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PROPER INDOOR CLIMATE BY THE ADOPTION OF RETROFITTED WOOD-BURNING STOVES

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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

1 Introduction

In Europe, the residential sector represents 40% of the energy consumption, and is the reason why the European Commission has stressed the importance of increasing buildings' thermal performance, including the usage of labelled elements. Wood-burning stoves (WBSs) are the most popular technology being used for combined heating and cosiness in dwellings (Carvalho et al., 2013). During the last decade the wood consumption in households has been increasing and particle emissions from WBSs have become a subject of public discussion all over the continent (EU, 2010).

In Nordic countries, where there is a well-developed energy grid, WBSs are used as a secondary heating system mainly, which is part of the Scandinavian family lifestyle in search for cosiness. In Denmark, the share of wood is estimated to be 18 % of the total amount of fuel input used for heating in single-family houses, and amounts to 60 % of the renewable energy contribution in these houses (Carvalho et al., 2013). It was estimated that about 50% of the PM2.5 emissions are generated by household wood combustion appliances. In Norway, it is estimated that more than 20 % of the population have a WBS in their house, especially in detached houses. There is currently a climate debate ongoing about the potential measures that should be implemented in order to mitigate the emission of particles and especially black carbon from WBS, the latter with impacts also on the ice cap in the artic regions (A. Stohl, 2013).

The replacement of old appliances by efficient ones, can be a key and sustainable strategy for this sector, as demonstrated in Norway when the town government of Oslo decided to promote the installation of new stoves.

Concerning the stove performance, it is possible to conclude that modern appliances can save more than e.g. 40% of the wood consumption, it is not possible to assume that the same improvement will result on the indoor climate (Carvalho et al., 2014). Household air pollution (HAP) and the related health risks are mostly concerned about the emission of fine particles that can be stacked in the atmosphere during the winter temperature inversions or generated directly indoors through the leakage of particles from WBS. Typically, the wood heating activities in Nordic countries are mostly influenced by fine particle concentration ratios Indoor/Outdoor>1 in remote dwellings with natural ventilation, higher when we talk about heating activities in households with high air tightness/insulation (Carvalho et al., 2014).

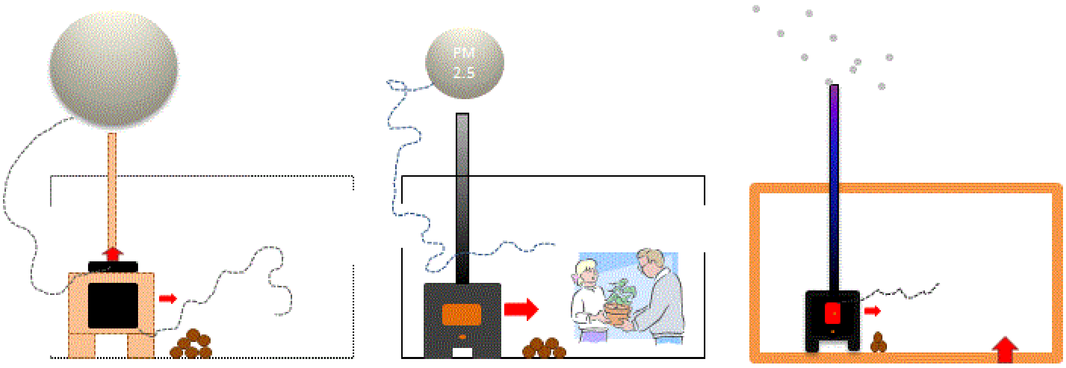

Figure 1. Particle emissions and variations with the air-tightness of envelope/stove.

Figure 1 shows three typical combinations of building envelopes with stove models from low to high air-tightness. On the left side, a masonry 2-air inlet stove is presented as a common construction found in rural housing with natural ventilation and a higher air exchange rate, of more than 0.4 h^{-1}. In the middle, a 3-air inlet cast iron certified stove is illustrated as a popular model of standard appliances being used in dwellings with air-change rates varying from 0.4-0.6 h^{-1}. On the right side, an emerging model is shown; a low wattage stove in low energy dwellings.

