upgrading existing digital applications to support users in the control of fuel loads, combustion air-intakes and operation of chimney dampers in function of the low heating demands and ventilation conditions in modern houses. The installation of chimney heat exchangers coupled to stove air-intakes that can directly use combustion air from the outdoor environment is recommended for low-energy houses.

The exploratory research carried out in Brazilian and Peruvian rural houses points out the relevance of developing further IAP studies in these regions for longer exposure periods in order to investigate and develop more efficient retrofits for improved vented cookstoves. The so called ICSs implemented in these regions reduce the fuel consumption, however, in some of the houses, its operation caused significant variations in the IAQ due to the outdoor-indoor transport of particles. The new cookstove designs should address cultural localities related to women´s traditional cooking habits towards the transition to more efficient and cleaner wood cooking behaviours. The work conducted in Portugal suggests that the testing methods applied to determine the real-world performance of stove installations can be used to develop high-efficiency stove retrofits at low-cost, but more work needs to be conducted to reduce $PM_{2.5}$ below the Ecodesign requirements. Moreover, the use of pellet stoves might play a major role in the transition to cleaner wood-burning practices, yet at a higher cost. In this case, the heat transfer from the automatic appliances can be adjusted to the building heat demands. However, the heat output from these stoves also varies with the type of biofuels used. Thus, further research developments in the interplay between this technology and the operation of different biofuels should be addressed in order to expand the efficient use of this type of automatic stoves and cleaner wood pellets at a feasible cost.

This study also shows the importance of field research in testing the interaction of advanced stove applications with real homes. In general, innovations in forefront technologies of WBSs might consider the social changes in modern society. For instance, in Nordic countries, automatic stoves might be combined with electronic sensors (e.g. CO_2, temperature) that can optimize the energy savings in buildings. In South-America, advances should be focused on the improvement of energy conversion technologies and their interaction with chimneys. In the case of Peru, the technological transformations might not only be designed to address cooking practices, but they should also take into account the heating requirements of the dwellings in the region. The studied chimney retrofits in Portuguese stoves can also be applied to improve the thermal efficiency of cookstoves used for heating in Andean communities. As a low-cost digital application, the Aduro Smart Response app presents a potential to be adopted by users in these Southern countries to assist users in operating wood fuels more efficiently if customized for the consumers in these countries.

CHAPTER 4. POLICY AND ENERGY EFFICIENCY MEASURES

This section presents a discussion about possible mitigation measures that might support the transition to an intelligent use of cleaner biomass stoves as carbon neutral household energy sources. This part of the thesis presents suggestions for the development of proper policies and energy efficiency measures that can promote a proper integration of biomass stoves in homes worldwide, namely through: information campaigns on cleaner wood-burning practices (4.1), strategic regulations defined according to each socio-economic context (4.2), advances in retrofits at low-cost between technologies in dwellings (4.3) and incentives to the adoption of more advanced technologies and applications (4.4). The discussion presented in this chapter is based on both the analysis of the scientific review and case studies on innovation potentials presented in the previous sections.

Across periods of socio-economic crisis, the development of WBSs have been shaped by the necessities to reduce the wood fuel consumption, not being so focused on the mitigation of environmental health effects. Since the industrial revolution, people have been exposed to the instabilities in the fossil prices, being the usage of wood fuel strongly correlated with geopolitical aspects. For instance, during the last decade, the prices of oil and gas have been forcing many families to return to wood-burning in many parts of the world, however, more recently, there was again an inversion in this trend. In most of the developing countries, the inaccessibility to gas cylinders is still a major factor that explains the intensive usage of wood fuels. In these regions, the environmental costs of burning wet wood fuels and mineral coal is a major cause of climate and health risks.

Worldwide, the lacks of awareness of the population in general concerning the potential health impacts of burning wood inefficiently for cooking and heating is a major political issue. Indeed, most of the people does not know about the economic, environmental and health benefits of using wood intelligently also by adopting cleaner energy conversion technologies.

On this background, political incentives to promote cleaner energy in homes are demanded almost in every country in the world. Even though the direct effect of wood smoke on health is less problematic in developed countries, the fact that many users continue to use wood fuels in a traditional way during the inversion season becomes a major environmental health threat, too. In fact, few users burning solid-fuels inappropriately can harm the local air quality, exposing an entire community to adverse health risks.

Beyond the environmental health effects caused by the unsustainable use of wood fuels cause external costs for the economy of a country or a region. This fact can be used as an argument to call for more attention from policy makers. It is important to point out that the usage of wood fuel per capita has little relation with development, but more with the availability of biomass and cultural aspects (26). However, the usage of inefficient installations of WBSs might have a correlation with the accessibility to the best available technologies. In the wealthiest countries, many people are already using more efficient residential energy conversion systems. However, a recent study carried out by the Centre for Environment and Energy (DCE) shows that emissions from WBSs in Denmark still lead to increased social costs in the order of a little more than half a million Euros every year. In this developed country, the small fraction of use of old stoves in relation to the operation of modern stoves might still contribute to up to 14% of the entire social costs of air pollution, being estimated to cause approximately 550 premature deaths per year (88). These numbers can be considered as very small when compared to the mortality rates associated with the intensive usage of these types of conventional energy sources in places like India or China.

