Evaluation of a New System Combining Wood-Burning Stove, Flue Gas Heat Exchanger and Mechanical Ventilation with Heat Recovery in Highly-Insulated Houses

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Abstract

The performance of an innovative flue gas heat exchanger (FGHE) located at the exit of a wood-burning stove (log or pellet) to pre-heat ventilation air has been assessed for highly insulated detached houses. For this purpose, transient thermal simulations (TRNSYS+TRNFlow) were carried out on a Norwegian house typology (passive house standard NS3700) and a French house typology (building regulation RT2012) – both equipped with mechanical ventilation systems with heat recovery (MVHR). Seven different climates were considered ranging from mixed (Nice, France) to subarctic conditions (Karasjok, Norway) in order to evaluate the impact of the system in terms of energy use for space-heating and thermal comfort for a broad range of operating conditions. The tested system allowed an improvement of the thermal comfort in the bedrooms furthest away from the stove: up to 7.6°C of the 5th percentile of the operative temperature ($T_{op\ 5\%}$) for France and up to 9.5°C for Norway, compared to the houses without the system. Furthermore, energy savings of up to 19% over the space-heating season were reported, depending on the type of wood-burning stove (i.e. log or pellet) and control used during operation.

1. INTRODUCTION

The general context of this work is the use of wood-burning stoves (log or pellet) to cover the space-heating needs of highly insulated dwellings. In fact, the recent building regulations in European countries have led to an increased insulation and airtightness for the newly constructed dwellings, and therefore to a great reduction of the space-heating needs [1-2]. Hence, it has become mandatory to adapt the wood-heating systems to, on the first hand, avoid overheating in the room where the stove is located, and, on the second hand, to ensure that a sufficient temperature is obtained in the rooms located furthest away from the stove [3-5]. In this prospect, different measures can be implemented, such as reducing the nominal power of the stoves and improving the combustion control in order to provide a more stable release of heat [6-7]. New solutions adapted to highly insulated buildings are however needed in order to ensure a comfortable indoor climate within the whole dwelling [8]. Several new concepts and technologies have been developed lately, among which thermal energy storage in stovepipes using phase change material (PCM) [9], hybrid stoves fueled by either pellet or log [10], upgrading fuel quality by using charcoal [11], or improving the combustion chamber design and stove materials in order to increase its efficiency [12-14]. In this context, it is proposed to study the relevance of integrating a triple concentric flue gas heat exchanger (FGHE) at the exit of a wood-burning stove for use in highly insulated single-family houses. This innovative heat exchanger (illustrated in Figure 1) enables to recover a part of the heat in the flue gas. Its principle is as follows: the flue gas (FG) is evacuated through the inner tube, the ventilation air (VA) is heated from top to bottom in the space between the inner tube and the intermediate tube, and the combustion air (CA) which ensures the correct operation of the wood stove is brought down between the intermediate tube and the outer tube (see left system in Figure 1). Another version of the system exists for stoves without chimney Combustion Air intake, in which case the space between the intermediate tube and the outer tube is filled with insulating material (see right system in Figure 1). The FGHE has been patented and detailed information regarding its principles have been presented in previous communications [15-17].

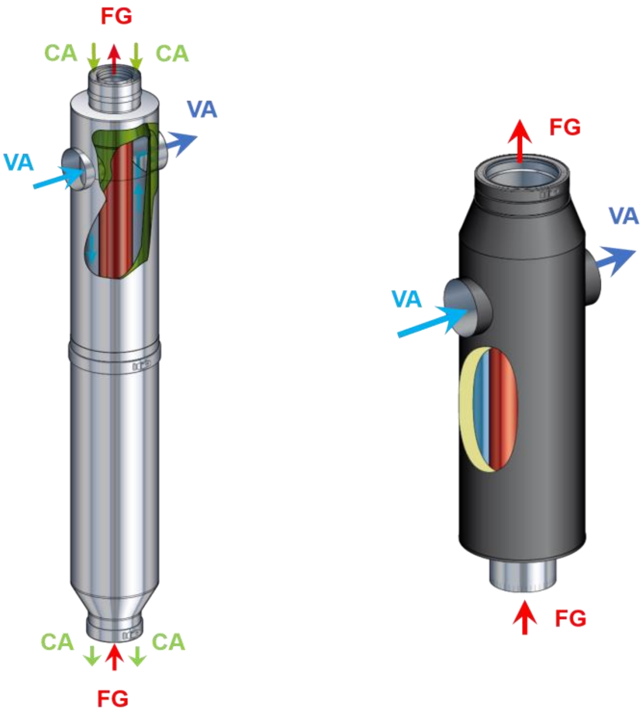


Figure 1. View of the triple concentric flue gas heat exchanger (FGHE) for wood-burning stoves with (left) and without (right) chimney combustion air intake, with FG: Flue Gases, VA: Ventilation Air, CA: Combustion Air (© Poujoulat).

The recovered heat is then transferred to the supply ventilation air, and distributed into the rooms of the dwelling through the mechanical ventilation system with heat recovery (MVHR), as depicted in Figure 2. The FGHE is located downstream of the MVHR and coupled to the ventilation network. In terms of control, the FGHE and the MVHR are controlled independently of each other. Hence, it is an air heating concept aiming to both save energy and improve the thermal comfort in the dwelling by improving the heat distribution. Air heating as a way to cover the space-heating needs of residential buildings has been evaluated in numerous studies, namely in Germany [18], Denmark [19-20], Norway [21-22], Lithuania [23] and France [24-25], as well as in office buildings in Norway [26-27] and Lithuania [28]. Promising results have been obtained in terms of perceived indoor climate with such systems. However, several studies insisted on the need for temperature zoning in energy-efficient residential dwellings [5] [28-30]. In particular, many occupants would like to be able to adjust the bedroom temperature independently from the temperature in the other rooms, as a lower bedroom temperature is usually considered more comfortable.

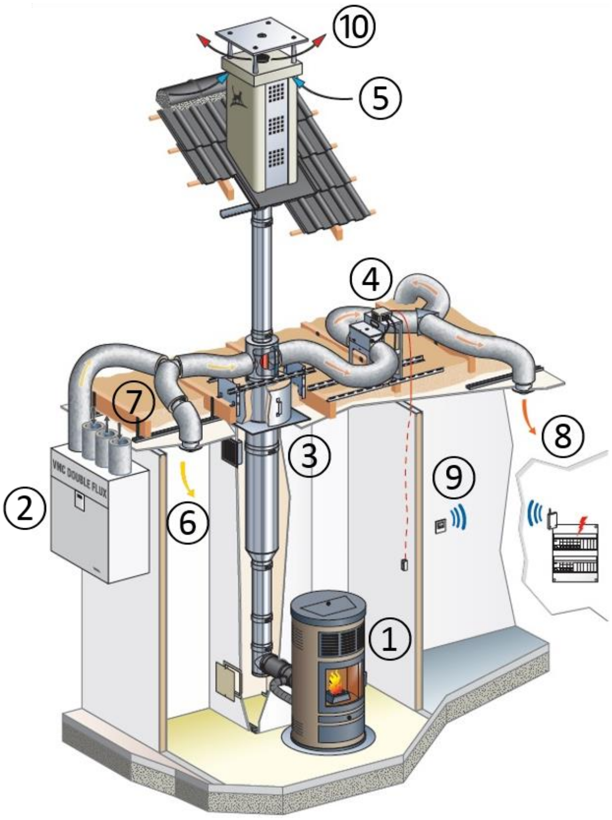


Figure 2. View of the ALLIANCE system (© Poujoulat): ① Wood-pellet stove; ② MVHR; ③ FGHE; ④ Electric heating coil; ⑤ Combustion air inlet; ⑥ Supplied ventilation air in living-room; ⑦ Balancing damper; ⑧ Supplied pre-heated ventilation air in bedroom; ⑨ Bedroom temperature set-point; ⑩ Flue gas outlet.

