'Power gap' in Heat Load calculations – EN12831-1 versus monitoring and simulation results.

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Abstract. For a long time, research and policy has focussed on reducing energy demand and increasing energy efficiency. However, with increasing renewable energy production, also the profile of this energy demand and the potential for demand side management needs to be assessed. Moreover, due to energy distribution restrictions, simultaneous power peaks on the grid need to be reduced or shifted. Regarding dwellings, for which heating still determines the bulk of the energy use in most of the EU, this means that reducing, or at least better characterizing and managing the heat load becomes more important. The current method for the calculation of the design heat load, according to the EN12831-1, is a static method and tends to overestimate the heat load.
This research based on 50 in-situ measurement cases suggest indeed an oversizing between 25% and 100%! Further linear regression analysis and a parametric study based on dynamic building simulation was used to pinpoint possible physical causes for this 'power gap'. Following possible causes could be identified: The standard assumes a 100% simultaneous occurrence of all worst case boundary conditions (low design outdoor temperature – relatively high wind speeds and pressures leading to high infiltration losses – no solar gains – no internal heat gains) which does not occur in reality. Furthermore, the heat load for the heat generator (at building level) is defined as a simple sum of the heat load of each individual space. This might also lead to oversizing, as infiltration or ventilation are not at their maximum in all spaces at the same time. Finally, the difference between monitoring and simulation results suggests that users adapt their behaviour below 0 °C, by reducing their comfort expectations (e.g. less window opening) or other heat loss reducing actions (e.g. keep inner doors closed so that less heat is transferred to unheated zones). Formal conclusions could be used for eventual future standard improvements.

Keywords. Heat load, power gap, sizing of heating systems, thermal inertia, thermal comfort, user behaviour.

1. Importance of heat load

With the focus shifting from increasing renewable energy production towards energy distribution issues and finding a continuous grid-match between supply and demand, the need for correct heat load estimations of buildings also increases. Whereas calculations in the past mainly focused on comfort and 'enough power at any moment', a better understanding of the profiles of the required heating power is necessary to bring it in line with renewable energy availability. In addition, the investment costs of highly efficient systems such as heat pumps are more dependent on the installed heat capacity compared with classic fuel burning boiler systems. A clear view on power needs is also required for the sizing of thermal grids, heat distribution and emission systems, geothermal sources and heat storage systems.

It is common practice to adapt distribution and emitter system temperatures in accordance with the real load in order to improve thermal comfort and to optimise the performance of the heating system. For that purpose, a heating curve, often expressed as a linear relation between the outdoor temperature and the distribution medium temperature is used. This assumption fails on various grounds; the heat load does not only depend on the outdoor temperature but also, among others, on wind, solar and internal gains, resulting in a wide spread of actual heat loads at a certain outdoor temperature.

On top of all that, in order to obtain a grid-match between supply and demand of power, a clear view is required over the load profiles for the following hours or days, and the possibility to shift this load by adapting temperature comfort profiles or adding storage capacity.

2. Calculation standard

Generally, the design heat load is calculated in accordance with the standard EN 12831-1:2017 [1] and its country specific annexe NBN EN 12831-1 ANB:2020 for Belgium [2]. Although this calculation method is elaborate, requiring a lot of input data, the confidence in the market of the resulting heat load is not very high. An oversizing of 20 to 30 % is suspected.

Major possible issues are:

- The heat load is only calculated at the lowest possible outdoor temperature, assuming a simultaneous occurrence of all worst case conditions (no sun, strong wind, no internal heat gains…)
- The lowest possible outdoor temperature is determined on a 24h basis and the resulting heat load is a 24h average, assuming sufficient damping by the building thermal mass. Questions arise whether at 1h time scale higher heating installation power is required, especially in buildings with low thermal inertia.
- The standard calculates a heat load for every room, adding all the individual loads to obtain the required heat load on building level.
- The leak infiltration ratio (LIR) to convert a measured infiltration rate at 50Pa to an infiltration rate at more realistic 24h averaged pressure conditions, is set at 0.1 but has little scientific basis. On building level, the sum of all maximum room infiltrations is assumed.
- Several reheat factors are proposed for temperature setback schemes, taking into account the building mass, the setback temperature, the setback time as well as the reheat time. These factors assume a heat distribution and emission system with step function response (without any inertia) which is very unlikely.
- Room temperatures are defined as operational temperatures, in accordance with the required thermal comfort. However, the calculation uses room air temperatures, that are assumed to be equal with the operational temperatures. In reality, the difference between both depends strongly on the insulation level of the building envelope.
- The standard EN 12831-1 looks to heating, the EN 12831-3 to domestic hot water. The required combined power of both is only assessed in EN 12828 in a very general way.
- The standard uses several assumptions and default values, supposed to lead to a heat load 'on the save side'. A more statistical sound method should be used to treat the distribution of actual values and distinguish dependent and non-dependent parameters and statistical distribution. This should give the designer a better insight in the average safety margins.

