Evaluation of the flexibility potential of buildings in the Greater Region to contribute to the management of the grid: study case for two reference buildings in Belgium

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Abstract:

The Interreg Va Pth4GR²ID project ("Power to Heat For the Greater Region' Renewables Integration and Development") focuses on the determination of an optimal solution at a technical, economic and ecological point of view for the use of heat pumps in Greater Region (Wallonia BE, Luxembourg LU, Grand-Est FR, Rhineland-Palatinate and Saarland DE) as storage solution to absorb the part of local renewable electrical production that could not be injected into the grid (because of grid generation congestion risks). The decision to work with this kind of solution is justified because of the important part of total energy consumed in the residential sector for buildings heating. The present paper focuses on the flexibility potential evaluation of two residential buildings in order to evaluate their contribution to the electrical grid management in the Greater Region. The work is based upon simulations which are run with TRNSYS software. The capacity of buildings to deal with a heating system cut-off strategy during winter is assessed by means of comfort and energy performance indicators. The goal of this study is to assess in which way the selected buildings will respond to a heating cut-off (in case of grid congestion, the heat pumps will be switched off) and to analyse their "flexibility" as a function of design parameters series. The flexibility takes into account the comfort and the energy aspect of buildings performance. The first part of this paper presents the method used to select the reference buildings in Wallonia and the second part is dedicated to the evaluation their flexibility according to several heating management scenarios. This evaluation is realized by means of specific performance indicators which were developed the project.

Keywords:
Energy Storage, Grid Management, Heat Pumps, Flexibility, TRNSYS.

1. Introduction

During the last decades the « smart-grids » concept spread through EU and has never stopped to developing including the major challenge of renewables (which are intermittent energy resources) integration into the electrical grid.

Concomitantly to this technical challenge a real issue is the aging of the building stock in EU. Indeed around 35% of European buildings are more than 50 years old [1]. If today new constructions become compliant with sophisticated energy management applications, in order to improve their efficiency and to allow them to be easily connected to a smart-grid environment, they offer to their owners the possibility to be an actor of the energy market [2]. But it is not the case for the oldest buildings. Therefore in this context refurbishment strategies must be defined and adapted in order to allow an optimal integration of the whole residential buildings into the smart-grids.

Another aspect to take into account is the balancing requirement of the grid, which means that power generation must match at all times the users' demand. This will depend on the flexibility of both producer and consumer. The stakes are still more important because this balance between production and consumption will enable to limit or avoid the congestion issues, breakdown or in extreme case, black-out of the grid [3].

On the other side the increase of renewables share (mainly solar and wind energy) in electricity production imposes a host of constraints on the grid management due to the variable and difficult prediction nature of these energy sources. At the Greater Region level (Wallonia in Belgium, Grand-Est in France, Luxembourg, Rhineland-Palatinate and Saarland in Germany) the energy transition is more advanced in Germany with 35% of renewables in the final energy consumption (11% Luxembourg, 13% Wallonia, 23% France) [4]. It is forecast that the installed renewable electricity in Rhineland-Palatinate within the 2025 horizon will be equivalent to twice the peak electricity demand. The grid management will become harder in these conditions.

Different options can be considered to absorb the excess of local electricity production that could not be injected to the grid. One of them is the electricity production surplus storage (in the form of thermal energy) by means of heat pumps to meet the grid balancing objectives that is the concept of "power to heat". This kind of solution is justified because an important part of total energy consumed in the residential sector is for heating of buildings. The Interreg Va- Greater Region (GR) project PTH4GR²ID (Power to heat for the Greater Region's Renewable Integration and Development) aims to analyse this possibility and try to develop a scheme for the future reorganization of the electricity market. One of the actions of the project aims to evaluate the residential building thermal potential in order to contribute to the grid management in the GR. This paper tries to demonstrate how flexible the buildings are when facing a constraint in their heating system strategy. To evaluate this concept of flexibility with heating load displacement, the thermal behaviour of residential buildings was studied by numerical simulations when submitted to cut-off strategies of the heating system. The simulations were conducted using the TRNSYS software. This paper will present the first results of this analysis as the project is still ongoing.