A flexible space-heating system should be able to follow the preferences from users. Upon request from occupants, it should be able to generate relatively high temperature in bedrooms (i.e. ~21°C) or let the bedroom temperature decrease to lower values (i.e. in the range of 16°C). Therefore, to ensure high indoor temperatures for the rooms furthest away from the stove, the present study considers an electric heating coil (HC) placed after the FGHE. This heating coil controls the temperature of the ventilation air to be supplied into the rooms according to a temperature sensor placed in the coldest bedroom. The resulting system (FGHE + HC) is mentioned as “ALLIANCE” in the following. Thus, the present work was carried out to assess the performance of such a combined wood-based heating and ventilation system, both in terms of temperature distribution in highly insulated dwellings and in terms of impact on the energy used for space-heating (to maintain a given level of comfort). For this purpose, detailed transient simulations (software TRNSYS [31]) were used for two different countries (i.e. Norway and France) and their respective typologies of detached house. In addition, specific model components were developed to take into account the wood-log and pellet stove, as well as the MVHR and FGHE in the simulations.

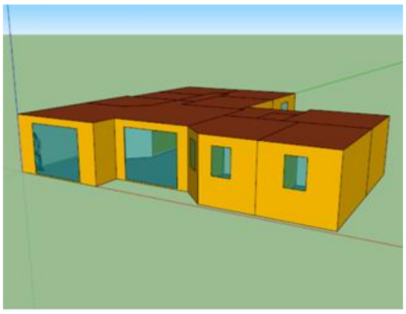
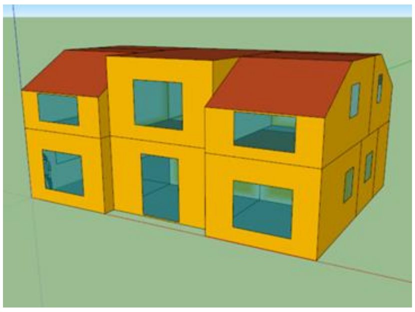
2. METHODOLOGY

2.1. Norwegian and French house typology

Investigations have been performed using Building Performance Simulation (BPS), here TRNSYS. The multi-zone building model of TRNSYS, called Type 56, was used for the simulations. Two typical Norwegian and French single-family house typologies were considered. For both buildings, the countries' respective building energy and ventilation standards have been taken into account (RT 2012 in France [1], NS3700 in Norway [2]). The characteristics of the considered houses are summarized in Table 1.

Table 1. Summary of the studied house typologies.

Country	**France**	**Norway**
Building regulation	RT 2012	NS3700
Stories	1	2
Heated Area	148.4m^2	173.5m^2
Infiltration rate	n_{50}=0.6 [1/h]	n_{50}=0.6 [1/h]
Net space heating needs	25.9 kWh/m^2/year (for La Rochelle)	18.9 kWh/m^2/year (for Oslo)
Ventilation	MVHR	MVHR
Ventilation rate	125 m^3/h	225 m^3/h
Efficiency of the ventilation heat exchanger	85%	85%

Internal gains	4.2 W/m^2	4.2 W/m^2
Heat source	Wood-log or pellet stove	Wood-log or pellet stove
CAD Geometry		
Climate locations		

A light masonry structure was chosen for the French house typology, while a light wooden structure was retained for the Norwegian house typology, see Table 2. Space and time varying internal gains, corresponding to an average of 4.2 W/m^2 were considered in accordance with the definition in the Norwegian passive house standard NS3700. It has been assumed that 50% of internal gains are emitted by convection and 50% by longwave radiation. For the sake of comparison, the same average value of 4.2 W/m^2 was considered for the internal gains for the French case. Since winter climatic conditions strongly depends on the location in Norway, the performance of the building envelope is adapted to the different Norwegian climate zones as required by NS3700, see Table 3. On the contrary, the performance of the building envelope is kept constant for the French house whatever the climate zones.

Table 2. Construction mode of the building typology in France and Norway: overall building thermal inertia (using EN13790 [32]), constitution of walls and thermal transmittance of the partition walls in W/m²K.

Construction mode	**Thermal inertia**	**Envelope thermal insulation**				**Internal thermal insulation (W/m^{2}K)**		
		External wall	Ground slab	Roof	Windows	Floor/Ceiling	Partition Wall	Bearing wall
France: Masonry light	Light	LWA +EPS	Concrete +EPS	WS +GW	DGW	WS+GW (0.243)	WS+GW (0.33)	WS+GW (0.33)
Norway: Wooden light	Very light	WS +GW	Concrete +EPS	WS +GW	TGW	WS+GW (0.21)	WS+GW (0.33)	WS+GW (0.25)

LWA for lightweight aggregate block, C for concrete, WS for wooden structure, TGW for triple-glazing window, DGW for double-glazing window, GW for glass wool, EPS for expanded polystyrene.

Table 3. Building envelope performance as a function of location: thermal transmittance (U) of external walls (Uext), the roof (Uroof), the slab (Uslab), and the windows (Uwin); normalized cold bridges (Ψ'').

Location	**U_{ext} [W/m^{2}K]**	**U_{roof} [W/m^{2}K]**	**U_{slab} [W/m^{2}K]**	**U_{win} [W/m^{2}K]**	**Ψ'' [W/m^{2}K]**
Nice	0.20	0.11	0.24	1.2-1.5	0.02-0.09
La Rochelle	0.20	0.11	0.24	1.2-1.5	0.02-0.09
Paris	0.20	0.11	0.24	1.2-1.5	0.02-0.09
Strasbourg	0.20	0.11	0.24	1.2-1.5	0.02-0.09
Bergen	0.15	0.13	0.11	0.80	0.03
Oslo	0.15	0.12	0.11	0.72	0.03
Tromsø	0.14	0.11	0.11	0.72	0.03
Karasjok	0.12	0.10	0.08	0.72	0.03

2.2. Climate locations

A broad range of climates is considered to evaluate the performances of the system, ranging from the milder Mixed climate (Nice) to the Subarctic climate (Karasjok), as defined by ASHRAE Standard 90.1 [33]. Three climate zones are considered in France, corresponding to Nice, La Rochelle, and Strasbourg, while four climate zones are considered in Norway, corresponding to Bergen, Oslo, Tromsø and Karasjok. The main characteristics of the local weather for the studied locations and corresponding climate zones are summarized in Table 4. Heating degree day (HDD18) is a measured index that aims to reflect the energy needs for space-heating of a building at a specific location. The simulations are carried out over the space-heating season, defined in the study as October 1st to March 31st for both countries. Typical Meteorological Year (TMY) conditions are considered for simulations. It is assumed that the building is located in a flat terrain without obstacle so that no shading has been taken into account. It is also assumed that the building is located at an altitude between 0 and 400 m.

Table 4. Local weather characteristics for the studied locations, and corresponding climate zones.

Location	**Θe conventional outside temperature (France)/ ΘSH,dim [°C] (Norway)**	**HDD18 [°Cday]**	**Climate zone (ASHRAE[33]/RT2012[2])**
Nice	-3	1558	4, Mixed / H3
La Rochelle	-6	2087	4, Mixed / H2b
Strasbourg	-9	2874	5, Cool / H1b
Bergen	-11.7	3858	5, Cool
Oslo	-20	4423	6, Cold
Tromsø	-14.6	5508	7, Very-cold
Karasjok	-48	7538	8, Subarctic

2.3. Stove modelling

Either a wood stove or a pellet stove located in the living room was considered in the simulations. The power emitted by the stove by convection and longwave radiation was injected into the building model in the form of internal gains in TRNSYS. This modeling procedure to evaluate the influence of wood stoves on the indoor thermal environment of buildings has been validated by Georges et al. [34]. A nominal power of 6 kW was retained for both the log and the pellet stove, a value which would allow to cover the space-heating demand in both cases, and which is congruent with previous studies [4]. The combustion process in the wood stove was considered as a batch process. A specific software developed by SINTEF Energy Research [35-36] based on measurements was used to determine the time profile of the log-combustion power of the stove. A relatively small batch load was retained (5 kWh), in accordance with the recommendations given by stove's manufacturers in order to ensure a stable release of heat, and which corresponds roughly to 1.2 kg of dry wood (<20% humidity). The wood-log stove had a thermal inertia of 5kJ/K and a combustion cycle duration of 1.8h. A single thermal capacitance is used to model the stove envelope so that the knowledge of the stove thermal inertia enables to evaluate the power emitted by the stove to the room based on the time profile of the combustion power. The wood stove is controlled manually by the occupant. This was implemented in TRNSYS in the following way: a stove combustion cycle starts if one occupant is present and active (assumed from 6:00 to 9:00 and from 16:30 to 22:30), and if the air temperature in the living room Troom<21°C. The profile of heat emitted to the room by the wood stove is then called by TRNSYS, and the corresponding convection and radiation heat fluxes are applied as internal gains in the room. Its behavior over a period of 36 hours is illustrated in Figure 3, with the power emitted by the stove (P_STOVE), the air temperature in the living room (T_ZONE1), and the occupancy (OCCUPANCY, ≠ 0 if one or more occupants are assumed present and active in the house).