3. Methodology

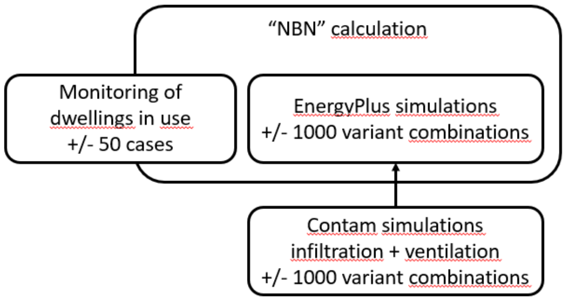

Figure 1: Overview of the set of monitoring, calculation and simulation cases

The research primarily focussed on the comparison of actual used power in dwellings, and the calculated power according to the standard. A monitoring campaign on dwellings provided the necessary data in various weather conditions and in real-life use. However, for a number of monitoring cases some necessary building and user data was missing and the corresponding standard calculation could not be performed. Moreover, the set of the remaining 13 cases is limited in quantity and variation (statistically not evenly distributed), so that is difficult to deduce detailed conclusions from only this data set.

Therefore dynamic simulations are added, with a parametric analysis parallel to the monitoring campaign, aiming to understand the origin of differences between the static standard approach and dynamic building behaviour as well as the influence of individual parameters. Contam simulations of infiltration (and interaction with ventilation) were performed and the resulting air flows are used in the heating demand simulations in EnergyPlus,

4. Monitoring of dwellings

The power delivered to the heating system of some 50 dwellings has been monitored during 2 heating seasons, with a measurement frequency between 5 minutes and 1 day. The resulting heating power is related to the outdoor temperature in next figures, and compared with the calculated load, according to the Belgian annex (referenced in figures as 'NBN'). The resampling time is set at 24h to correspond with the daily averaged approach in the standard. Resampling on monitoring data with 1h base generally leads to data that is more difficult to evaluate, since 1h power profiles depend more on the control strategy and domestic hot water (DHW). Although the standard calculation only focusses on the heat load at the (lowest) design temperature (depending on the region, i.e. -7°C in the centre of Belgium), the required power is assumed to be proportional to the temperature difference (between indoor and outdoor), and therefore expressed as a straight line in Figure 2.

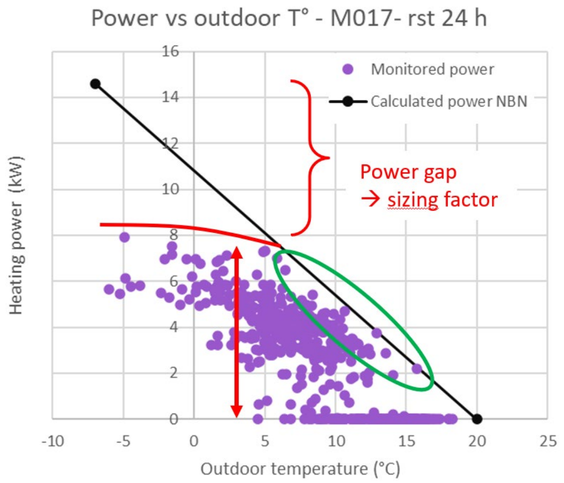

Figure 2: Measured compared to calculated heat load - case M017 - resampling time 24 h

The case in Figure 2 reveals:

- The monitored heating power shows a high variability, even at the same outdoor temperature.
- Within the temperature range between 5 and 15 °C, the maximum used power corresponds closely with the assumed calculated heat load, suggesting that the EN/NBN-standard assumptions in this temperature range are quite correct.
- At lower temperatures (below 0-5°C) the curve with measurement maxima tends to deflect downwards, resulting in a substantial power gap with the standard at the design outdoor temperature (-7°C).