2 Study design

This field study was carried out in 12 households (old before 1980, renovated between 1980 and 2008 and brand new after 2009) located in Denmark and Norway through qualitative interviews and indoor air quality (IAQ) measurements during 3 winter seasons.

***Table 1**: Field study design, households and WBS.*

Type of building	*Year of construc.*	*Location*	*Energy class*	*Primary energy*	*Type of stove*	*Mode of operation*	*Energy label*
Old	1977	Espergærde	D	Natural gas	Masonry	Manual	Solbyg
Renovated	2001	Hillerød	C	NG	Cast iron	Manual	DS+Swan
Renovated	2006	Ringsted	B	District H.	Masonry	Manual	Helbro
Renovated	2007	Virum	B	NG	Cast iron	Manual	DS+Plus
Renovated	2008	Værløse I	B	NG	Cast iron	Manual	DS+Swan
Brand new	2009	Esrum I	A2	Heat pump	Cast iron	Manual	DS+Swan
Brand new	2009	Esrum II	A2	HP	Cast iron	Manual	DS+Swan
Old	1975	Rungsted	N.A.	NG/solar	Cast iron	Auto	DS+Swan

Old	1985	Værløse II	N.A.	NG	Cast iron	Auto	DS+Swan
Old	1998	Bagsværd	N.A.	HP	Cast iron	Auto	DS+Swan
Brand new	2011	Skandenborg	A2	HP	Cast iron	Auto	DS+Swan
Brand new	2011	Langhus	A2	Elec/solar	Cast iron	Hydro	NS

The research aimed to understand how the indoor concentrations of ultra-fine particles and indoor temperatures varied during the wood combustion cycles when operating the stove either manually with an expert in lighting or automatically using a computer added device (CAD) by controlling the 3 air inlets as a strategy to reduce overheating in low energy housing. The use of hydro stoves that accumulate the excess heat in water tanks is also a way to control this issue and was also evaluated as an advance stove. The case study was developed in 4 old households (energy class D or lower), 4 renovated dwellings (energy classes between C and B) and 4 brand new homes (energy class A). The Table 1 presents detailed information about the dwellings and WBSs analysed in this field study.