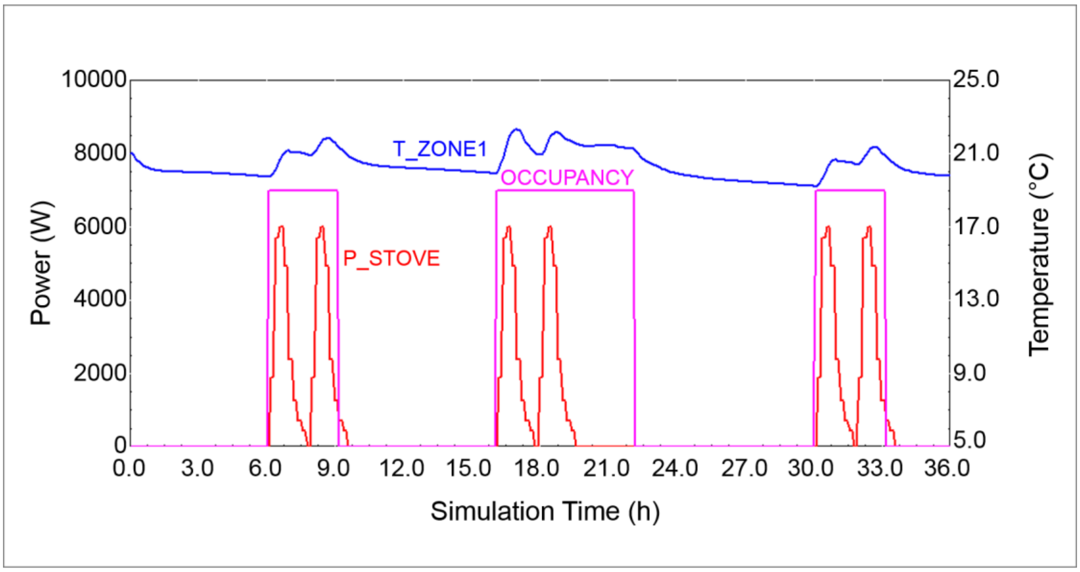


Figure 3. Illustration of the wood stove model over a period of 36 hours.

Regarding the pellet stove model, the power emitted by the stove is controlled continuously by a Proportional Integral (PI) action to enforce the zone air temperature in the living room to a setpoint temperature of 21°C. The stove is able to modulate between 30% and 100% of its nominal power. In good accordance with the typical surface temperatures of stoves, a convective to radiative heat exchange ratio of 0.4/0.6 was considered, meaning 40% of heat emitted by convection and 60% of heat emitted by radiation. The pellet stove starts when Troom<20°C. It stops if Troom >22°C and if the stove has operated for a minimum period of time equal to 0.5h, such as to represent a realistic pellet stove behavior. This behavior is shown in Figure 4 for a period of 36 hours with the power emitted by the stove (P_STOVE), the air temperature in the living room (T_ZONE1) as well as the occupancy (OCCUPANCY, ≠ 0 if one or more occupants are assumed present and active in the house). As expected, the control of the stove is independent of the presence of the occupants. With a minimum power modulation of 30%, the variation of the emitted power ranges between Pmin=2kW and Pmax=6kW.

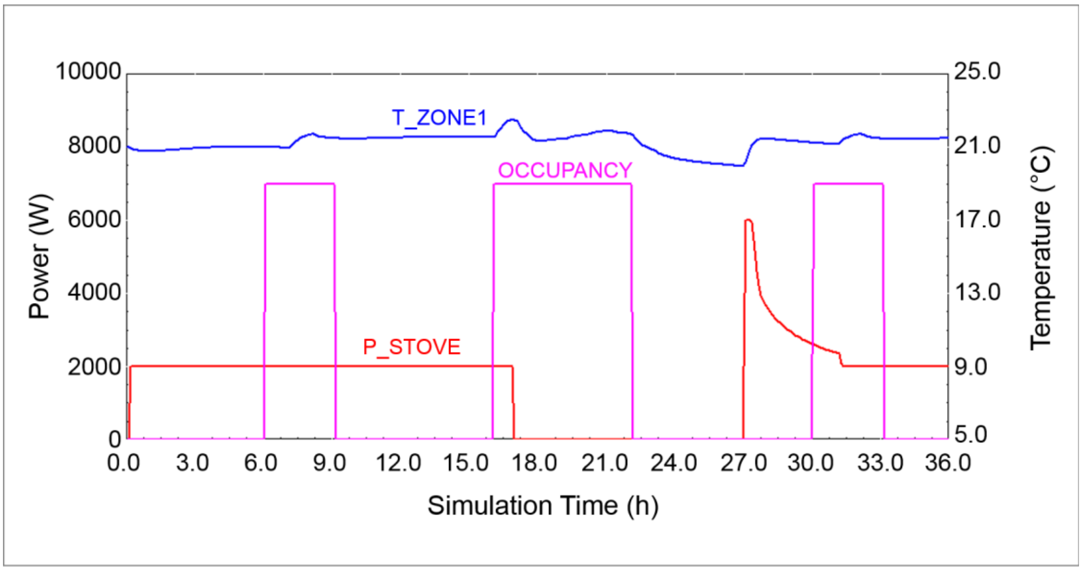


Figure 4. Illustration of the pellet stove model over a period of 36 hours.

2.4. Ventilation and ductwork modelling

A ventilation network model [37] (here using TRNFLOW) was employed to take into account the airflow rates through the ventilation system and between the rooms. A model of a balanced mechanical ventilation system with heat recovery was implemented. The ventilation airflow rates corresponding to the respective building regulations of France and Norway have been applied, i.e. a supply airflow rate of ~0.81 $m^3/h/m^2$ of heated area during normal operation for France and ~1.25 $m^3/h/m^2$ for Norway. In practice, a constant ventilation rate over the day is considered in TRNSYS, taking into account 2 hours of forced ventilation to account for the use of the bathrooms and kitchen, i.e. $(22h/24h*120m^3/h)+(2h/24h*180m^3/h)=125m^3/h$ of total ventilation rate for supply and exhaust in the French case and $(22h/24h*216m^3/h)+(2h/24h*330 m^3/h)=225 m^3/h$ for Norway. A cascade-flow principle is implemented, i.e. the fresh air is supplied into the living room and bedrooms, while the polluted air is exhausted in the bathrooms and kitchen. Regarding the air handling unit, a counter flow heat exchanger is considered transferring heat from the exhaust air to the supply air, with a constant recovery efficiency ε of 85% for all cases. Similarly to how most individual houses in France and Norway operate, no humidity treatment of the supply air is assumed by the MVHR during the heating season. All doors are considered closed in order to consider the worst-case scenario in terms of heat distribution. A specific macro was developed to take the heat losses from the ventilation ducts into account, see [6]. The heat transfer by conduction in the ventilation ducts as well as from the duct outside surface to the room are modeled (again assuming 40% convection and 60% radiation).