Similar observations could be made for other measured cases. For a sizing factor defined as the ratio between the maximum monitored power and the calculated heat load according to the NBN standard calculation, the values vary between 0.4 and 0.8, as shown in Figure 3 for the 13 most relevant cases. This means that in some dwellings, the actual used heating power is only 40 % of the calculated heat load.

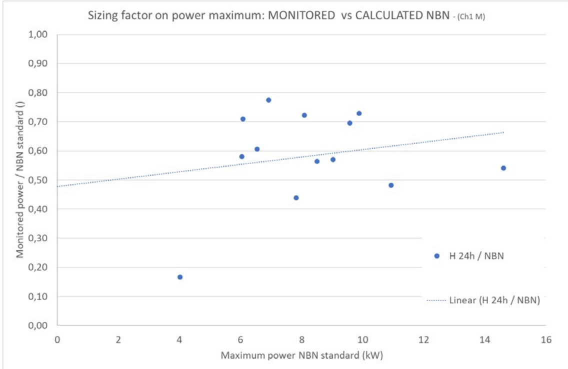

Figure 3: Sizing factor for 13 monitored cases - resampling time 24 h

To understand the lack of correspondence between monitored power data and the pure temperature difference based relationship, following research steps were undertaken:

- A polynomial regression on the monitoring data gives a better understanding of the individual influence of outdoor temperature, wind speed and solar radiation.
- Next paragraphs discuss the use of infiltration simulation (using CONTAM®) and a whole building simulation model (using EnergyPlus®) to analyse some 1000 different variants in a parametric study.

Various polynomial regression equations were evaluated on 10 monitoring cases to find the best fit. A number of the evaluated equations were based on the assumed physics, other evaluated formats were not based on the physics. Used parameters are temperature difference (indoor-outdoor), wind speed and solar irradiation on a horizontal plane Both linear equations and power functions were used. The evaluation of the resulting polynominals was based upon following statistical criteria; a minimal Akaike Information Criterion (AIC) [3,4], a minimal Bayesian Information Criterion (BIC) and average error, but a maximal Pearson correlation coefficient (Rpearson) [5].

Finally the best correlation showed to be:

$$\boldsymbol{\Phi} = \boldsymbol{f1}(\boldsymbol{\theta_{int,i}} - \boldsymbol{\theta_e}) + \boldsymbol{f2w}(\boldsymbol{\theta_{int,i}} - \boldsymbol{\theta_e}) + \boldsymbol{f3Isol,h} + \boldsymbol{c1} \quad (1)$$

with Φ the heat load, θ_{int} the indoor temperature, θ_e the outdoor temperature, w the wind speed, $I_{sol,h}$ the solar irradiation on a horizontal plane (all variables daily averaged) and *f1, f2, f3, c1* different constants. Applying this equation to the measured weather data set, results in **Figure 4** for case M017.

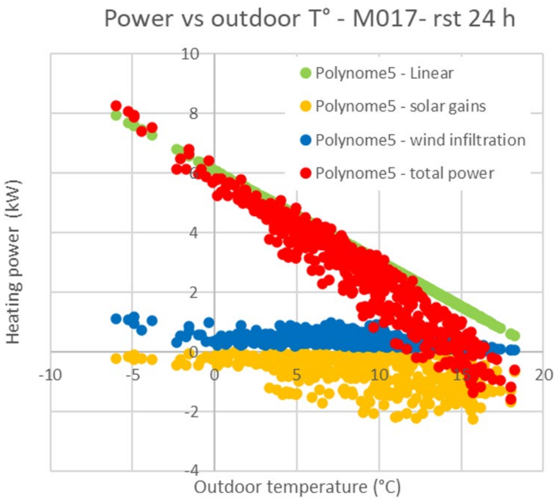

Figure 4: Monitored power breakdown to weather parameters - case M017 – rst 24 h

A distinction can be made between:

- Effects linear to temperature difference such as transmission losses and buoyancy infiltration (stack effect) – green dots.

- Effects related to solar radiation, expressed as a negative heat load – yellow dots. Quite a number of days present hardly any solar gains, but very cold days seem to offer always some gains, although lower values and on daily base, unlikely to be a major source of the curve flattening. At higher outdoor temperatures, solar gains can be very substantial, compared to the total load and even compensate heat losses completely (as from 12 °C for this case).