Having a significant global warming potential, the toxic aerosols generated by a certain community can be transported over long ranges, reason why this issue requires international political strategies, including regional regulations and comparable standards. The next section points out some of the arguments concerning the adoption of cleaner wood-burning practices, involving not only policy makers, but also local sector stakeholders.

4.1. CLEANER BIOMASS BURNING PRACTICES

Globally, there is little awareness on the environmental health risks caused by traditional wood-burning practices. Few countries in the world have been doing political efforts to develop public campaigns and market analysis to give recommendations on cleaner biomass burning practices towards the adoption of feasible stove technologies. Recently, networks of stakeholders established by governmental and non-profit organizations in the United States (89) and in some European countries, including chimney sweeping associations and local communities, are working on advances towards a better use of more efficient and cleaner WBSs in this country. In spite of the fact that public campaigns have been carried out in countries like Norway, Denmark and US, there is still a lack of regional programs that include educative actions among the inhabitants living in areas with a high density of traditional wood-burning appliances. In most of the countries, there is little knowledge among citizens on how to operate and maintain stove installations, including the associated capacities and economic costs required to guarantee cleaner wood-burning behaviours. For instance, in Eastern and Southern Europe most of the states do not provide any information campaigns to raise awareness about benefits of chopping and seasoning wood-logs properly as well as on the environmental gains that can be achieved by the adoption of top-down lightning techniques to avoid unnecessary particulate emissions in the start-up phase, as shown by several scientific studies conducted in Europe (33,90). In fact, in many parts of the world, there is not only a lack of information on the best stove operating behaviours and technologies, but also a limited know-how on proper maintenance procedures, available services and economic costs associated with the sweeping of the combustion chambers and chimneys on a regular basis. For instance, in countries like Portugal and Peru there is a clear lack of human and material resources to address this issue.

The use of biomass pellets made from agricultural residues and waste (e.g. from industrial or domestic residues such as furniture, paper, organic waste) might contribute to the reduction in the emissions of gaseous and particulate matter, however, here the use of certified pellets is recommended due to the presence of toxic elements in some industrial residues as shown in a laboratory study conducted by Vicente et. al. (91). Considering that certified pellets are costly for low-income families, the use of such type of biofuels is not so attractive in areas with direct access to low-cost wood fuels (sometimes free of cost) as it happens in some rural settings with a garden or located near forests as it was described in the case studies conducted in the Iberian and Nordic countries. Another barrier concerning the adoption of this type of high-efficient automatic stove technologies is the fact that they might require a regular maintenance of the electronic components that are part of this advanced stove technologies involving extra maintenance costs when compared with the use of wood stoves that are manually operated. For instance, the fans of the pellet stoves need to be replaced on a regular basis, depending this on their mode of operation. For that reason, the adoption of high-efficient stove retrofits and low-cost digital apps can be more feasible from both the social and economic points of view. Here, the challenge is related to the design of technological components at low-cost, which can easily be cleaned by the users in a regular basis. Another challenge is to design applications that comply with the international standards established to regulate the $PM_{2.5}$ emissions from WBSs. Here, technical efforts to develop user friendly combustion chambers, functioning chimneys and digital applications that can optimize the wood combustion processes are recommended. The new advanced stoves should be able to achieve higher flame temperatures and an increased mixing of combustion products in relation to the operation of the most popular marketed stoves.

For these reasons, the most recent transnational research projects on the development of new testing approaches for WBSs, conducted in Europe and in other parts of the world, have been focusing on looking at how behavioural aspects may influence the thermal performance of cleaner biomass stoves. For instance, the Bereal research project (33) presents new suggestions to upgrade the existing European testing methods in order to represent real-world situations. On the other hand, many research projects have been focusing on testing the influence of cookstove interventions in the local air quality in communities located in developing countries, supporting the development of international standards such as that established by the IWA through an International Organization for Standardization (ISO) consensus. These emerging testing approaches can be used to compare and design more advanced stove applications, involving the participation of users in the development of cleaner technologies.

4.2. PROPER REGULATIONS

Worldwide, there is not a common system to evaluate the performance of both biomass cookstoves and local-space heaters, but only one global system that is focused on establishing requirements and testing methods on the performance of solid-fuel cookstoves. Moreover, there are other regional certification systems, respectively applied for space-heating appliances in Europe (Ecodesign framework), in the United States (NSPS) and other countries located in cold and/or temperate zones. However, the different existing standards are presented in different metric systems, not representing in most of the circumstances real-world conditions. On this background, this thesis points out a need to establish a global and common classification system concerning the quality and performance of space-heating stoves. Moreover, this type of regulations is still inexistent in most of the developing countries located in cold and temperate climate zones. Beyond the development and implementation of certification systems in a wider scale, this work identifies a clear lack of regulations concerning the inspection of stove and chimney installations, a very important subject to tackle the formation of toxic particulate matter. Indeed, excluding some developed countries, in most of the regions in the world, there are no regulations of this kind.