2.5. Description and modelling of the FGHE

The flue gas heat exchanger is located right after the exit of the wood-burning stove. The FGHE is made of three concentric stainless steel tubes of 0.4 mm thickness. The diameters of the three tubes are 80 mm, 180 mm and 230 mm, respectively, and the total height is 1945 mm. Technical details regarding the FGHE and its parameters can be found in [15-17]. The heating of the ventilation air through the FGHE is taken into account in the model by computing the air temperature at the exhaust temperature of the heat exchanger (T_out), depending on the air temperature at the inlet of the heat exchanger (T_in), the mass airflow rate through the exchanger (Qm), the heat capacity of the air (cp) and the power recovered by the heat exchanger (P), according to the following equation:

$$\mathrm{T\_out} = \mathrm{T\_in} + \frac{\mathrm{P}}{\mathrm{Qm.cp}} \qquad (1)$$

A constant heat recovery (P) of 400W from the flue gas to the ventilation air is assumed under operation, i.e. when the combustion is ongoing in the stove. This constant mean value is representative of laboratory measurements, where the average amount of heat recovered by the ventilation air ranged from 350W to 700W for flue gases temperatures of 205 to 320°C, resulting in an heat exchanger effectiveness of about 30% (a value which is adequate to heat the ventilation air without affecting the proper discharge of flue gases, which remains the primary objective of the chimney) [15-17]. Furthermore, a delay of 18 minutes before heat is recovered by the FGHE after the beginning of the combustion in the stove is implemented in the model. The corresponding impact of the FGHE on the air supply temperature is illustrated in Figure 5, with the power emitted by the pellet stove (P_STOVE), the air temperature at the entrance of the flue gas heat exchanger (T_IN_FGHE), and at its exit (T_OUT_FGHE) before delivery to the bedrooms.

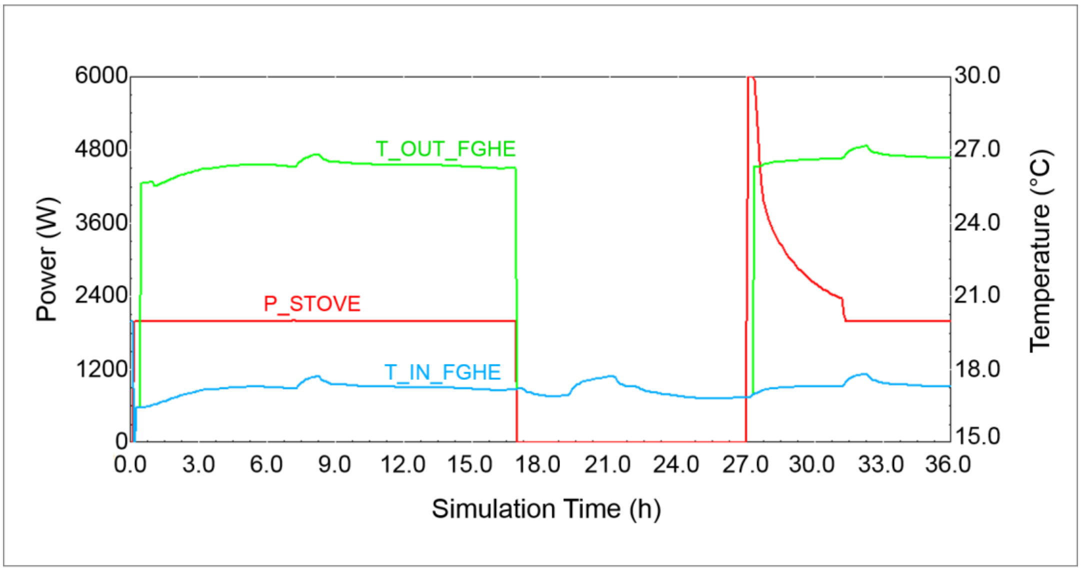


Figure 5. Illustration of the FGHE model over a period of 36 hours.

2.6. Electric heating coil modelling

In addition, an electric heating coil (HC) located at the exit of the FGHE in the ventilation duct leading to the bedrooms was considered for the scenarios including the ALLIANCE system. The purpose of the HC is to ensure a minimum temperature in the coldest room at all times, according to the occupants' choice, hence complementing if needed the heat recovered by the FGHE. A PID control was used to regulate the heating power released by the HC to the ventilation air in order to maintain the setpoint temperature Tset in the bedroom furthest away from the stove, with Tset=19°C considered in this study. A maximum power for the heating coil PHC_max=1200W was specified. Moreover, the HC is controlled in a way that the temperature in the ducts after the HC does not go beyond a maximum temperature Tmax=55°C, thus avoiding carbonization of dust in the ventilation air which can be detrimental to indoor air quality [18]. The influence of the HC on the air supply temperature is presented in Figure 6, with the power emitted by the log stove (P_STOVE), the air temperature at the entrance of the flue gas heat exchanger (T_IN_FGHE), at its exit (T_OUT_FGHE), and at the exit of the heating coil (T_OUT_HC) before delivery. The relevance of the HC is shown both during the combustion (e.g. at t ≈ 17h) and outside of the combustion periods (e.g. at t ≈ 22h) to complement the FGHE.

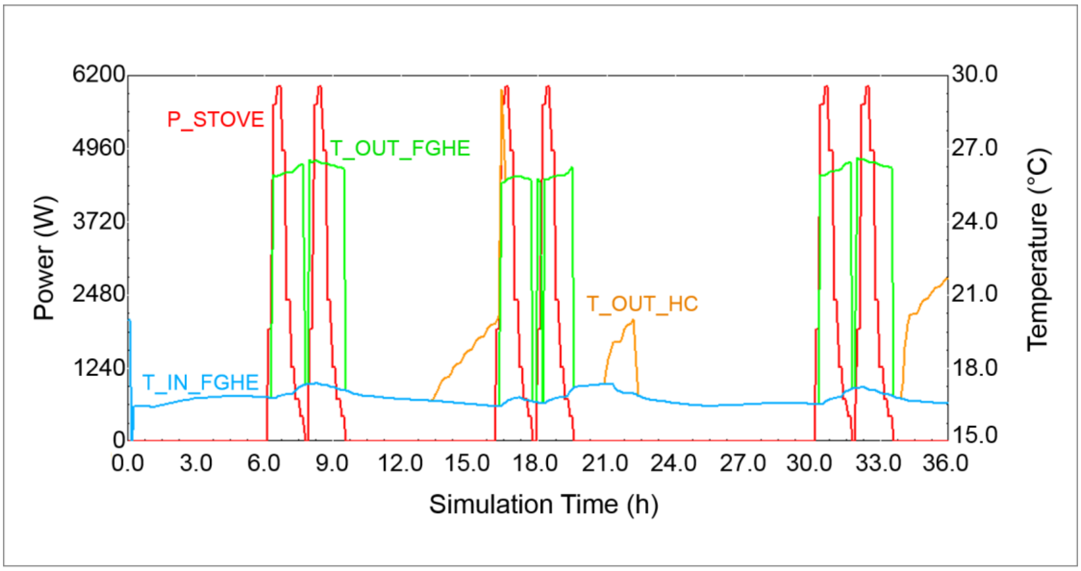


Figure 6. Illustration of the HC model over a period of 36 hours.

2.7. Performance indexes

Thermal comfort

In building science, the ISO 7730 standard [38] is typically used in order to assess the thermal comfort in dwellings, resorting to the Predicted Mean Vote (PMV) – Predicted Percentage of

Dissatisfied (PPD) model based on the sensation of an average person. However, the PMV-PPD model assumes a homogeneous radiative environment. It is not the case with a punctual heat source such as in a room heated by a stove. Therefore, the operative temperature (Top) is here considered in order to evaluate the thermal comfort in each room. The operative temperature is evaluated according to the EN15251 [39] standard. For a given location in the room, Top is the arithmetic mean between the mean radiant temperature Trm (calculated using surface temperatures in the room and the corresponding view factors from the location considered to these walls) and the dry bulb temperature (Tair) in the room.

$$\mathrm{Top} = \frac{\mathrm{Tair} + \mathrm{Trm}}{2} \qquad (2)$$

Regarding Tair, it is assumed that the air is perfectly mixed in each room so that this value is independent of the user location. This is an acceptable assumption as mixing ventilation is applied. Furthermore, the results in the following are presented in terms of the 5th (Top 5%) and 95th (Top 95%) percentile of the operative temperature over the heating season : this means that the operative temperature is 90% of the time between Top 5% and Top 95% in the considered room. This method allows to evaluate the performance of the system over the heating season in terms of under- and overheating, illustrating both temperature level and duration. Indeed, using the maximum and minimum of Top over the space-heating season would have exaggerated results as these events may occur for a very limited amount of time.