2. Methodology

2.1. Reference buildings

For the flexibility potential study in the Belgian side of the area covered by the project consortium two reference buildings were chosen to represent the building stock in Wallonia (Belgium). In order to fit with the current state of the real-estate in the Walloon region statistical data from the Federal government of Belgium were extracted and synthetized [5]. The information was also compared to the one provided by previous projects where reference buildings were also defined to represent the building stock of Wallonia [6][7][8][9]. It results that the most representative typology in Wallonia is an old building built before 1945 with a terraced configuration. This kind of building represents about 25% of the Walloon real-estate [3], see *Fig.1*. Another building typology was chosen for the study. It is a recent construction (built after 2006) with a free-standing geometry and it meets the walloon energy performance criteria for a new construction [10]. This type of buildings represents less than 5% of the real estate in Wallonia but for the study it was considered that they have a quickly usable potential in a project promoting the "Power-To-Heat". This type of buildings is very recent with insulation levels compatible to the use of heat pumps, or even already equipped with such a system. On the contrary, the first old building is highly representative of the housing stock, but it may need some refurbishment. This type of buildings could represent a large thermal storage potential because of their thermal mass. In the text, the first building (the old and terraced one) will be called "B1", and the second one will be called "B2", see *Fig.2*.

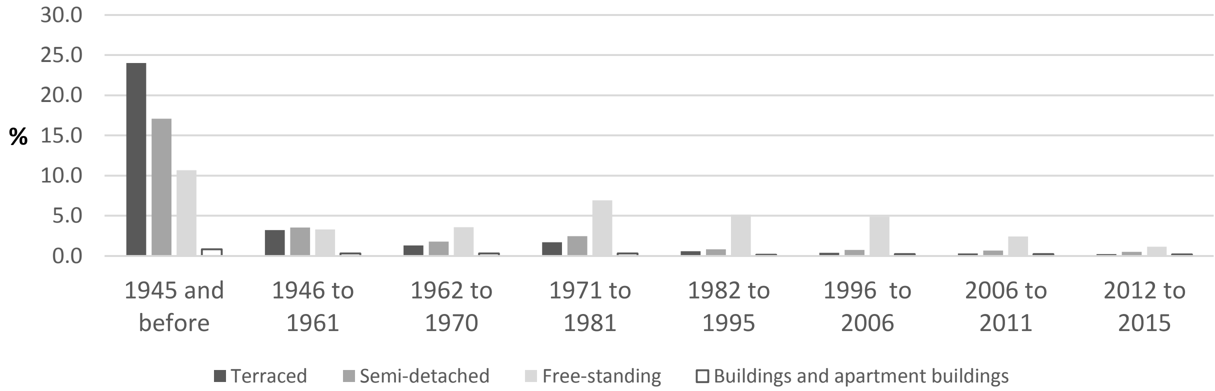

Fig.1. Typology of buildings sorted by year of construction [5]

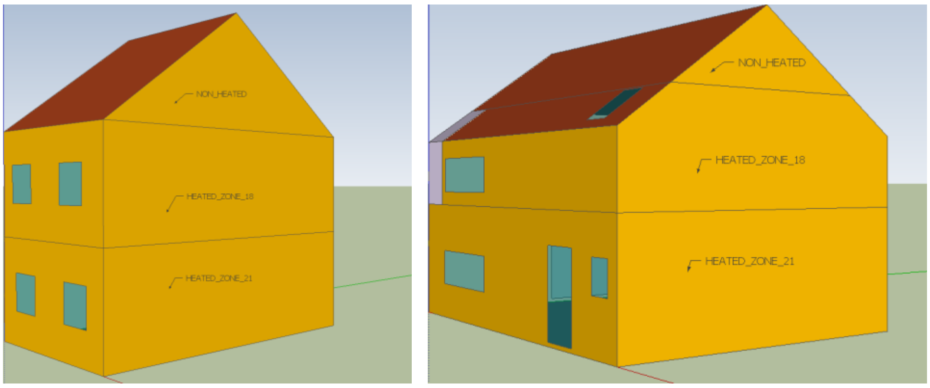

Fig.2. 3D geometries and thermal zoning (3 zones) of B1 (left) and B2 (right) designed with the 3D plugin of TRNSYS (TRNSYS3d) in Google SketchUp.

For each building different scenario of envelope insulation were applied. For B1 model, two cases were defined: one without insulation, as 65% of Walloon real estate [11], and one with a refurbishment strategy where the level of insulation meets the requirements of the energy building performance regulation of Wallonia (called “PEB”) for residential sector with a maximal U value to satisfy for each construction element [10]. Two cases were also defined for B2 model. The first one also meets the PEB criteria and the second variant of B2 is a passive version of the building. The results of energy demand for the four cases were compared to the PEB values for these typologies of buildings. The annual energy consumptions simulated in TRNSYS for each buildings scenarios are similar to the normal observed values for these types of buildings. Its specific annual heating energy demand is lower or equal than 15 kWh/m².an [12]. In order to compare the models, the mean heat transfer coefficient (Um in W/m².K)[13] was computed as shown by *Table 1*.