Another subject concerning solid-fuel burning regulations is related to the operation of unseasoned fuels with high moisture contents. Even some non-certified pelletized biomass fuels are also made of toxic industrial products containing for instance heavy metals. For these reasons, the quality control of marketed biomass fuels constitutes a relevant measure to reduce particulate emissions by promoting an efficient and proper operation of biomass stoves. These issues need to be addressed through networks of sector stakeholders by involving fuel suppliers and stove producers, as well as retailers in the process developing and implementing new certification systems for biofuels.

The development of regulatory instruments that promote cleaner biomass burning practices will contribute to significant reductions in the emissions of gaseous and particulate pollutants, reducing the ash accumulation and slag formation with consequences in the operation of biomass combustion appliances as described by a study conducted by Carvalho et al. (92).

4.3. RETROFITS AND ADVANCED INTERPLAYS

The development and dissemination of efficient stove retrofits through the integration of user friendly and low-cost components in WBSs constitutes a very relevant measure to be addressed in low and mid income settings. The development of policies to promote building refurbishments and the proper installation of stove retrofits might increase the thermal performance of existing appliances to levels closed to those achieved by the operation of automatic stoves. This measure might be quite relevant in many rural areas worldwide. Advances in the interplay between seasoned fuels, high-efficient stoves and electronic devices might optimize the energy and environmental performance of wood-burning in real-life conditions. The design of these systems and their penetration in the market might be based on user preferences and behaviours, reason why further research needs to be conducted to assess the usage of biomass fuels and stoves in different socio-economic contexts.

Considering that this thesis is focused on the issue of wood heating in cold and temperate zones, the Figure 4-1 shows the technological transformations and effects on the environment and health of types of 3 interventions that can be found worldwide. This illustration emphasises the importance of the interplay between the stove technology and the building insulation.

On the left are described the high levels of energy losses in traditional stoves[74] when compared with improved stoves (on the right side of it) that mostly operate under smouldering wood combustion conditions, being still a relevant source of local and regional air pollution by the emission of a significant mass of health damaging ambient $PM_{2.5}$ (and BC) per amount of fuel burnt in both indoor and outdoor living areas. Considering that this type of intervention is mostly found in low-income settings located in mountainous regions of developing countries, these issues might be tackled by the adoption of functioning chimneys, robust materials and insulation components that can be design and installed by using local materials at low-cost. On the other hand, here, it was identified a lack of knowledge concerning the proper operation and maintenance of these type of installations, the reason why the design and implementation of these technological retrofits should be accompanied by educational campaigns to involve users in these processes towards a more efficient usage of the retrofitted stoves.

In the centre of the Figure 4-1 are represented the improved wood-burning conditions resulting from intermittent heating processes, still causing significant (mild) energy losses, but smaller than those observed for the use of traditional systems (on the left). The installation of steel or cast-iron stoves in non-insulated houses has become a common practice in mid-income countries. In these types of

[74] In many developing countries these installations are used for both heating and cooking.

interventions, the main environmental health issues are related to the emission of a considerable amount of mass of $PM_{2.5}$ (including a mix of toxic pollutants) to the outdoor air. In this context, strategic retrofits can be addressed at an accessible cost in order to increase their energy efficiency by integrating thermal mass materials and heat recovery systems in these stoves.

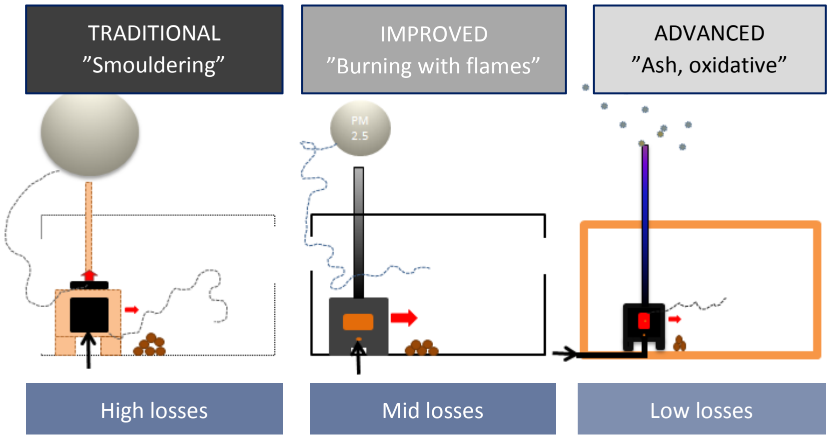

Figure 4-1 Technological transformations in wood-burning stove installations worldwide, according to energy losses and type of particulate emissions.

On the right hand side of the Figure 4-1 are illustrated the issues concerning the integration of high-efficiency wood-burning appliances and their optimized interplay with modern dwellings (low energy losses). In this case, the energy savings are maximized by the usage of thermal insulation, although, here, the usage of modern cast-iron stoves might cause undue overheating events. In spite of the fact that this type of installations generates a lower mass of $PM_{2.5}$ (per amount of fuel burnt) than the conventional stoves, the fact that this type of stoves is characterized by an increased air-tightness might contribute, in some circumstances (38,93), to the generation of a significant number of UFPs per unit of air volume in modern dwellings using certified cast-iron stoves. In spite of the fact that some studies have shown that these particles present a potential to cause adverse health effects, however, there is still a limited number of investigations that relate these aspects with the emissions and generation of UFPs from more advanced WBSs[75]. In this context, it is recommended the development of further research in this field in order to increase the knowledge about this issue. Anyway, in this type of installations, commonly found in Scandinavia, the design of better interplays between stoves and ventilation systems becomes a relevant issue to avoid both

[75] With an increased air-tightness.

indoor overheating and undue UFPs associated with the competition between the chimney draft and the ventilation systems in the house[76] (38).