Energy use

The energy use for space-heating (Etot) presented in the results section includes the actual energy emitted by the stove to the room, as well as the heat transmitted by the HC to the supply ventilation air. The calculation of the energy use without and with the ALLIANCE system allows to evaluate how much additional energy is necessary in order to provide the temperature increase of the ventilation air. Accordingly, the following terms are introduced and used in the results section:

- ΔEtot (kWh): Difference in energy use for the space-heating of the house with the ALLIANCE system compared to the same house without the ALLIANCE system, see Eq.(3).

$$\Delta \mathrm{Etot} = \mathrm{Etot}_{\text{with ALLIANCE}} - \mathrm{Etot}_{\text{without ALLIANCE}} \tag{3}$$

- CICC (%): Comfort Increase Cost Coefficient, which is equivalent to ΔEtot but expressed in terms of percentage, see Eq.(4).

$$\mathrm{CICC} = \frac{\Delta \mathrm{Etot}}{\mathrm{Etot}_{\text{without ALLIANCE}}} \tag{4}$$

The energy use is considered in terms of final energy, no conversion to primary energy is carried out in the context of this study since the conversion factors vary from country to country. The energy use for ventilation consists of the electricity used by the fans to supply the fresh ventilation air into the building and to exhaust the ventilation air from wet rooms. The calculation of the power use of the supply and exhaust fans depends on the total pressure rise across the fan (ΔPtot). This value is based on manufacturer data sheets for a typical MVHR linking the Specific Fan Power to ΔPtot. Defining Q_FGHE as the ventilation flow rate through the FGHE, the ALLIANCE system induces an additional pressure loss of 0.002 Q_FGHE that the supply fan has to compensate for. This pressure loss corresponds to approximately 30 Pa for an airflow rate of 120 m^3/h. This effect has been taken into account in the simulations by using the instantaneous airflow rate passing through the FGHE, in order to compare the energy used by the ventilation fans for both systems.

3. RESULTS AND DISCUSSION

Both the operative temperature increase and the energy use compared to the same houses without the tested system have been evaluated for the wood-log and the pellet stove scenarios.

3.1. Wood-log stove

For the 6 kW wood stove, the 5th and 95th percentile of the operative temperature over the heating season in the living room and in the bedroom furthest away from the stove are presented in Table 5 for the French and the Norwegian houses.

In the case of a house with a wood stove as single heating source ("ALLIANCE OFF" in Table 5), the 5th percentile of the operative temperature (Top 5%) is too low, especially in the bedroom furthest away from the stove: Top 5% ranges from 7.1°C to 14.9°C in France, and from 8.4°C to 15.4°C in Norway. It holds true as well for the living room for the coldest climates considered, with 14.9°C in France (Strasbourg) and 13.9°C in Norway (Karasjok). This is due to the fact that the operating time of the wood stove is reduced (only working 11 to 35 % of the time in France and 27 to 42% of the time in Norway) because of the manual control of the stove starting only when the occupant is present and active.

However, when the ALLIANCE system is implemented, an increase of the 5th percentile of the operative temperature (Top 5%) is observed in the bedroom furthest away from the stove, raising its value by 3.8°C to 7.6°C in France, and by 3.1°C to 9.5°C in Norway, thus allowing to reach more acceptable Top 5% values of 14.7 to 18.7°C and 17.8 to 18.5°C, respectively. This means that the operative temperature in this specific bedroom is in a range which is satisfactory according to the EN15251 standard 90% of the time [34]. The Top 5% in the living room is as well increased by 0.7°C to 4.9°C in all climates considered. However, overheating can be observed in the living room in the milder climates of Nice and La Rochelle for the French house typology with a Top 95% temperature of 32.7°C and 30.7°C, respectively.

This may be due to the contribution of the solar heat load, as the living room is facing south with a large window area without any solar protection.

Table 5. 5th percentile (Top 5%) and 95th percentile (Top 95%) of the operative temperature in the living room and in the bedroom furthest away from the stove over the heating season with and without the ALLIANCE system. 6 kW wood stove.

Wood stove			**Living room**			**Bedroom**		
			ALLIANCE		**ΔTop 5%**	**ALLIANCE**		**ΔTop 5%**
Location	**Climate**	**Unit**	**ON**	**OFF**		**ON**	**OFF**	
Nice	4, mixed	Top 5% (°C)	19.5	18.8	**0.7**	18.7	14.9	**3.8**
		Top 95% (°C)	32.7	32.0		23.7	23.7	
La Rochelle	4, mixed	Top 5% (°C)	18.4	16.6	**1.8**	18.3	11.5	**6.9**
		Top 95% (°C)	30.7	29.8		21.8	21.8	
Strasbourg	5, cool	Top 5% (°C)	14.9	11.8	**3.1**	14.7	7.1	**7.6**
		Top 95% (°C)	25.7	24.0		19.6	18.2	
Bergen	5, cool	Top 5% (°C)	18.3	16.9	**1.4**	18.5	15.4	**3.1**
		Top 95% (°C)	23.3	23.2		22.7	22.6	
Oslo	6, cold	Top 5% (°C)	17.5	15.3	**2.2**	18.4	14.1	**4.3**
		Top 95% (°C)	24.3	24.3		23.5	23.5	
Tromsø	7, very cold	Top 5% (°C)	17.0	14.4	**2.6**	18.3	13.2	**5.1**
		Top 95% (°C)	22.2	22.0		21.6	21.4	
Karasjok	8, subarctic	Top 5% (°C)	13.9	9.1	**4.9**	17.8	8.4	**9.5**
		Top 95% (°C)	22.0	21.8		21.4	21.1	

For the 6 kW wood stove, the results in terms of energy use and operating time are presented in Table 6. Regarding energy use, 150 to 611 kWh of energy is recovered by the FGHE over the heating season, all cases considered. This coincides with a drop of the operating time of the stove of 3% to 5% for France, and of 1% to 3% for Norway. As a consequence, the energy used by the stove for space-heating decreased as well, by 337 to 617 kWh for France and by 124 to 498 kWh for Norway.

In order to increase comfort in the room furthest away from the stove, the HC located downstream of the FGHE has however been working 41 to 85% of the time for the French cases, and 25 to 70% of the time for the Norwegian cases. The energy use of the fans is also slightly increased due to the additional pressure drop caused by the FGHE. Considering all these parameters, the increase of comfort in the case of a 6 kW wood stove comes at a cost of 305 to 1438 kWh for the energy use for space-heating and ventilation, or +16 to 30%, compared to the same case without the ALLIANCE system in France, and -14 to 1585 kWh (or -0.3 to +28%) in the case of Norway. This results from the fact that the operating time of the FGHE is restricted because of the manual control of the stove, requiring the occupants to be present to take advantage of it. The energy savings (-14kWh) with the tested system in the case of Bergen can be explained by the milder climate of this region (ASHRAE climate zone 5, Cool) comparatively to the rest of Norway which results in a reduced energy use for the HC and by the overall better insulation for the Norwegian house than for the French house typology for cases with similar climate conditions (e.g. Strasbourg).

Table 6. Energy use per component over the space-heating season. 6 kW wood stove.