- Effects of wind, with the wind speed multiplied by the temperature difference – blue dots. Important to notice is that the wind induced heat load at design outdoor temperature (-7 °C in this case) is of the same order of magnitude as the heat load at outdoor temperatures between 5 and 10 °C and could explain the power curve flattening to some extent. This effect finds its origin in the wind distribution in most Belgium weather stations; at very low temperatures, the wind speed is much lower than at higher outdoor temperatures, as shown in **Figure *5***. Be aware that this profile can be different in other climate zones; in Belgium mild South-West winds are prevailing, certainly at higher wind speeds.

Cases with high building envelope permeability present higher wind heat load, reenforcing this flattening effect.

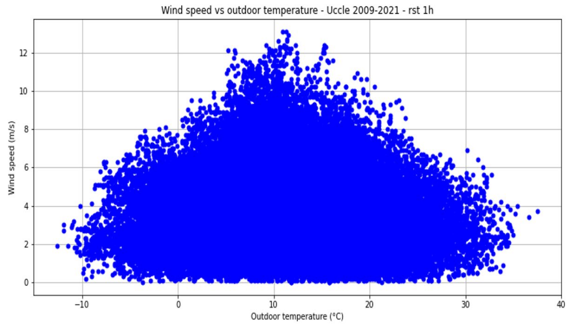

Figure 5: Wind speed versus outdoor temperature – rst 1 h based on RMI data of Uccle (2009-2019) (6)

As a conclusion on this regression analysis, the heat power curve flattening effect can be only partly explained by the absence of days that combine a 100% simultaneous occurrence of power demanding parameters (temperature – wind for infiltration – no solar gains). Other sources of this effect can only be assumed based on the monitoring campaign, not proven. At low outdoor temperatures the occupiers might change their habits: reducing ventilation and IAQ expectations, keeping outdoor (and indoor) doors closed more carefully, reduce the thermal comfort demands, ….

Some other interesting observations can be based upon the monitoring results:

- The monitored maximum power on 1h basis cannot be used for analyses of the real required heating power because this maximum heating power is influenced by the heat generator and its control; especially during reheat intervals the generator will operate at its maximum heat power, but also at other instances the developed heat output can be higher than strictly needed. For this reason most of the analysis is done on a 24h basis.

- Apart from reheat requirements resulting from set-back schemes (considered by the heat load standard in a rather rough way), reheat after priority given to DHW (out of scope of the standard EN 12831-1), we could observe another (third) reheat occurrence, generally not taken into account. In case of underfloor heating, with substantial thermal inertia, this emitter will cool down completely to room temperature when heating is not required for quite some hours, e.g. on a sunny afternoon during a colder day. At sunset, with the heat demand ramping up, the high inertia emitter isn't able to supply this load at once, because it's capacity should be reloaded first. This "high inertia emitter reheat" load is generally not taken into account, and might require some additional power or alternatively an adapted control strategy.

- The standard calculates the design heat load as a 24h average, assuming sufficient damping in the building. Monitoring shows however some important day variations, for instance on cold days with sunny afternoons but very cold mornings. Regardless the 3 above mentioned reheat effects, one could assume that the heat load on shorter time basis (1- 4 h) will be higher, but this is not actually taken into account in the standard. These issues were investigated by dynamic simulation.

5. Infiltration simulation

In the Belgian standard, the leak infiltration ratio (LIR) to convert a measured infiltration rate at 50 Pa to an infiltration rate in real pressure conditions, on a 24 h basis, is set at 0.1. The European standard suggests more differentiated values, taking into account the number of external facades, the height above ground level and the zone height as well as the shielding, but without strong scientific basis.

Based on 4 dwelling models and the multizone airflow simulation software CONTAM® [7,8], the leak infiltration (and ratio) were defined using the combination of a set of variables such as building orientation and wind shielding, various airtightness levels (between 1 and 12 (m^3/h)/m^2) and leak distribution, the infiltration was simulated for 10 year weather data (2009-2019) from 3 Belgian locations. A total of 1000 simulations were run and evaluated. A first observation is that the infiltration maximum is higher at moderate outdoor temperatures (as wind reaches higher values between 5 and 10 °C) than at the design outdoor temperature (between -6 and -11 °C in Belgium). This could partly explain the curve deflection observed in the monitoring results (§ 4). Further evaluation is limited to the low design outdoor temperature. Another important element is that infiltration is only accounted as real infiltration when the cold air entering the building exceeds the ventilation requirements. This means that infiltration (and the LIR to be used) is strongly influenced by the ventilation system itself and both cannot be accessed independently; if another ventilation system or control strategy is used, the LIR will alter accordingly.