The rest of this section focuses on the aspects concerning the optimization of the interplay between efficient energy conversion systems, electronic applications and modern building elements, including their interaction with certain ventilation systems like kitchen and toilet fans. The improvement of the interplay between these elements constitutes a relevant step on the future integration of cleaner stoves in low-carbon houses, the reason why this issue is being highlighted at the end of this section. Taking into account the indoor air quality studies conducted in Nordic houses, it is now possible to consider that there are other factors, other than the adoption of an advanced energy conversion system, that affect the indoor climate conditions in modern homes. Figure 4-2 illustrates the variations on the indoor concentration of UFPs in number of particles per unit of air volume (#/cm^3) found in the centre of the living rooms where advanced stove applications were installed. Here, it is represented how the IAQ might change with the type of combustion air-let and chimney installation (household interventions).

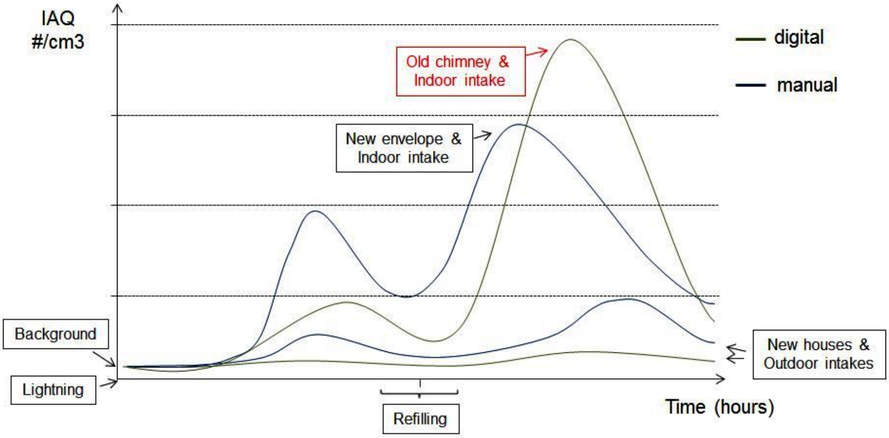

Figure 4-2 Real-time concentration in number of ultra-fine particles per unit of air volume (#/m^{-3}) installed in old and modern dwellings during the operation of advanced stove applications[77].

The results described in Figure 4-2 suggest that advanced interplays between efficient stove applications[13] and dwellings, using combustion air-inlets from

[76] In cases where the combustion air-inlet is placed indoors.

[77] Certified cast-iron stove with a digital device that supports the user to regulate the fuel loads, combustion air-inlets and the heat output to the house.

outdoors, digital devices[78] and functioning chimneys[79], might contribute to the reduction of the influence of user behaviours on the emission of UFPs to the indoor environment by increasing the energy savings in the total system (less heat losses in the dwelling through extra infiltrations that would occur if the combustion air intake was placed indoors). For the advanced interventions, it is possible to envision that heat exchangers could be coupled to the stoves and certain building elements that are usually installed near them (e.g. floor heating systems, ducts that transport the combustion air from outdoors, solar hot water jackets, and phase change materials in the building walls) in order to increase the total energy savings in the household heating grid.

Regarding the operation of cookstoves in climatic regions where there is no needs for space-heating, the efforts should be concentrated on designing high-efficiency conversion technologies and functioning chimneys. In spite of the fact that the forced air stoves are among the most efficient energy conversion systems, the development and dissemination of applications operating with natural draft might be very convenient, taking into account the large fraction of the world population cooking with wood in low-income settings.

4.4. INCENTIVES

Taking into account that the residential energy sector represents a large fraction of the total energy consumption and CO_{2e} emissions worldwide, the creation of programs of incentives to increase the access to more advanced WBSs constitute a very relevant political argument in the climate change debate. In general, the development and implementation of systems of smart subsidies and financial incentives constitutes an important measure to address environmental health issues in developing countries towards a transition to low-emission (advanced) biomass stoves applied in function of each socio-economic context. From the case studies conducted in Europe, it was possible to verify that the adoption of advanced biomass stoves have a large potential to decrease GHG emissions from the residential sector. Independently of the final usage (heating or cooking), this type of highly efficient energy conversion technologies present a large potential to mitigate climate and health effects in a global scale. However, further technological developments, including the adoption of low-cost components, are necessary to make these forefront innovations more simple, accessible and easy to operate.

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[78] Either computer added devices to control combustion air-inlets automatically or smart phone apps to guide users in the operation of fuel loads and combustion air valves.

[79] Properly designed to ensure a sufficient dispersion of pollutant gases and particles and easy to maintain (by the users).