Wood stove			**ALLIANCE ON**				**ALLIANCE OFF**		**ON - OFF**
			STOVE	**FANS**	**FGHE**	**HC**	**STOVE**	**FANS**	**ΔE_{TOT} / CICC**
Location	**Climate**	**Unit**							
Nice	4, mixed	E (kWh)	1258	368	150	585	1595	311	**305**
		E (%/E_{TOT})	53 %	16 %	6 %	25 %	84 %	16 %	**16.0 %**
		Op.Time (%)	11 %	100 %	9 %	41 %	14 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	768	-	-	-
La Rochelle	4, mixed	E (kWh)	2131	359	257	1096	2697	308	**581**
		E (%/E_{TOT})	55 %	9 %	7 %	29 %	90 %	10 %	**19 %**
		Op.Time (%)	19 %	100 %	15 %	61 %	24 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	776	-	-	-
Strasbourg	5, cool	E (kWh)	3941	348	495	2021	4558	315	**1438**
		E (%/E_{TOT})	58 %	5 %	7 %	30 %	94 %	6 %	**30 %**
		Op.Time (%)	35 %	100 %	28 %	85 %	40 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	793	-	-	-
Bergen	5, cool	E (kWh)	3091	1077	382	204	3589	797	**-14**
		E (%/E_{TOT})	65 %	23 %	8 %	4 %	82 %	18 %	**-0.3 %**
		Op.Time (%)	27 %	100 %	22 %	25 %	31 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	636	-	-	-
Oslo	6, cold	E (kWh)	3045	1087	383	294	3438	803	**185**
		E (%/E_{TOT})	63 %	23 %	8 %	6 %	81 %	19 %	**4 %**
		Op.Time (%)	27 %	100 %	22 %	31 %	30 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	804	-	-	-
Tromsø	7, very cold	E (kWh)	4454	1081	571	599	4721	800	**613**

		E (%/E_{TOT})	66 %	16 %	9 %	9 %	86 %	14 %	**11 %**
		Op.Time (%)	39 %	100 %	33 %	54 %	42 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	893	-	-	-
Karasjok	8, subarctic	E (kWh)	4727	1121	611	1414	4851	826	**1585**
		E (%/E_{TOT})	60 %	14 %	8 %	18 %	85 %	15 %	**28 %**
		Op.Time (%)	42 %	100 %	35 %	70 %	43 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	1200	-	-	-

3.2. Pellet stove

For the 6 kW pellet stove cases, the 5th and 95th percentile of the operative temperature over the heating season in the living room and in the bedroom furthest away from the stove are presented in Table 7 for both the French and the Norwegian house typologies.

It can be observed that the Top 5% operative temperature is overall higher and more stable for the 6 kW pellet stove than for the 6 kW wood stove, especially in the living room. In the case of France, the indoor temperatures ranges between 20.6 and 20.8°C, and between 11.8 and 18.8°C with and without the tested system, respectively. The range of 9.1°C to 16.9°C increases to 19.3 to 20.4°C for the case of Norway. In fact, this stems from the operating time of the stove over the heating season which increases to up to 60% of the time in the case of France, and up to 74% in the case of Norway. The main reason is the better control with the pellet stove, which operates even when the occupants are not active (*i.e.* at night, or when the house is empty). The influence of the ALLIANCE system is still important under this configuration, since an increase of the Top 5% temperature of 3.7 to 7.4°C for France and 2.1 to 4.4°C in Norway can be observed in the bedroom furthest away from the stove, and a slight decrease in the living room due to the reduced operative time of the stove when the tested system is active. Hardly any influence can be observed in pellet stove cases regarding the 95th percentile (Top 95%) of the operative temperature.

Table 7. 5th percentile (Top 5%) and 95th percentile (Top 95%) of the operative temperature in the living room and in the bedroom furthest away from the stove over the heating season with and without the ALLIANCE system. 6 kW pellet stove.

Pellet stove			**Living room**			**Bedroom**		
			ALLIANCE		**ΔTop$_{5\%}$**	**ALLIANCE**		**ΔTop$_{5\%}$**
Location	**Climate**	**Unit**	**ON**	**OFF**		**ON**	**OFF**	
Nice	4, mixed	Top$_{5\%}$ (°C)	19.5	20.6	**-1.1**	18.7	15.0	**3.7**
		Top$_{95\%}$ (°C)	32.7	32.2		23.7	23.7	
La Rochelle	4, mixed	Top$_{5\%}$ (°C)	20.4	20.6	**-0.2**	18.4	11.8	**6.6**
		Top$_{95\%}$ (°C)	30.9	30.3		21.8	21.8	
Strasbourg	5, cool	Top$_{5\%}$ (°C)	20.5	20.8	**-0.3**	15.4	8.0	**7.4**
		Top$_{95\%}$ (°C)	26.7	25.8		19.7	19.0	
Bergen	5, cool	Top$_{5\%}$ (°C)	20.3	20.4	**-0.1**	19.1	17.1	**2.1**
		Top$_{95\%}$ (°C)	23.3	23.3		22.7	22.7	
Oslo	6, cold	Top$_{5\%}$ (°C)	20.4	20.3	**0.1**	19.0	16.6	**2.3**
		Top$_{95\%}$ (°C)	24.4	24.4		23.6	23.5	
Tromsø	7, very cold	Top$_{5\%}$ (°C)	20.3	20.4	**-0.1**	18.8	16.2	**2.6**
		Top$_{95\%}$ (°C)	22.1	22.3		21.7	21.5	
Karasjok	8, subarctic	Top$_{5\%}$ (°C)	20.1	19.3	**0.9**	18.2	13.8	**4.4**
		Top$_{95\%}$ (°C)	22.2	22.1		21.8	21.4	

In terms of energy use, 242 to 1032 kWh and 632 to 1281 kWh of energy is recovered by the FGHE over the heating season for the French and Norwegian cases, respectively, as presented in Table 8. In fact, thanks to the increased operating time of the pellet stove as compared to the wood stove, the FGHE also benefits the user over a longer period of the heating season of 14 up to 59% of the time for France and 36 to 73% for Norway, as opposed to a maximum of 35% reported for the wood stove cases. Savings in terms of energy use for the pellet stove with and without the ALLIANCE system are hence significant in this case, accounting for up to 3492 kWh of savings for France and 3088 kWh for Norway for the coldest climates considered. Thus, the increase of comfort provided by the ALLIANCE system is associated with energy savings of 10 to 19% (energy use for heating and ventilation) compared to the same case without the system in France, and energy savings of 17 to 20% in Norway.

Furthermore, the operating time of the electric HC is here greatly reduced in particular for the Norwegian case, with only 3 to 6% of operating time for the cool and cold climates over the heating season, but which was necessary in order to maintain an acceptable temperature in the bedroom furthest away from the stove during the coldest period of the space-heating season. The HC is still working 39 to 84% of the time in France. This difference results from the variations between the considered house typologies, *i.e.* the stricter energy regulation and insulation in Norway and difference between house configurations (1 story in France against a more compact 2 stories dwelling in Norway with the bedrooms above the living room).

Table 8. Energy use per component over the space-heating season. 6 kW pellet stove.