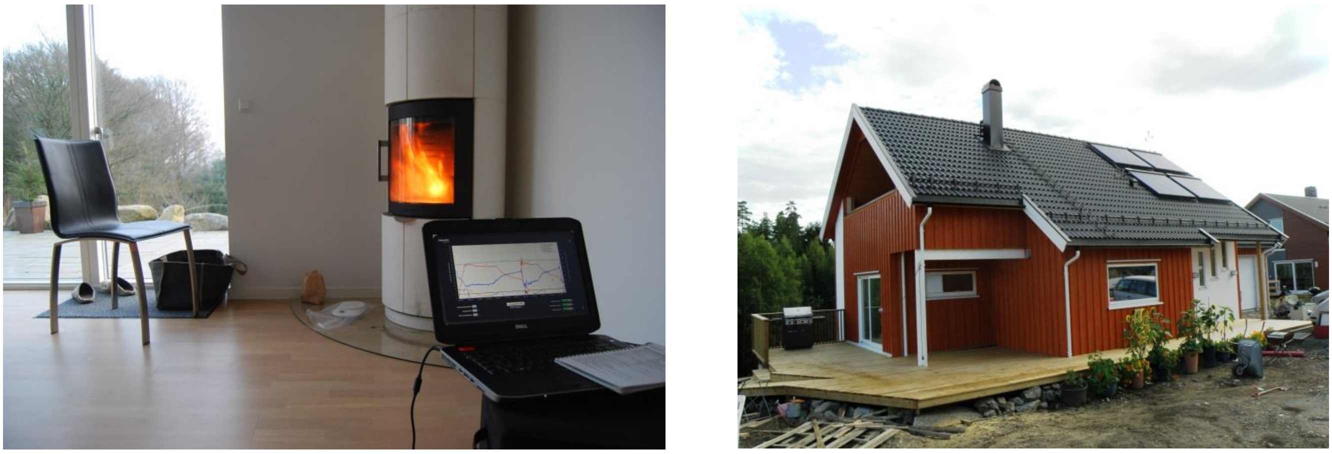

Figure 2. Auto-pilot wbs in a brand new house in Skaderborg/Denmark (left) and hydrostove with solar heating in Langhus/Norway (right).

On Figure 2 it is possible to observe the auto-pilot with 3 valves to regulate the primary, secondary and tertiary air (Fig. 2 on the left) or water jacket with manual adaptor to regulate the secondary air (Fig. 2 on the right) to control the injection of combustion air, by monitoring the flame and room temperatures in two low energy houses (class A2).

2.1 Heat production

The shares of final energy consumption from the WBS and other energy systems were calculated in order to better comprehend the user´s operating practices. In this field study, the households had as the main heating systems: district heating, solar thermal, heat pumps, electrical heating and natural gas, depending on the geography and location of the dwellings. The net heat production by the WBS (nHwbs) was calculated taking into account the part of the heat generated by the wood conversion that is used for heating (hwbs) and the heat losses from the dwelling (hl) when using combustion air from the outdoors that has been preheated to the indoors temperature using the Equation 1.

$$nHwbs = h_{wbs} – h_{l} \text{ (MWh)} \quad (1)$$

$$h_{l} = SFc \text{ x } ha_{F} \text{ (MWh)} \quad (2)$$

The energy loss by the use of indoor air (h1) was calculated by multiplying the solid fuel consumption (SFc) by the heat transferred per mass unit of combustion air (haF).

Table 2 presents data related to the annual energy consumption from the WBS and the other energy systems, in order to understand the contribution of household wood burning as a secondary heating system in the context of the studied Scandinavian dwellings.

***Table 2**: Annual energy production by WBS and other heating systems.*

Location	*Firewood (kg)*	*Stove efficiency (%)*	*Wbs heat production (MWh)*	*Other heating systems (MWh)*	*Heat production (MWh)*
Espergærde	2520	80	8.1	31.6	39.8
Hillerød	1750	75	5.3	9.8	15.2
Ringsted	980	85	3.4	7.8	11.2
Virum	350	70	1.0	15.2	16.3
Værløse I	350	75	1.1	12.0	13.1
Esrum I	875	75	2.6	8.5	11.2
Esrum II	1400	75	4.2	12.0	16.3
Rungsted	0	81	0.0	66.0	65.9
Værløse II	2000	83	6.7	9	15.5
Bagsværd	1500	83	5.0	14	19.3
Skandenborg	1200	83	4.0	3	7.3
Langhus	960	80	3.0	16.3	19.5

The usage of wood in the certified Nordic WBS (efficiencies from 70-85 %) varied between 350 (renovated house) and 2520 kg (the house with the lowest energy performance) per year. The net heat production by the WBS varied between 1 (renovated house) and 8.1 MWh/year (old house).