Table 1. Insulation scenario for each reference building B1 and B2 with global U-value for whole building

Models*	*Description*	*Um (W/m².K)*
B1_base	B1 model without insulation	2.96
B1_peb	B1 model with max. U-values requirements of PEB norm	0.25
B2_peb	B2 model with max. U-values requirements of PEB norm	0.28
B1_passive	B2 model with max. U-values requirements of passive standard	0.16

**The nomenclature in column “model” will be used in the next of this paper to designate each version of building model.*

For B1 and B2 buildings models, a division into three different thermal zones was done as follows:

- non-heated zone,
- zone heated at 18°C in continuous,
- zone heated at 21°C by intermittent heating system, see *Fig.2*.

2.2. Common characteristics of both buildings

In order to compare B1 and B2, some characteristics were assumed common to both buildings. For instance the same schedules for heating system, internal gains (occupation, appliance and lighting) were applied to both buildings. Of course, sizing of the heating system and values for the internal gains have been adjusted to take account of both energy needs and geometry (volumes) differences between the models. The modelling of the heating system has been simplified to a 100% efficiency system, as a consequence no COP is taken into the energy performance indicators. Moreover the heating system is assumed as intermittent between high and low temperature setpoints of 21°C and 18°C respectively. The heating system is assumed as intermittent between high and low temperature setpoints of 21°C and 18°C respectively. The normal system sizing presented a problem for both models because the system wasn't able to reach the high setpoint after less than 2 hours of heating system restart. For this reason it was decided to apply a reheat factor called F_{RH} for each building [14]. This factor represents the over-power added to the initial sizing of the heating system. This allows the high temperature setpoint to be reached for each model in less than an hour. For sake of simplification it was assumed that no ventilation system is installed. No thermal storage other than the thermal mass of the building is considered either.

2.3. Flexibility assessment assumptions

In order to understand how flexibility potential is evaluated here it is necessary to define first what it is meant by "flexibility". In the literature the flexibility can be defined as the capacity at demand side to shift (or avoid) some electrical loads in the time in response to a given signal (e.g. a price signal) [15][16]. Based on this definition the present study is focusing on the more specific ability of the buildings to modulate some electrical consumption related to their heating system. Therefore it was decided to assess the flexibility of reference buildings through the application of a cut-off strategy of the heating system and to study the energy and thermal comfort aspects of such a constraint.

In this study's simulations, "cut-off" does not mean a real shutdown of the heating system but consists instead of a decrease in the set temperature during a certain period of time. Two cut-off scenarios are studied in this paper. The first one is a simple cut-off of two hours between 18h and 20h switching the set temperature from 21°C to 18°C. The second one is the same cut-off as the first one but preceded by one hour of "pre-heating", which means that the room is heated at a higher set temperature (i.e. 22°C). For both cases, the simulation data are generated for a whole year with same applied cut-off strategy every day.

Different indicators are used to assess the flexibility of the reference buildings and to show the influence of cut-off in terms of energy and thermal comfort: the energy impact (*EI*), the overconsumption (*OC*) and the time without discomfort (*TWD*) see *Fig.3*. On the one hand the energy indicators will inform to what extent some consumption related to the heating system can be shifted; on the other hand the thermal comfort indicator (*TWD*) evaluates the impact of shifting those consumptions on the occupants. Those indicators are described more in detail in the next sub-sections.

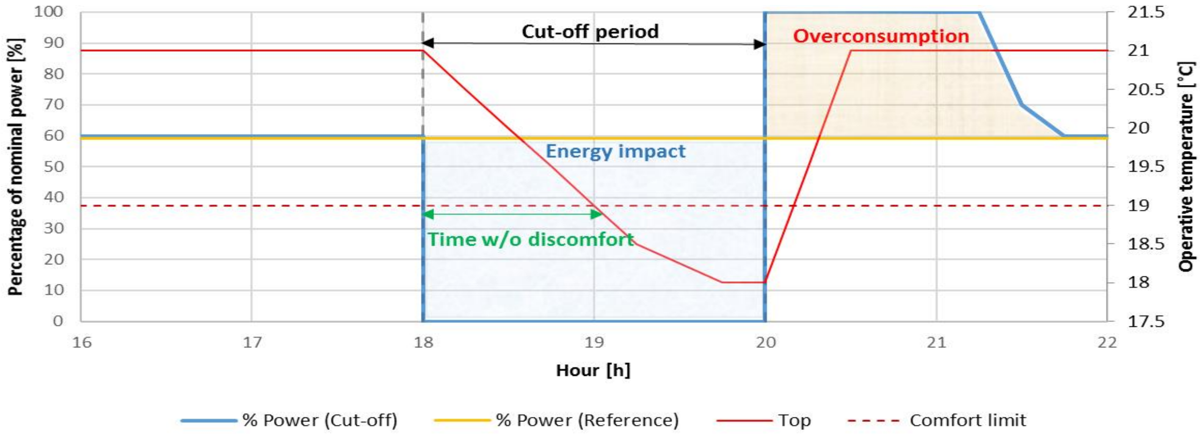

Fig.3. Schematic illustration of the different studied indicators: energy impact, overconsumption and time without discomfort.