For instance, in Europe, the adoption of these modern technologies is limited by the costs associated to their installation, operation and maintenance.

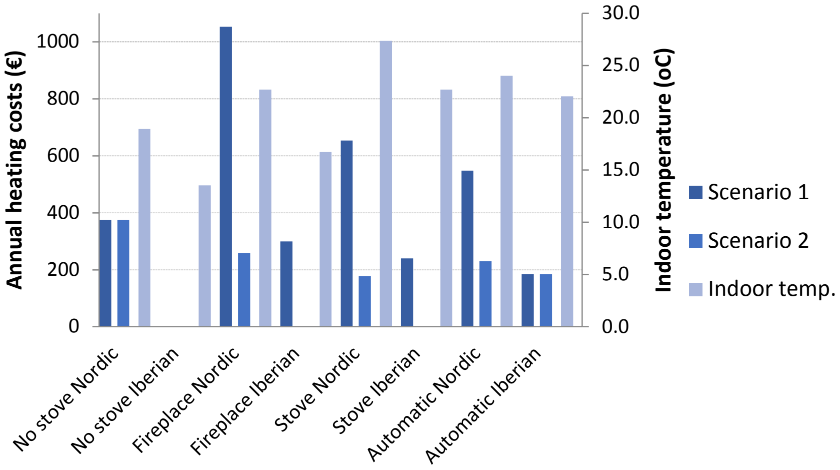

Figure 4-3 Operational costs of biomass stove installations in Portuguese and Danish houses based on an estimation of their annual usage and prices of firewood[80], wood pellets[81] and natural gas[82] in the two countries.

Figure 4-3 illustrates the annual operating costs concerning the usage of stove installations in Portuguese and Danish dwellings. Here, it is also included information concerning the operational costs of conventional heating systems[83] when the houses do not have any biomass stove. These estimations are based on the field and modelling studies conducted for non-insulated Iberian and insulated Scandinavian houses. These calculations were associated with two different scenarios. The first scenario represents a situation where wood fuels are purchased in the local market (Costs 1). The second scenario is related to a condition where the families collect the residual wood fuels from their gardens or near forest - without any cost (Costs 2). On one hand, from the estimations made for the scenario

[80] Prices of wood (2011) ranging between 0.16 €/kg_F in Portugal and 0.25 €/kg_F in Denmark (100).

[81] Price of certified wood pellets “Pinewills” (2016) in Portugal in the order of 0.25 €/kg_F.

[82] Price of natural gas (2015) ranging between 0.076 €/kWh in Denmark and 0.098 €/kWh in Portugal (101).

[83] Considering that the conventional heating systems are modern gas boilers with 90% thermal efficiency.

1, it is possible to observe that the adoption of automatic stoves might decrease the operating costs by 39% in Portugal and 48% in Denmark in relation to the usage of the fireplace. For this scenario, it was estimated that even the operation of automatic stoves in well-insulated dwellings in combination with the usage of natural gas boilers increased the operating costs of the household heating grid by 46% in relation to the condition where only the gas boiler is used to reach a set point temperature of 19^{o}C. However, this scenario does not characterize what happens in many rural settings in Europe where families do not have to buy firewood in the market place. On the other hand, the estimations made for scenario 2 suggest that the usage of residual wood fuels in efficient stoves reduces the operating costs of the residential heating grid, reducing the annual expenses with the usage of non-renewable energy by more than 30%.

In spite of the fact that wood-burning can be economically feasible in many parts of the world, the optimistic estimation made for advanced stove installations in well-insulated houses located in Nordic countries did not consider the costs associated with the proper maintenance of combustion chambers and chimneys, the reason why efforts might be done at a political level to empower citizens to maintain their stove installations (e.g. through regular cleaning practices). Here, governmental incentives are highly recommended to incite people to conduct regular inspections to their stoves and chimneys (still inexistent in many countries around the world). Such measures might be followed by information campaigns concerning the benefits of these actions and the negative consequences of improper practices on the air pollution and health. On this background, the transition to more intelligent interplays between advanced stoves and dwellings can be driven by social, cultural and economic aspects. For instance, in peri-urban and urban areas, the development of new tax systems to regulate the prices of the operation and maintenance of small-scale biomass combustion systems (as renewable energy sources) might facilitate the accessibility to the best available technologies of WBSs. Moreover, in most of the rural areas worldwide, the design of smart subsidies can be focused in reducing the initial investment required to buy an efficient biomass stove.

These economic incentives should always be combined with international and national educational campaigns to raise awareness on the cleanest available biomass fuels, efficient stove retrofits, and highly efficient energy conversion technologies as well as labelling systems and cleaner burning practices in order to promote the expansion of an intelligent usage of biomass in dwellings towards both the diversification of the energy mix and acceleration of the transition to renewables worldwide.

CHAPTER 5. OVERALL CONCLUSIONS

As introduced in Chapter 1, the control of fire by mankind contributed to our social expansion, placing wood-burning as a central human activity as our ancestors expanded their intelligence and social skills by cooking and heating around the fireplaces in shelters by re-designing the landscape to grow food in safer places. Today, wood-burning continues to be a “surviving practice”. Wherever we are we may reutilize the residual biomass either available in our backyards or near forests. For instance, when we are lost in the wild, out of grid in remote areas or during socio-economic crisis, there is no more independent and reliable energy source other than a wood-burning stove. As humans, we chop and burn wood not only because we need warmth and cooked food, but also because of our innate survival instincts and skills.