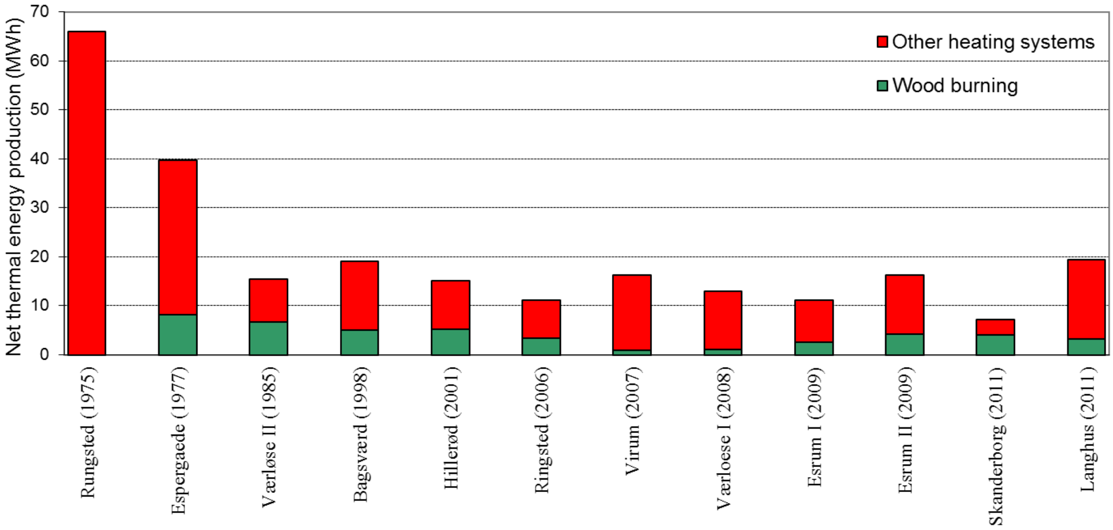

Figure 2. Net thermal energy production and share between wood burning and other heating systems.

The annual energy consumption for heating varied between 7.3 (low energy house) and 65.9 MWh (old house) and the share of wood consumed varied between 6 and 54.9% (low energy house). Some renovated houses, Ringsted (2006) and Værløse I (2008), presented an energy consumption for heating lower than some low energy houses, Esrum II (2009) and Langhus (2011).

2.2 Indoor climate campaigns

Measurements of the concentration of (ultra)fine particles (UFPs), temperatures and relative humidity were carried out both indoors and outdoors; before, during and after lighting the stove, during 3 heating seasons. The instruments were positioned in the centre of the main living room of each dwelling at the height of 1 meter. Outdoors, the sensors were placed around 2 meters from the building walls or windows, distant from the WBS chimney and the ventilation system inlets or outlets. The concentrations of UFP were monitored by means of two condensation particle counters, TSI model P-Trak 8025 and TSI model CPC 3007. In order to understand the concentration levels of fine particles in Nordic low energy houses, the concentration of PM2.5 were measured only on the low energy house in Langhus, using a Dust track monitor.

3 Results and discussion

This study shows no correlation between the building type and the share of use of wood for recreational purposes or as a secondary heating system in Scandinavian households. The households with lower heat requirements can have also a large share of heat produced by the WBS.

On the other hand, the usage of modern WBS can have a larger impact on the IAQ in dwellings with higher tightness or insufficient exhaust capabilities (chimney draft).

3.1 Particle variations and emissions

This study revealed that the mass concentration of fine particles were lower than 20 µg/m^3 with negligible variations after lightning the WBS in the low energy house in Langhus (Norway). Assuming that the mass concentration of PM2.5 does not change with the operation of modern WBS in single-family homes, this research focused on the variations of ultra-fine particles.

Table 3*: Particle concentrations and variations.*

Location	*Air-change rates (h-1)*	*Background concentration (#/m^3)*	*Max. concentration (#/m^3) series 1*	*Max. concentration (#/m^3) series 2*	*Increased by (times)*
Espergærde	0.61	5.82E+09	3.00E+09	2.40E+10	4
Hillerød	0.58	5.86E+09	-	1.55E+11	26
Ringsted	0.55	5.86E+09	5.00E+09	1.10E+10	2
Virum	0.55	5.86E+09	-	9.90E+10	17
Værløse I	0.40	5.86E+09	2.20E+10	8.00E+10	14
Esrum I	**0.33**	5.93E+09	2.23E+11	2.16E+11	**38**
Esrum II	0.58	5.84E+09	2.36E+11	-	**40**
Rungsted	>0.4	9.76E+08	-	2.99E+11	**306**
Værløse II	>0.4	5.06E+09	1.43E+11	-	28
Bagsværd	>0.4	1.02E+10	1.85E+11	-	18