2.3.1. Energy impact (*EI*)

The "energy impact" quantifies the energy that will not be spent during the cut-off compared to a reference case without any cut-off neither preheating. Figure 3 illustrates the energy impact as the integration of the reference power minus the integration of the eventual power spent during the cut-off (see blue area on *Fig.3*). In order to calculate this indicator, the reference data in terms of energy consumption of a standard case without cut-off has to be generated at first. This data will thereafter be used as input in cut-off cases simulations to calculate the indicator. As the simulation period is the whole year and as the energy impact varies with the weather conditions, the large numbers of data are presented in the form of a statistical distribution of the energy impact's mean values in function of the average internal and external temperature difference during the cut-off. Moreover for the purpose of objectively comparing the results of the different reference buildings, the *EI* will be reported per unit of area (Wh/m²).

2.3.2. Overconsumption (*OC*)

The overconsumption quantifies the extra energy that is consumed outside the cut-off period compared to a reference case without any cut-off neither preheating. This energy is typically the energy used either for an eventual preheating before the cut-off period or used for the restart of the heating system to reach the standard setpoint. Figure 3 illustrates the overconsumption as being the integration of the power of the cut-off simulation outside the cut-off period case minus the integration of the power spent in the reference case (see orange area on *Fig.3*). For this reason, and as for the energy impact, the calculation of the overconsumption needs the reference data of energy consumption for standard case without cut-off, which will be used as input data in cut-off simulations. The results are also presented as a statistical distribution of the overconsumption's mean values in function of the average internal and external temperature difference during the cut-off and reported per unit of area (Wh/m²).

2.3.3. Comfort indicators: Time without discomfort (*TWD*)

The time without discomfort calculates the time during which an occupant can stay in the building without having any thermal comfort inconvenience caused by the cut-off. This indicator gives a good estimation of how long a cut-off strategy could be applied. The *TWD* is calculated as the time it takes after the beginning of the cut-off to the operative temperature to decrease below a comfort limit that has been fixed to 19°C. The lower limit of comfort of 19°C has been chosen in order to have, according to Fanger study, 15% people dissatisfied (taking into account a clothing of 1 clo, a metabolic activity of 1,2 met, 50% of relative humidity and an air velocity of 0,15 m/s) [17]. The results of this indicator are presented as a statistical distribution of the mean time without discomfort in function of the average internal and external temperature difference during the cut-off.

3. Results for the two reference buildings

3.1. Results for Energy Indicators

The energy impact (*EI*) is the highest for building with lowest insulation level, see *Fig.4*. The B1_base model (description in *Table 1*) reaches its maximum of *EI* close to 50 Wh/m² compared to between 25 to 30 Wh/m² for the "PEB" models (B1 and B2) and around 20 Wh/m² for B2_passive model. A higher energy shifting during the cut-off in B1_base model is directly related to the lower energy performances. For PEB models (B1 and B2) where insulation levels are obviously higher than B1_base model, the *EI* is lowered by around 50% compared to the non-insulated B1 building. This observation is true for intermediate temperature differences (Δ*T*, between 10 and 20°C). For the passive case (B2_passive) the *EI* is lowered between 86 to 100% compared to the PEB models (B1 and B2).

Energy impact also increases much more rapidly with the Δ*T* in the B1_base model. If the B1 model, with lower insulation performances reaches its maximum *EI* shortly after 5°C of Δ*T*, the increase of *EI* already slows when the Δ*T* increases between 13 and 17°C for the two PEB models and 25°C for B2_passive model. The *EI* tends to stabilize to a certain value because the temperature in the room is lower than the 18°C setpoint and because the heating system must be switched on again. For a given model the stagnancy of *EI* is observed for higher Δ*T*. If models are compared to each other the stagnancy of *EI* appears for lower Δ*T* when the envelop performance is weaker.