Taking into account that wood fuel is available at low-cost almost in every rural and peri-urban area in the world, using it inefficiently in simple open fires and stoves has become a popular energy behaviour that strongly contributes to the formation of climate forcing and health damaging particles in the atmosphere. In spite of the environmental health risks described in detail in Chapter 2, the persistence on the usage of woody fuels for cooking and heating is an almost inevitable happening for many people around the world as the most well-known, cheapest and easiest way to produce energy, comfort and pleasure in our homes. Considering that there is no relation between the use of wood fuel per capita and development, the design and dissemination of more attractive and cleaner wood-burning practices constitutes relevant energy efficiency measure to address climate and health risks worldwide.

The scientific review on innovation potentials presented in this thesis points out that despite of the positive effects of the dissemination of chimney stoves used to tackle indoor air pollution issues, the widespread inefficient use of stoves with poor energy conversion efficiency remains as a main source of ambient air pollution worldwide.

In spite of the fact that 40% of the world population using traditional WBSs is located in developing countries, over more than 200 million Europeans and North Americans are using solid-fuels inefficiently, contributing to the acceleration of climate change in the arctic region. Thus, the transition to a more intelligent use of cleaner biomass stoves should be taken seriously, following the recommendations of the WHO. However, the existing global guidelines and ISO standards on household fuel combustion technologies are mostly applied for cookstoves in developing countries, not including requirements for heating appliances in a global scale. In fact, at the current stage, there are only two regional frameworks concerning the regulation of the $PM_{2.5}$ emissions from WBSs, namely the

Ecodesign and the NSPS regulations respectively applied to Europe (5 g/kg_F) and North-America (2 g/h), although using different metric systems. In these cases, the $PM_{2.5}$ emission targets are less ambitious than those established by the WHO (7 mg/min). The achievement of such goals will depend not only on the adoption of the most advanced energy conversion technologies, but also their interaction with users and building elements. The speed of the transition to the usage of these advanced interventions can be increased through the dissemination of cleaner wood-burning practices, including the operation of chimney retrofits and the adoption of digital devices to optimize combustion air-staging processes in high-efficient stoves (advanced appliances). From this thesis, it is possible to conclude that information campaigns on the environmental health benefits associated to the proper operation of seasoned biomass residues in their interplay with stove combustion air-inlets is a universal and reachable issue to address.

As the most efficient and the cleanest available technologies, automatic stoves require less tending by users giving them the possibility to program the level of heat transfer according to the desired function. In places with limited access to the electricity grid, the expedite use of advanced gasifiers and forced air stoves constitutes the cleanest practice with a large potential to be disseminated in both developing and developed regions. Although, some of these advanced applications require special attention from users during their manual operation. For that reason, new designs of multi-fuel stoves that operate in both the automatic and manual modes were recently developed, being promising forefront technologies of WBSs. In this case, the users have the possibility to operate the stove manually, keeping the tradition of burning wood-logs when they have more time available for tending a recreational fire, and operate the stove automatically, when they have less time to do so.

On the background of the scientific review and case studies on innovation potentials, it is possible to identify 4 core strategies to incite the transition to an intelligent use of more advanced biomass stoves worldwide:

- First, inform the public in general about the socio-economic advantages of the adoption of cleaner biomass residues and associated operating techniques on the usage of efficient stoves and functioning chimneys;
- Second, regulate the use of efficient and low-cost (certified) biomass stoves with at least 45% thermal efficiency (80% for heating stoves) through proper interplays between user behaviours, stoves and functioning chimneys by adopting thermal mass and heat accumulating materials;
- Third, incite the expansion of optimized interplays between both the automatic and manual operation of WBSs through an optimized interaction between certified biomass fuels, combustion air-inlets and building elements, possibly through the adoption of multi-fuel advanced gasifiers and automatic stoves in low-carbon dwellings.

- Fourth, promote the accessibility to the usage of the most advanced (low-emission) stove and chimney installations, including their integration with solar energy systems and thermal mass materials;

The first point constitutes an overall recommendation based on the fact that the transition to low-emission behaviours in a wide scale is very much dependent on the people´s awareness and knowledge concerning the best practices.

The second suggestion is associated with the regulation of the use of stoves around the world where there is a resistance towards the adoption of efficient technologies. For instance, in Brazil, it was possible to observe that the inefficient interaction between cooks, inefficient stoves and chimneys resulted in IAP events. In these places, combustion chambers can be re-dimensioned to reduce the people´s exposure to wood smoke according to WHO guidelines by addressing cultural localities and awareness campaigns with a focus on women and children as the most exposed groups.

The third outcome is related to the development and expansion of the use of digital applications to assist the regulation of the thermal energy supply, providing a more controlled heat supply in function of the energy demands (e.g. below $3kW_{th}$ in low energy houses). These can be achieved through an advanced operation of certified biomass fuels and stoves at low wood-burning rates ranging from 0.8 to 1.5 kg h^{-1}. Moreover, functioning chimneys and outdoor combustion air-intakes can be coupled to heat-exchangers in the house as additional energy saving measures that avoid fine and ultra-fine particles in the living-room.