Skandenborg	**0.35**	6.33E+09	7.12E+09	-	**1**
Langhus	0.50	1.72E+09	4.94E+10	-	29

Table 3 presents the parameters studied to understand how the concentration of particles changed over time during the operation of a typical cycle of wood-burning according to the study design (Table 1). The concentrations of UFPs increase with the variations of the air-change rates and air-tightness when the manual cast-iron appliances were operated, increasing with 38-40 times in the low energy houses Esrum I and II (Asfhari et al., 2011), due to the user´s interaction with the WBSs. The adoption of new computer added devices (CAD) can increase the stove performance and reduce the number of refills by optimizing exhaust smoke draft through the chimney. The construction norms can be very relevant to ensure the removal of UFPs from the indoor spaces. The concentrations of particles when using masonry or automatic cast-iron WBSs properly installed in older dwellings seems to be irrelevant when comparing with the modern houses, increasing only by 1-2 times. The usage of heat recovery through a water tank as tested in Norway at Langhus can store heat in a solar hot water system. Figure 3 shows how the particle concentrations changed in the dwellings using computer controlled stoves and the hydro stove (LEH Langhus).

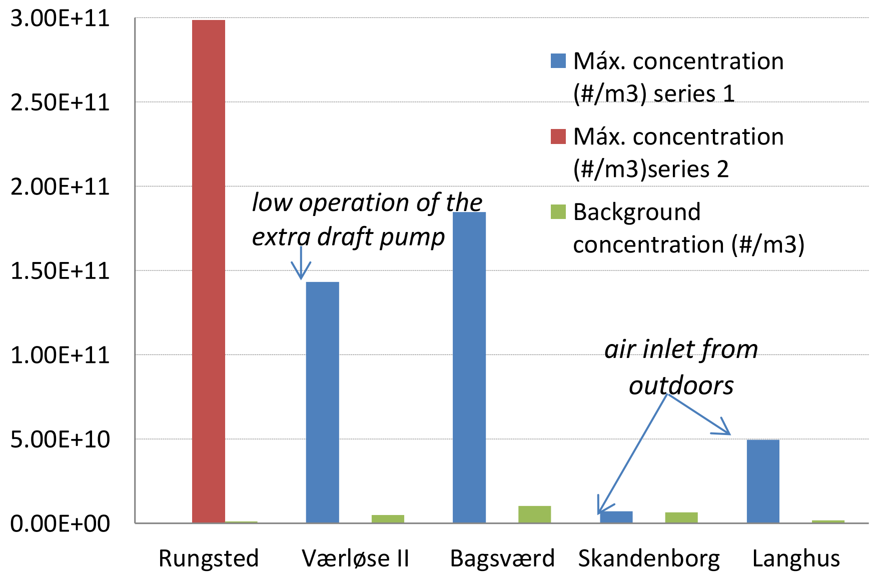

Figure 3. Variations of particle concentrations in households using advanced wbs.

It is important is to point out that in the two low energy houses using the advanced WBS the combustion air was from outdoors. Figure 3 shows that for these two air-tight and brand new houses, the emission of UFPs increased only by 1 and 29 times, respectively. The use of an air inlet from outside can avoid the reflux of exhaust when the flame temperature in the chamber is lower, however, it seems that the chimney design and users interaction with the combustion chamber are the dominant aspects concerning the emission and transport of UFPs. The background concentrations of UFPs outdoors presented very low variations and magnitude when compared to the indoor air pollution experienced when lighting and operating all the tested WBSs (indoor/outdoor larger than 1). It is possible to understand from Figure 3 that the operation of advanced WBSs (either CAD or water jacket) might impact on the IAQ, depending on the household interventions and installation of the appliances, height of the chimney, chamber insulation, draft design and doors of the WBS.