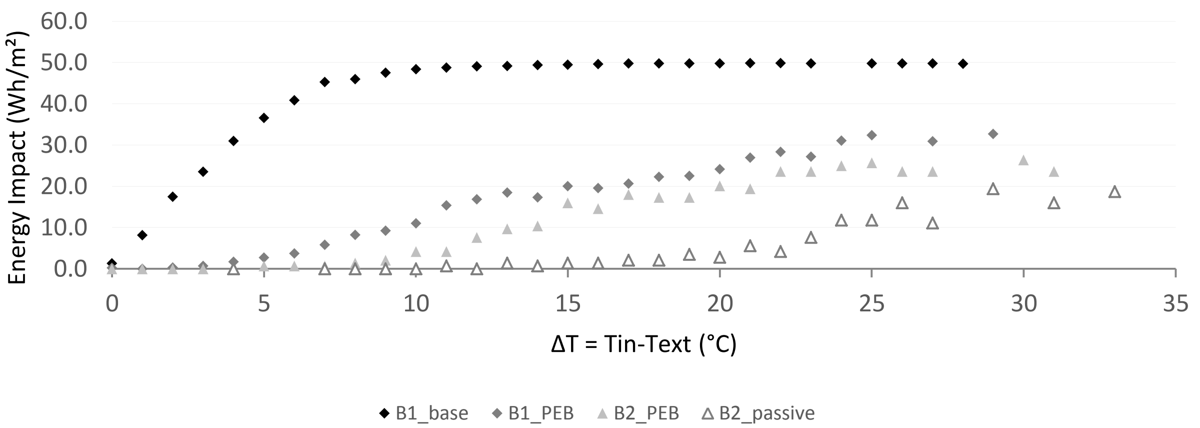

Fig.4.Energy impact results for scenario with a cut-off of 2 hours for different versions of B1and B2

For the scenario of one hour preheating at the set temperature of 22°C before the cut-off the results are in the same range of values as for the cut-off scenario without preheating, see *Table 2*. The difference between the two scenarios is noticeable in B1_base model but for the other models pre-heating doesn't seem to have a significant impact on the *EI*. It seems that even if the Δ*T* increases, the impact of pre-heating no longer affect the potential energy savings made during the cut-off. It could be possible that the pre-heating duration of one hour or the temperature of pre-heating or both are insufficient to have any impact on the *EI*.

Table 2. Energy impact values (Wh/m².an) comparison between cut-off strategy scenarios

Δ*T* (°C)	Cut-off strategy	B1_base	B1_peb	B2_peb	B2_passive
0	Cut-off	1.3	0.2	0	0
	Pre-heating + Cut-off	**6.0**	**0.2**	**0**	**0**
5	Cut-off	36.6	2.7	0.7	0
	Pre-heating + Cut-off	**35.8**	**1.8**	**0**	**0**
10	Cut-off	48.4	11.0	4.2	0
	Pre-heating + Cut-off	**50.9**	**11.7**	**4.2**	**0**
15	Cut-off	49.5	20.0	15.9	1.4
	Pre-heating + Cut-off	**52.3**	**20.2**	**13.9**	**1.4**
20	Cut-off	49.8	24.1	20.1	2.8
	Pre-heating + Cut-off	**53.3**	**24.4**	**19.4**	**2.8**
25	Cut-off	49.8	32.3	25.7	11.8
	Pre-heating + Cut-off	**51.7**	**31.1**	**25.7**	**11.1**
30	Cut-off	-	-	26.3	19.4
	Pre-heating + Cut-off	**-**	**-**	**26.3**	**19.4**

3.2. Results for overconsumption

The overconsumption (*OC*) follows the same trends but to a less extent than for the *EI*, and once again the highest *OC* are observed for models with lower insulation. Figure 5 shows that the B1_base model reaches a maximum overconsumption near 40 Wh/m² compared to 10 Wh/m² for B2_passive model and intermediate values between around 20 Wh/m² for both B1 and B2 PEB-standard buildings. The increase of the overconsumption related to the increasing Δ*T* is also similar to what has been observed for the *EI*. The *OC* for B1_base model seems to stabilize around a Δ*T* of 10°C whereas values for the B2_passive model seem to reach a maximum when the Δ*T* is above 25°C. At last, the increase of *OC* in the PEB models (B1 and B2) is slowing respectively at 13°C and 17°C. For intermediate Δ*T*, between 10°C and 20°C, the overconsumption decreases for more than 50% between B1_base model and the PEB models (B1 and B2) and till over 84% between the PEB models (B1 and B2) and the B2_passive model.