The fourth suggestion is related to the relevance of disseminating low-cost stove retrofits and automatic technologies worldwide towards the transition to a cleaner usage of low-emission stoves. In these cases, the adoption of proper thermal insulation in dwellings in combination with the usage of hydronic, solar energy and/or heat storage systems might contribute to adjust demand and supply in dwellings. Although promising, these retrofits require further optimizations at low-cost to be accessible for low and mid income families. On the one hand, the energy savings promoted by the adoption of highly efficient stoves will reduce $PM_{2.5}$ emissions. Further optimizations in the design and installation of stove combustion air-openings and components like heat exchangers might increase the performance of WBSs in order to reach the goals established by the WHO, the Ecodesign and the NSPS targets for $PM_{2.5}$ emissions.

Concerning the political instruments that can be used to tackle climate change and health issues, the development and implementation of international regulations applied for biomass fuels and heating stoves are remaining issues worldwide. Common labelling systems could be addressed to inform people about how clean both certified fuels and stoves might perform in the real-world. Here, the design of global and common testing protocols and standards for both cookstoves and local-space heaters using the same metric systems would require transnational efforts. For instance, the $PM_{2.5}$ emission targets can be established for both cooking and heating stoves in mass of PM emitted to the atmosphere per unit of delivered energy, reflecting the amount of wood smoke that is produced in function of the final energy supplied to the dwelling. The achievement of future wood-burning regulations and particulate emission targets will demand an active participation of different stakeholders such as wood fuel suppliers, chimney sweepers, non-governmental agencies, stove producers and retailers.

As a final conclusion, the transition to a more intelligent usage of advanced biomass stoves will depend not only on technical solutions, but also on the dynamic changes on the global society. This investment will contribute to the diversification of the energy mix, keeping the local resilience and resourcefulness of communities worldwide. Local capacities might emerge from the challenge of designing low-emission stoves by generating greener economies locally. In this context, the governments have a crucial role in rising awareness on the environmental health benefits concerning the transition to the efficient usage of the cleanest available biomass fuels and stoves. Further research is recommended to support future decision making processes in the transition to sustainable modes of heating and cooking that are clean enough to avoid harmful effects on the global climate and human health. To accomplish a better comprehension of these environmental health effects, future investigations should be oriented to provide a more detailed characterization on the thermal performance of a wide range of wood-burning stove interplays in the real-world in association with geographical and demographical aspects and their influence in the emission and formation of wood smoke elements such as BC and UFPs. Both of these parameters are considered to be relevant parameters to understand the influence of the usage of WBSs on both the global climate processes and human health.

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APPENDICES

Appendix A. Paper I

Mapping the performance of wood-burning stoves by installations worldwide

Ricardo L. Carvalho[1.2*], Ole M. Jensen[1], Luís A.C. Tarelho[2]

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

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Abstract: The combustion of solid-fuels for heating and cooking in traditional fireplaces and stoves remains as the most popular residential energy system for 40% of the world population. Among the major contributors to air pollution, the World Health Organization considers it the largest global environmental health risk. Research stressed the need to increase the performance of conventional interplays between users, stoves and buildings. This scientific review aims to characterize the performance and environmental effects of 9 wood-burning stove categories by installations worldwide. This investigation shows that the efficiency of new heating stoves tends to be higher than 80% (45% for cookstoves) when fuel loads are adjusted to heating requirements. The adoption of air-tight installations can reduce wood consumption by more than 50% when compared with fireplaces. Fine particulate matter emissions from wood combustion can be reduced by more than 30% when switching from appliances using a manual control of combustion air inlets to automate systems that optimize air-staging to values below 150 mg/MJ-del. The mitigation of household air pollution in areas with limited access to modern fuels requires information campaigns to tackle the new air quality standards. Further investigations are recommended to evaluate the performance of advanced stoves during daily-life practices.

Keywords: Wood combustion, wood-burning stoves, residential energy, energy performance, air pollution, health implications.

Appendix B. Paper II

Wood-burning stoves in low carbon dwellings

Ricardo L. Carvalho[1,2*], Ole M. Jensen[1], Alireza Afshari, Niels C. Bergsøe

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

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Abstract: The European climate change strategy intends to encourage the erection of low-carbon buildings and the upgrading of existing buildings to low-carbon level. At the same time, it is an EU vision to maximise the use of renewable energy resources. In this strategy, small-scale wood-burning is an overlooked source for heating. A wood-burning stove is considered low-carbon technology since its fuel is based on local residual biomass.

A field study investigating how modern wood-burning stoves operated in modern single-family houses showed that intermittent heat supply occasionally conflicted with the primary heating system and that chimney exhaust occasionally conflicted with the ventilation system causing overheating and particles in the indoor environment. Nonetheless, most of the wood-burning stoves contributed considerably to the total heating.