Figure 4 shows that the most modern installations of advanced WBSs (max. concentrations lower than 10^{10}#/m3) present much lower levels and variations in the concentration of UFPs than in the old and renovated dwellings (max. concentrations larger that 10^{10} #/m^3). The concentration of

UFPs increased between 30 and 306 after lightning the WBS for the households with small chimney installations with low air-tightness in the connection pipes to the stove (not following any guidelines) and air intake from indoors. The increase in the concentration of UFPs during refilling was not so sharp, due to the operation of the advanced stoves with high flame temperatures during the reloads. The largest variations in the concentration of UFPs were observed for the older buildings where no recommendations for the stove/chimney installation had been followed. The graph shows that the variation of concentration of UFPs can be very small in the low energy house (Skanderborg) with an integrated chimney installation following the recommendation for the design, height and dimensioned draft.

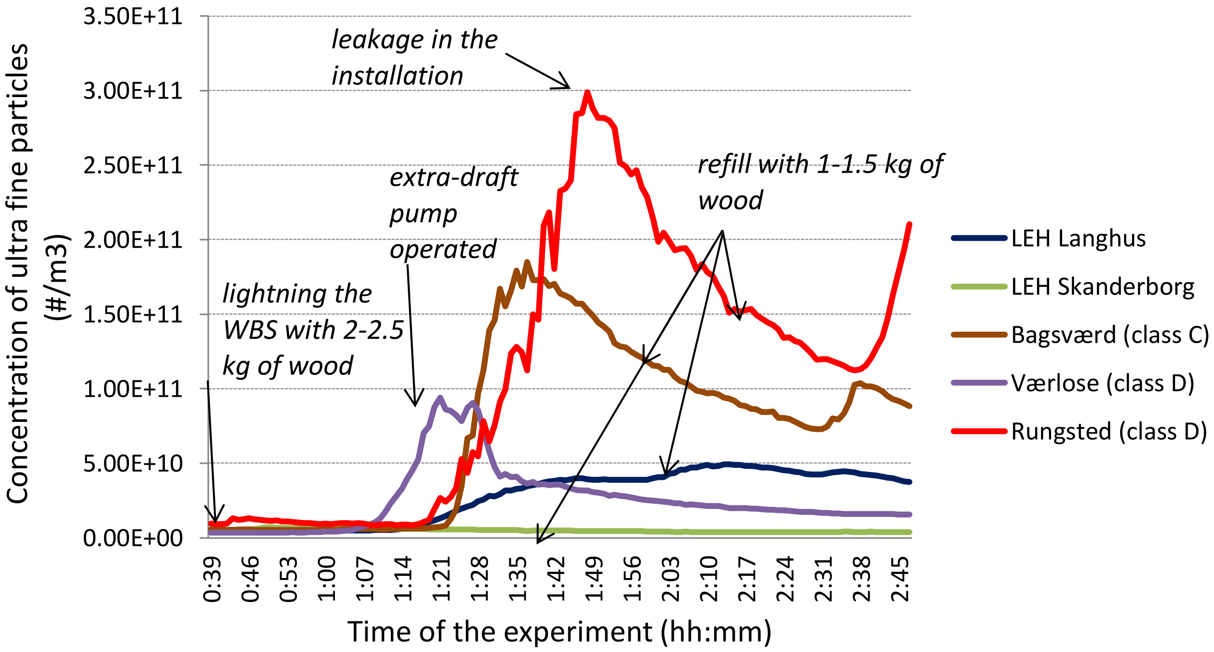

Figure 4. Variations of particle concentrations in households using advanced wbs.

The main reasons for the emission of particles can be a negative indoor outdoor pressure draft caused by the lower flame temperature and turbulence of the combustion gases in the chamber. The design of the door and combustion air inlet indoors is also a very relevant issue that influences the draft when opening it suddenly a large amount of particles can be emitted to the living room.