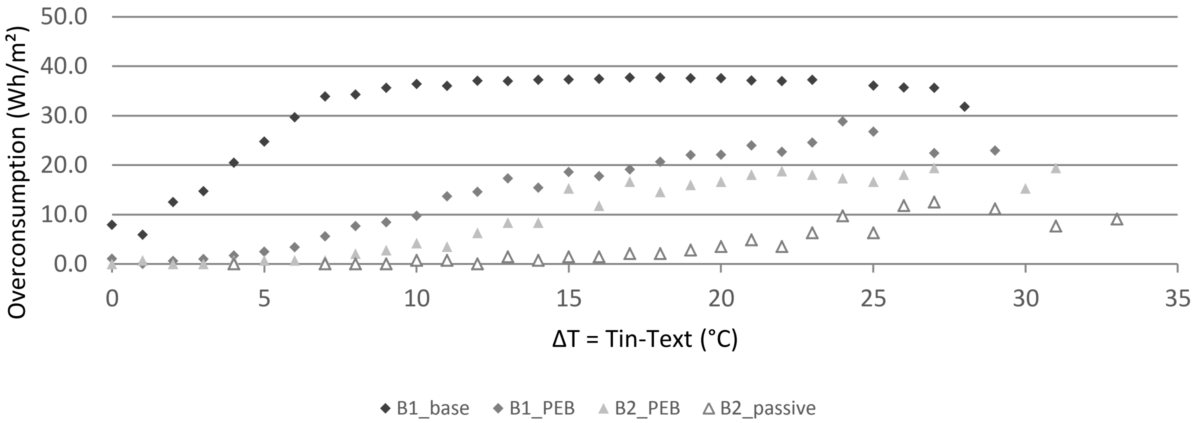

Fig.5. Overconsumption results for scenario with a cut-off of 2 hours for different versions of B1 and B2

Analysis of the preheating impact on the overconsumption shows slightly changes compared to the previous cut-off strategy, see *Fig.6*. The most important differences can be observed with B1_base model where *OC* for a pre-heating scenario is higher than the scenario without pre-heating. This observation is also true for the PEB models (B1 and B2) but in the passive case the difference between cut-off strategies scenarios are not significant.

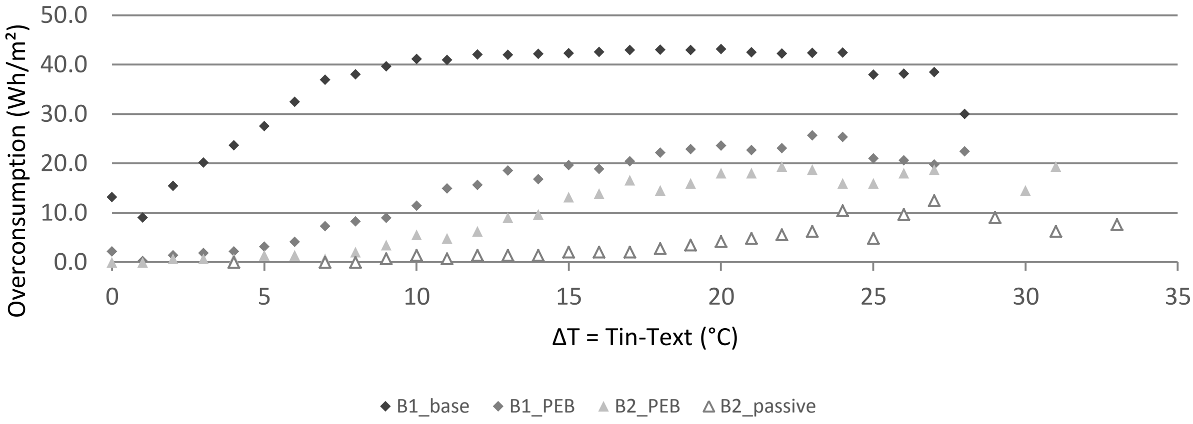

Fig.6. Overconsumption results for scenario with one hour preheating and a cut-off of 2 hours for different versions of B1 and B2

Finally comparing *EI* and *OC* allows evaluating to what extent application of a cut-off strategy will affect energy consumption in building models. These two indicators are compared in *Fig.7* for the PEB models (B1 and B2). For Δ*T* higher than 4°C, the overconsumption is systematically below the *EI*, which means that implementing a cut-off strategy results in a global energy saving for the building. The ratio *OC*/IE is in average 91% between Δ*T* of 4°C and 24°C. This ratio decreases for higher Δ*T* (over 24°C of difference) till 70% and may be slightly over 100% for Δt lower than 4°C. This can be explained by the fact that the *EI* for a low Δ*T* will be relatively insignificant (low consumption) but could still experience overconsumption due to the restart of the heating system at the standard set point (21°C). At the opposite, with the highest Δ*T*, the observed energy consumption in the reference case is already high due to the large temperature difference and consequently causes a decrease in the ratio *OC*/*EI*. The comparison of the energy indicators for the other reference buildings shows similar behaviours.