Pellet stove			ALLIANCE ON				ALLIANCE OFF		ON - OFF
Location	**Climate**	**Unit**	STOVE	FANS	FGHE	HC	STOVE	FANS	ΔE_{TOT} / CICC
Nice	4, mixed	E (kWh)	1399	368	242	489	2186	311	-240
		E (%/E_{TOT})	56 %	15 %	10 %	19.6 %	88 %	12 %	-10 %
		Op.Time (%)	14 %	100 %	14 %	39 %	21 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	768	-	-	-
La Rochelle	4, mixed	E (kWh)	2956	359	509	818	4567	307	-740
		E (%/E_{TOT})	64 %	8 %	11 %	17 %	94 %	6 %	-15 %
		Op.Time (%)	30 %	100 %	29 %	58 %	40 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	777	-	-	-
Strasbourg	5, cool	E (kWh)	6932	348	1032	1445	10424	305	-2004
		E (%/E_{TOT})	71 %	4 %	11 %	15 %	97 %	0.03 %	-19 %
		Op.Time (%)	60 %	100 %	59 %	84 %	69 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	1200	-	-	-
Bergen	5, cool	E (kWh)	4243	1073	632	11	5796	793	-1262
		E (%/E_{TOT})	71 %	18 %	11 %	0.2 %	88 %	12 %	-19 %
		Op.Time (%)	37 %	100 %	36 %	3 %	48 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	366	-	-	-
Oslo	6, cold	E (kWh)	4701	1083	669	21	6270	798	-1264
		E (%/E_{TOT})	73 %	17 %	10 %	0.3 %	89 %	11 %	-18 %
		Op.Time (%)	39 %	100 %	38 %	5 %	48 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	362	-	-	-
Tromsø	7, very cold	E (kWh)	7506	1074	1087	25	10008	792	-2195
		E (%/E_{TOT})	77 %	11 %	11 %	0.3 %	93 %	7 %	-20 %
		Op.Time (%)	63 %	100 %	62 %	6 %	74 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	347	-	-	-
Karasjok	8, subarctic	E (kWh)	11246	1108	1281	168	14334	811	-2624
		E (%/E_{TOT})	81 %	8 %	9 %	1 %	95 %	5 %	-17 %
		Op.Time (%)	74 %	100 %	73 %	21 %	80 %	100 %	-
		$Pmax_{HC}$ (W)	-	-	-	575	-	-	-

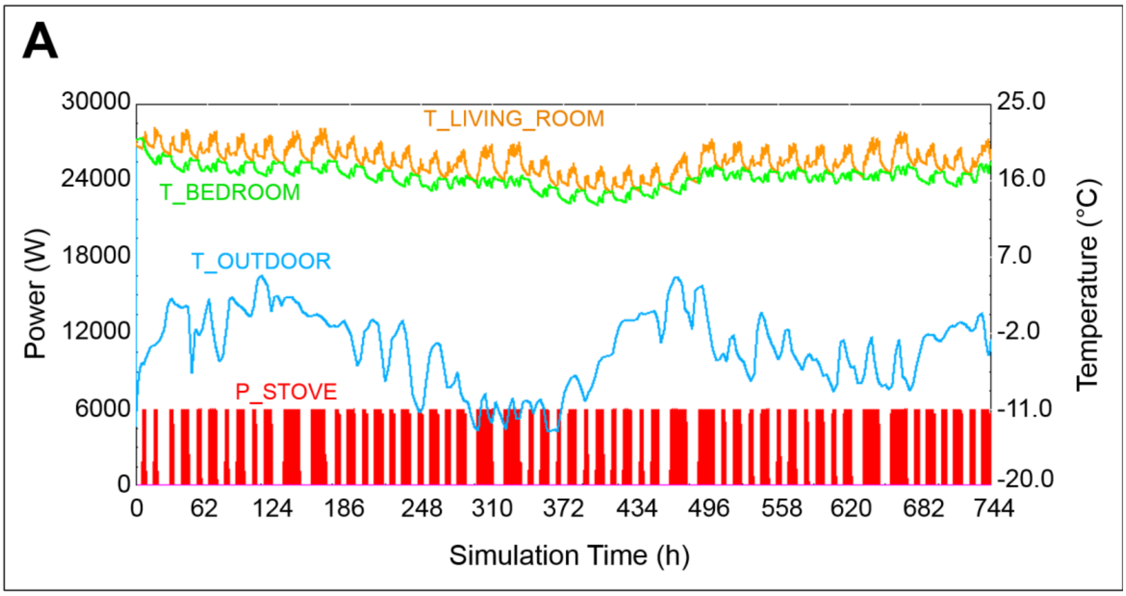
Therefore, under all climates studied, the ALLIANCE system enables an increase of the operative temperature in the dwelling, and particularly in the bedroom furthest away from the stove. In the case of the pellet stove, this increase of comfort is associated with a reduction of the total energy use for heating and ventilation over the heating season, compared to the case without the ALLIANCE system. In the case of the wood stove, the comfort improvement leads to an increase of the energy use in most cases. This is due to a longer operating time for the pellet stove, which induces a greater amount of energy recovered by the FGHE, and a lower energy use from the HC. Thus, the operating time of the stove has an important influence on the heat recovered by the FGHE.

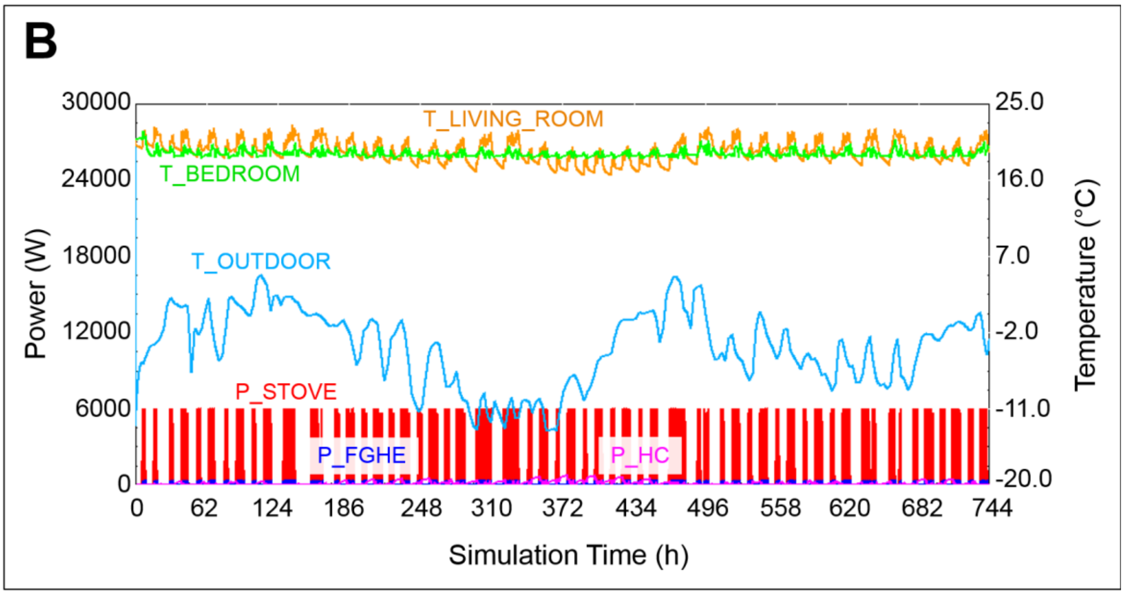
3.3. Variations during the coldest month of the heating season

For illustration purpose, the performance of the system over the coldest month of the year (January 1-31) is highlighted in Figure 7 for the climate of Oslo both for the wood stove and pellet stove. The power emitted by the stove (P_STOVE), the power recovered by the FGHE (P_FGHE), the power delivered by the additional HC (P_HC), the air temperature in the living room (T_LIVING_ROOM), and the air temperature in the coldest bedroom (T_BEDROOM) are shown. Consequently to the cold wave at about t=300h to t=372h, a temperature drop can be noticed both in the living room and in the coldest bedroom for the house with a wood stove as single heat source (see Figure 7A). This temperature drop is also present in the case of a pellet stove as single heat source, but only in the coldest bedroom (Figure 7C). However, when the ALLIANCE system is implemented, a stable air temperature of about 19°C is maintained in the coldest bedroom at all times, both for the wood stove and pellet stoves (Figure 7 B and D).

3.1. Impact of the local climate and regulation

Generally speaking, similar conclusions can be drawn regarding the performance of the system for France and for Norway, partly because the house insulation is increased proportionally to the colder climate present in Norway. Nevertheless, the difference in terms of ventilation airflow rates between both countries should be considered when designing the ALLIANCE system for a given house. Indeed, the ventilation rate in Norway is typically 1.5 times higher than the ventilation rate in France (see Section 2.4.). As a consequence, the temperature downstream of the FGHE and before the optional HC is lower in Norway. This parameter is important, as a higher air supply temperature typically leads to a poorer ventilation efficiency and drier indoor air [40]. However, as reported by numerous studies such as [21], [26-27] and [41], the preferences in terms of indoor temperature and humidity are highly personal. Therefore, it seems important to allow the occupant to specify himself the maximum acceptable supply air temperature, for instance by using a remote control or a dedicated smartphone application which would then set a threshold on the set-point temperature of the HC. For instance, it has been shown that bedrooms with a temperature of ~16°C is a frequent requirement for Norwegians [29].