On this background, it was concluded that better combustion technology and automatics, controlling the interplay between stove and house, can make wood-burning stoves suitable for low-carbon dwellings and meet the remaining heat demand during the coldest period. It was further concluded that new guidelines need to be elaborated about how to install and operate new stoves. For instance, lighting a modern stove requires far more skill that the scout-fire skill that was necessary for lighting an old stove.

Keywords: Low-carbon dwellings, renewable energy, building retrofitting, residential heating, wood-burning stoves, energy performance, particle emission.

Appendix C. Paper III

Proper indoor climate by the adoption of retrofitted wood-burning stoves

Ricardo L. Carvalho[1*], Ole M. Jensen[1], Øyvind Skreiberg[2], Morten Seljeskog[2], Franziska Goile[2], Laurent Georges[3]

[1] Danish Building Research Institute. Aalborg University. Denmark
[2]SINTEF Energy Research, Trondheim, Norway
[3]Norwegian University of Science and Technology, Trondheim, Norway

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Abstract: The indoor emission of (ultra)fine particles and overheating from wood-burning stoves are crucial problems in modern houses when wood is used for heating. The main cause for indoor particle emission is the interaction between user and stove when lighting and refilling the stove. The main causes for overheating are a high thermal insulation level of the house and high (peak) wattage of the stove. This research aims to understand how low wattage stoves with a computer added device and water jacket will perform on the indoor air quality as proper heating appliances for low energy houses. Two field studies were designed to compare the influence of the auto-pilot device and water jacket on the indoor climate. The first experiments were conducted in 8 renovated detached houses using certified stoves while the following experiments were conducted in 4 low energy houses using modern and advanced stoves. The results reveal that the users interaction impacts on the indoor air quality, although, the integration of the appliances in the dwellings, the air-inlets and the design of the chimney are the most relevant aspects to ensure a high indoor air quality.

Keywords: Household wood-burning, advanced wood-burning stoves, indoor air quality, overheating, particle emission.

Appendix D. Paper IV

Impacts of two improved wood-burning stoves on the indoor air quality: practices in Peru and Brazil

Ricardo L. Carvalho[1,2*], Ole M. Jensen[1], Luís A.C. Tarelho[2], Adeildo C. Silva[3]

[1] Danish Building Research Institute, Aalborg University, Denmark
[2]Department of Environment and Planning, Centre for Environmental and Marine Studies, University of Aveiro, Aveiro, Portugal
[3]Department of Civil Engineering, Federal Institute of Education, Science and Technology of Ceará, Fortaleza, Brazil

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Abstract: Large amounts of forest wood is still being used in rural housing in low and mid-income countries in South America - 36% in Peru and 6% in Brazil - generating hazardous wood smoke. Interviews were conducted to the users of improved stoves in 20 rural households. In Peru, the field study was carried out during the heating season. Real time concentrations of carbon monoxide were measured using HOBO data loggers while fine particles concentrations were measured in Brazil using a TSI Dust-track monitor before and during the stove operation. The adoption of improved stoves is limited by women cooking habits, safety aspects and the transition to LPG. CO concentrations never exceeded 60 mg/m^3 (30 minutes) while increased $PM_{2.5}$ concentrations exceeded 160 µg/m^3 (1-hour) in 4 dwellings. Indoor emissions from heating stoves were reported in closed rooms while outdoor-indoor transport was the main source of fine particle in open kitchen balconies.

Keywords: Fuel consumption, household interventions, improved stoves, indoor air quality, transition to modern fuels.

Appendix E. Paper V.

Transition to an intelligent use of biomass stoves

Ricardo L. Carvalho[1,2*], Ole M. Jensen[1], Estela D. Vicente[2], Luís A.C. Tarelho[2]

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

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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 non-insulated 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.

Keywords: Biomass stoves, thermal efficiency, proper behaviours, technological interplays, particulate matter emissions, CO_{2e} emissions.

SUMMARY

This thesis involves the understanding of anthropological aspects of wood-burning as a source of human evolution. Along the millenniums, the first humans emerged from the development of social-technical skills around the fire and later around the "wood-burning stove": a survival technology that made us what we are. Nowadays, traditional wood-burning stoves are far the most popular energy technologies in the world used for cooking and heating, constituting their inefficient use the major global environmental health risk. This research explores the characterization of existing wood-burning stoves, including the emerging cooking and heating technologies that might play an important role in the mitigation of global climate and health risks. This work points out the advanced gasifiers and automatic stoves as the best performing stove technologies able to meet the emission targets established by the World Health Organization. However, many interventions that happened in the past decade in different regions of the world focused on the installation of improved stoves that do not comply with such requirements. This thesis highlights that stoves are used for a diversity of purposes in a diversity of ways, depending on each socio-economic context. The cases studies conducted in 5 different countries covered the analysis of 4 relevant wood-burning practices: "cooking in Brazil", "cooking and heating in Peru", "heating in Portugal" and "recreational heating in Denmark and Norway". On the background of these theoretical and experimental studies, this thesis suggests that energy policies should be implemented taking into account, not only technical aspects on the development of low-emission wood-burning stoves, but also behavioral aspects on the design of intelligent interventions towards the dissemination of the most advanced stove technologies worldwide. Here, the adoption of a social-technical approach might constitute a relevant strategic measure to save the health of our planet.

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