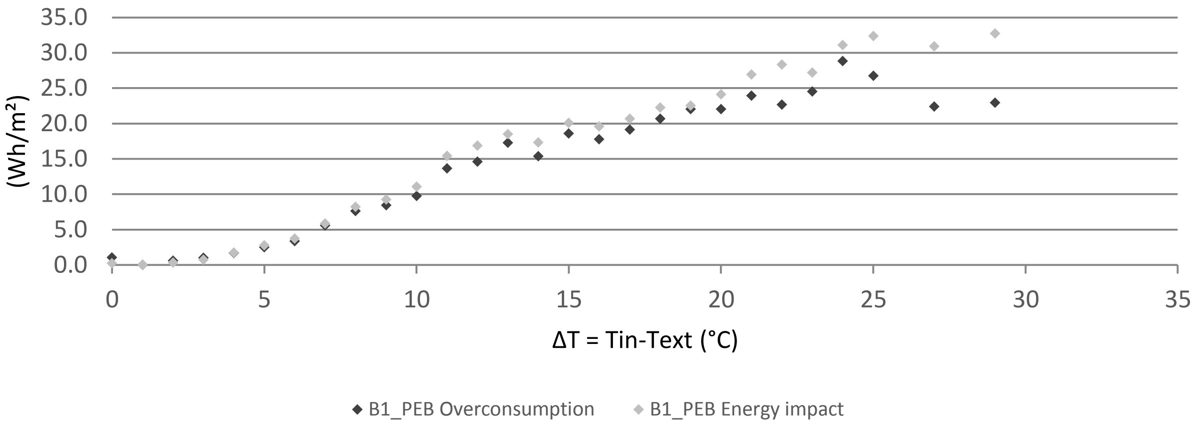

Fig.7. Overconsumption compared to energy impact - results for scenario with a cut-off of 2 hours for B1_peb model.

3.3. Time without discomfort (*TWD*)

According to *Fig.8*, the *TWD* for a non-insulated building drops dramatically with the application of a cut-off strategy, even for relatively low Δ*T*. The B1_base model has a *TWD* decreasing rapidly with only 3°C of difference between inside and outside and brings the occupants instantaneously in discomfort with a Δ*T* beyond 10°C. The models, B1_peb, B2_peb, and B2_passive keep the *TWD* at 2h for a Δ*T* respectively below 13°C, 11°C and 22°C, meaning there is no discomfort caused by the cut-off for those ranges of temperature difference between the room and the outdoor. Beyond these ΔT limits, the *TWD* decreases rapidly. Still respectively for the previous cited models, the *TWD* is of 1h for a ΔT of 21°C, 15°C and 26°C and becomes zero for a ΔT of 27°C for the B2_peb model and it still remains around 30 and 18 minutes of comfort for B1_peb and B2_passive respectively. For intermediate values of ΔT (between 10 to 25 °C) only the passive model will be able to avoid any thermal discomfort during the two hours of cut-off.

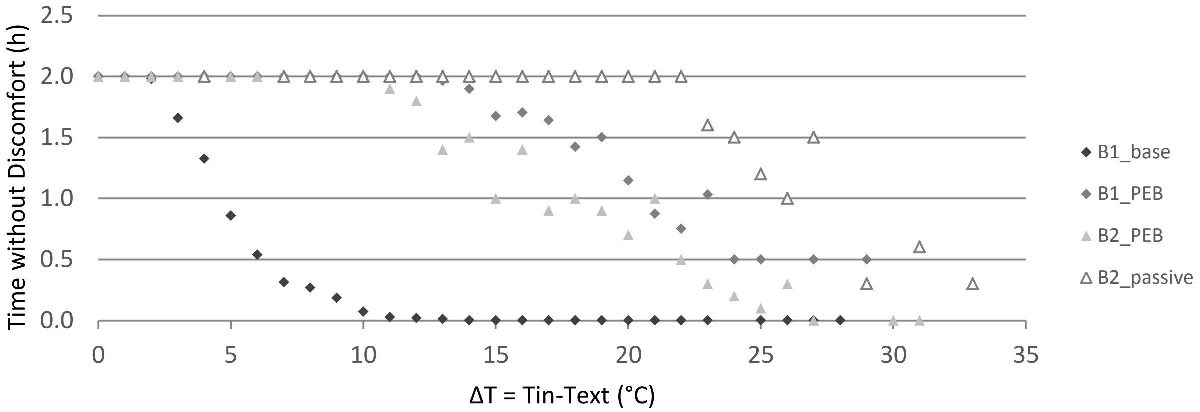

Fig.8. TWD results for scenario with a cut-off of 2 hours for different versions of B1 and B2

The setup of a preheating before the cut-off should logically extend the *TWD* observed in the first cut-off strategy. According to *Fig.9*, the effect of the preheating is slightly effective.