B
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24000
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6000
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Temperature (°C)
25.0
16.0
7.0
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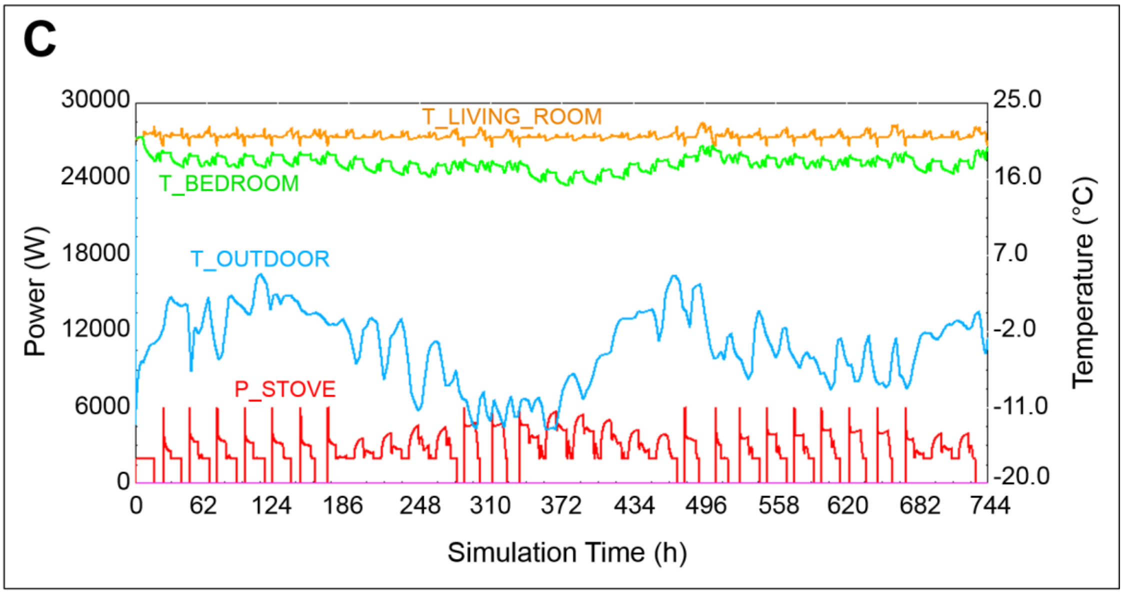
-11.0
-20.0
T_LIVING_ROOM
T_BEDROOM
T_OUTDOOR
P_STOVE
P_FGHE
P_HC
0
62
124
186
248
310
372
434
496
558
620
682
744
Simulation Time (h)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T_LIVING_ROOM
T_BEDROOM
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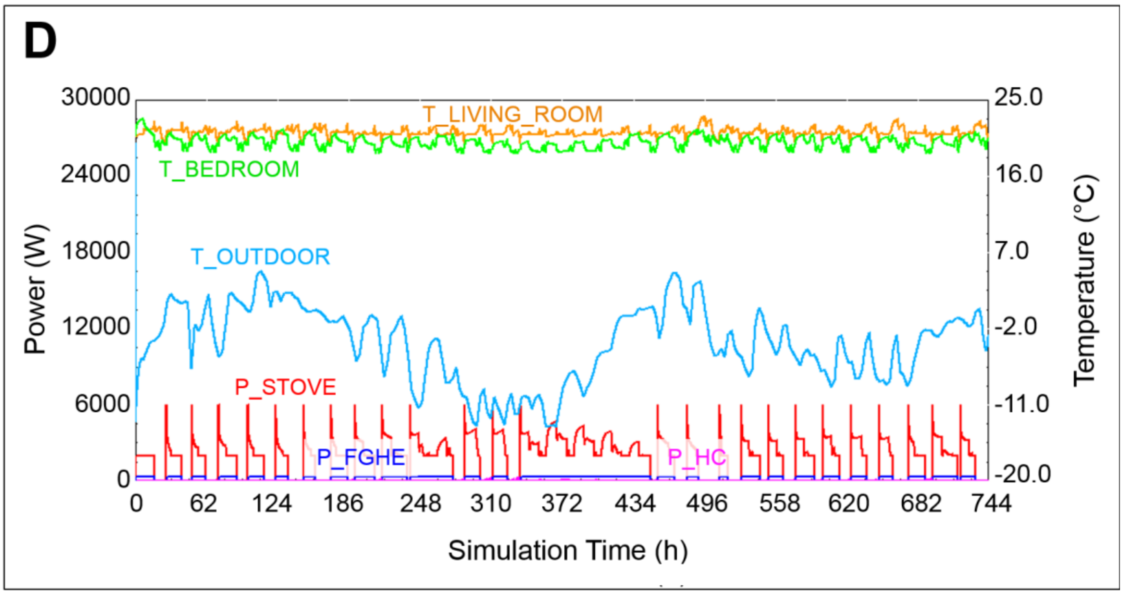
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Simulation Time (h)

Figure 7. Performance with and without ALLIANCE for the month of January in Oslo: (A) 6 kW wood-log stove without ALLIANCE, (B) 6 kW wood-log stove with ALLIANCE, (C) 6 kW pellet stove without ALLIANCE, (D) 6 kW pellet stove with ALLIANCE.

3.2. Perspectives

As a perspective, the influence of the control of the electric HC on the resulting comfort could be studied further by testing different locations for the sensor and/or different temperature setpoints for the specific rooms. The scenario where the occupants would be allowed to bypass the HC of the ALLIANCE system in the situations when no additional heat should be provided to the bedrooms could also be considered. Moreover, a constant mean heat recovery of 400W was assessed for the FGHE during the combustion in the stove in the present study. Further simulations taking into account a varying flue gas temperature and the corresponding measured heat exchange coefficient for the FGHE would allow to obtain even more precise results regarding the performance of the tested system. Finally, onsite measurements over an entire heating season in dwellings both in France and Norway would enable to quantify the performance of the ALLIANCE system in real conditions, and complete the previous measurements in laboratory and the present energy simulations.

4. CONCLUSIONS

The potential of a flue gas heat exchanger (FGHE) located at the exit of a wood or pellet stove to pre-heat ventilation air has been assessed for energy-efficient houses equipped with balanced mechanical ventilation. The performance has been evaluated in terms of improved thermal comfort and energy use by means of dynamic energy simulations (here with TRNSYS). Promising results have been obtained for both Norwegian (NS3700) and French (RT2012) house typologies.

In the case of the 6 kW wood stove, the tested system allowed to significantly increase the level of comfort in bedrooms, increasing the minimum operative temperature (Top 5%) by 3.8°C to

7.6°C in France, and by 3.1°C to 9.5°C in Norway. This improvement of comfort comes at a cost of +16 to +30% of energy use for heating and ventilation compared to the same case without the tested system (named ALLIANCE) in France, and -0.3 to +28% in Norway.

In the case of the 6 kW pellet stove, the ALLIANCE system also allows an increase of the minimum operative temperature (Top 5%) by 3.7 to 7.4°C in the bedroom furthest away from the stove for France, and 2.1 to 4.4°C in Norway. This increase of comfort is associated with energy savings of 10 to 19% (again for heating and ventilation) compared to the same case without the ALLIANCE system in France, and with energy savings of 17 to 20% in the case of Norway. Compared to the wood-log stove, the energy savings is due to the increased operating time of the pellet stove. Moreover, the waste energy recovered by the FGHE ranged from 150 to 611 kWh over the space-heating season for the wood stove, and from 242 to 1281 kWh for the pellet stove.

These results show that the tested flue gas heat exchanger would be a relevant technology to contribute to a better integration of wood-burning stoves in the current building concepts based on highly-insulated envelopes.

5. ACKNOWLEDGEMENTS

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