3.3 Overheating

According to previous indoor climate studies where manual certified WBS were operated in old and modern dwellings, it was concluded that mass stoves release heat constantly over time, while cast-iron stoves operated manually emit heat intermittently (heat losses in the lack of energy storage systems) and might overheat households over 26^{o}C with higher insulation (Esrum I and II).

This research tested the indoor climate performance of the new models WBS during a mild winter season through both temperature and relative humidity measurements in dwellings. The relative humidity outdoors varied between 55 and 97% and indoors 23 and 79%, being more stable in the LEH using mechanical ventilation systems (smaller variations between 32 and 41%). This study shows that these two models of WBSs caused overheating in low energy houses using the stoves as a secondary heating system during a mild winter season. The CAD as the ability to improve the control of the heat supply and give a more stable indoor temperature (3-5kW), while the water jacket stove (5-8kW) are very good technology to avoid energy losses, not fully avoiding the overheating effect. In the LEH Skanderborg there is a regulation of the heat output from the primary energy system (heat pump) which reflects the larger stability on the indoor temperature (mean value less than 25°C).

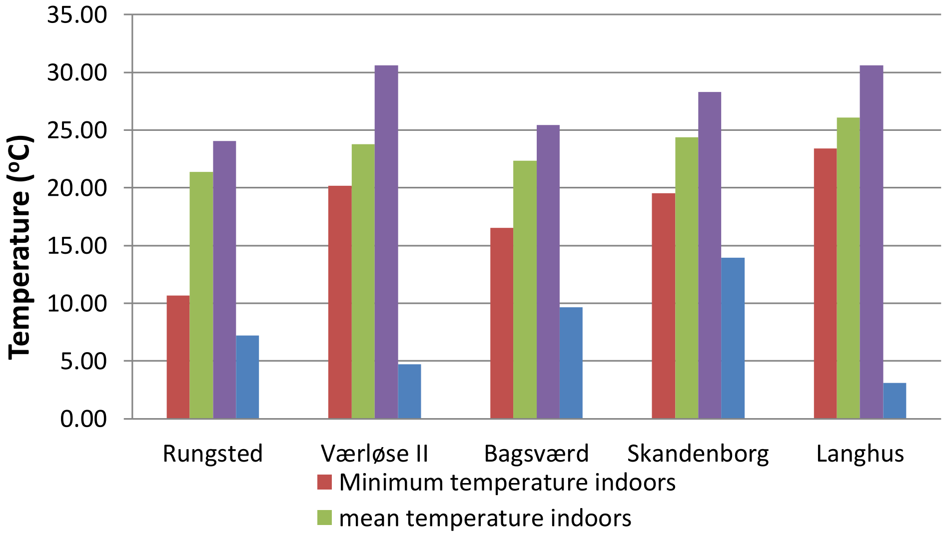

Figure 5. Temperatures indoors and outdoors during the operation of advanced WBS in a mild winter.

The installation of the hydro stove on the LEH revealed a larger variation of the indoor temperature, taking into account the set up temperature when operating only the primary energy system. The ability to synchronize the heat storage in this type of stove with the floor heating system seems to be a very relevant aspect on the future installation of hydro stoves.

4 Conclusions

The success of household interventions during the adoption of new wbs models in future housing depend on the integration of the appliances in the building envelope, primary energy systems, heat storage, including a proper chimney design and draft with the necessary location, exhaust and height to guarantee an environment free of harmful particles and black carbon.

Future regulations for the installation of WBSs in modern housing are extremely important to control the heat supply and demand, as well as the proper indoor climate adapted to the people´s preferences and health requirements. The new generation of WBS as a large potential to function either as a primary energy system for low energy houses (3-5kW) when distributed through water jackets or air flows to the rooms or as a secondary heating system when operating lower wood loads (less than 1 kg/h and 2 kW), integrated with a demand/control device with the primary energy system.

Further research is needed in order to characterize the heat flows from the advanced WBSs over its operation in order to develop its integration in future housing.

5 Acknowledgements

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