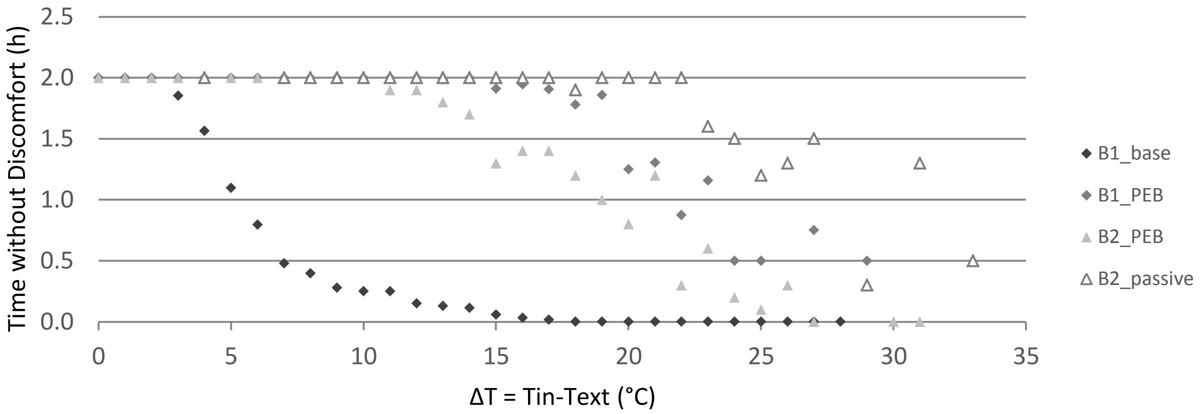

Fig.9. TWD results for scenario with one hour preheating and a cut-off of 2 hours for different versions of B1 and B2

4. Discussion

The results shown in this study are preliminary and some issues are to be pointed out. The first remark is about the data presentation chosen to express the different indicators. Indeed expressing *EI* and *OC* by reference area allows comparing buildings with each other but at the same time it does not reflect these indicators' impact on the whole building.

The second remark is about the dispersion of data for important values of ΔT. In fact for these extreme cases, where outside temperature is lower than -4°C (T_{in}-T_{ext} >25°C), there is a lack of representativeness of the simulation results. Considering the fact that indicators are evaluated by means of daily average during the cut-off, the averaging effect is no longer observable for ΔT data which are less representative on one year of simulation. The other side effect of the averaging of the value of indicators for a given ΔT is the dilution of the effects of other meteorological conditions, such as solar gains during the 2 hours of cut-off, on the obtained results.

It is difficult to compare the *TWD* results between B1 and B2 because of geometry difference between models. Indeed, B1 is a smaller building than B2, especially in terms of volumes while B2 is closer to actual residential constructions with higher room volumes than B1. Another difference is about the orientation of the buildings and their glazed area. B2 has the largest ratio of glazing surface which is mainly south and west oriented. For all these reasons, the comfort evaluation for B1 and B2 cannot be compared on a same basis.

5. Conclusion

In order to integrate an old building in a smart-grid solution using the flexibility of its heating demand, it is essential to go firstly through a phase of refurbishment. According to the results, the application of a cut-off of the heating system to such a building causes important thermal comfort problems even with small external/internal temperature differences. The occupants are for instance instantaneously in discomfort with ΔT of only 10°C. Applying a refurbishment strategy increases drastically the *TWD* but does not avoid having the two hours of cut-off without discomfort for more important ΔT. On the contrary, the observed energy indicators show that the energy that can be shifted through a preheating and/or cut-off strategy decreases when improving the energy performances of the building. That means that, without a specific thermal storage system, if the flexibility of the building is increased concerning the comfort aspects, inevitably it will decrease in terms of possible shifted energy. For the recent building B2 it seems that the impact of cut-off in the heating system is lower on the comfort than B1 but the part of loads that could be displaced is lower too. This means that less energy could be displaced in case of well insulated buildings but comfort could be maintained longer during a heating cut-off. In this paper the impact of a thermal storage was not assessed. Indeed such a system could improve the displacement of energy loads. Another point to integrate in the continuity of this work is the communication with the network in order to take into account when the network is saturated and the heating system must be cut off.

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Nomenclature

EI : Energy Impact, Wh/m²

GR : Greater Region

OC : Overconsumption, Wh/m²

T_{ext} : Internal air temperature, °C

T_{in} : External air temperature, °C

TWD : Time Without Discomfort, h

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