Figure 6 shows an example of the influence of the Meteorological conditions in 3 locations, with Middelkerke located at the sea coast, Uccle in the country centre and Humain in the Eastern and higher part of Belgium (295 m above sea level). We observe median values far below the Belgian LIR value of 0.1, a value that is closely approached in less than 1 % of the cases. We also obtain some higher values for Humain, where the wind absolute maximum values are lower than at the coast (Middelkerke), but higher wind speeds are observed at the lowest outdoor temperatures.

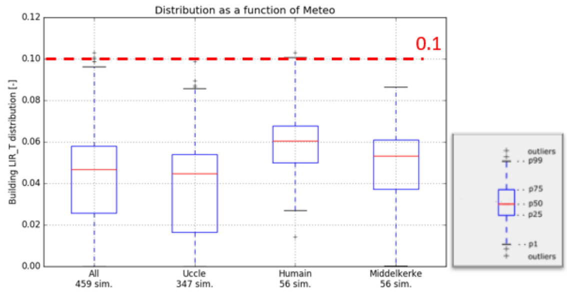

Figure 6: Infiltration ratios as a function of Meteo

Other observations are:

- The LIR values for individual rooms can be much higher than for the building as a whole. A more correct heat load calculation should make a distinction between building level (to size the heat generator) and individual rooms (to size the emission system), with infiltration ratios 2-3 times higher in the latter.
- The resampling time to evaluate the LIR can strongly influence the results, as shown in **Figure 7**. For energy calculations, an resampling time of 1 year results in an LIR of 0.037 (= 1/27). For heat load calculation, the p99 values are 2.5 times bigger on 24 h, and even 3 times on 1 h resampling time.

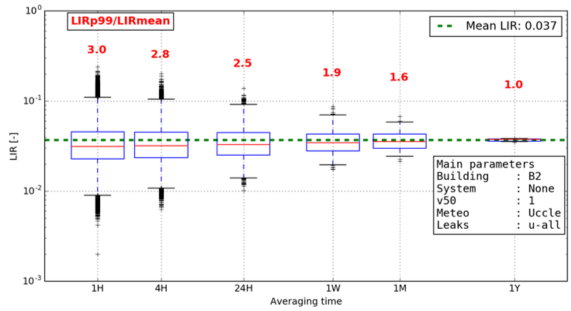

Figure 7: LIR as a function of resampling time (1 specific variant)

6. Heating power simulation

The dynamic building simulation software EnergyPlus® [9] was used to calculate the required heat load for 3 dwelling typologies (row house, semi-detached and lowrise dwelling) and this for each room in the dwelling, as well as the total simultaneous power for the building as a whole. The general set-up of the simulations can be found in the Ph.D of Stijn Verbeke [10]. The particular set of approximately 1000 variants consists of 3 different locations (weather files), 4 building envelope insulation level and 4 infiltration rates (input from the Contam simulations of § 5), 3 solar transmission values of glazing, 3 ventilation systems with different control options, 3 occupancy schedules and internal heat gains, 3 thermal inertias, combined with different temperature and setback schedules.

Regarding the weather files, a selection of cold waves amongst measured climate data of three Belgian locations between 2010 and 2020 was made, so that the dynamic simulations could be run throughout a representative but harsh winter period. Attention is paid to select the real accompanying solar and wind data with these temperature data so that realistic conditions are simulated. It should be noted that this is often not the case when using commercially available datasets for Extreme Cold Weather. This can lead to surprising results; for most of the 1000 variants, the simulated daily maximum heat load isn't reached at the lowest temperatures (daily averaged -10°C for Uccle in February 2012), but at a rather dark December day with an average temperature of -3°C.

The results can be expressed in a similar way as for the monitoring cases in § 4 (heat load in relation to outdoor temperature, resampling time 24 h, compared to the linear assumed calculated heat load according to the Belgian annex ('NBN'). Figure 8 shows this for one specific variant and reveals that the simulated power shows substantial variability at the same outdoor temperature, but less than in monitoring cases, suggesting an underestimation of the variability, probably related to the boundary conditions and user behaviour (e.g. window opening is not considered in the simulation model). The simulated power exceeds the NBN assumptions between 0 and 15 °C. We also observe some downward curve deflection at below 0°C, resulting in a power gap, but smaller than observed in most monitoring cases.

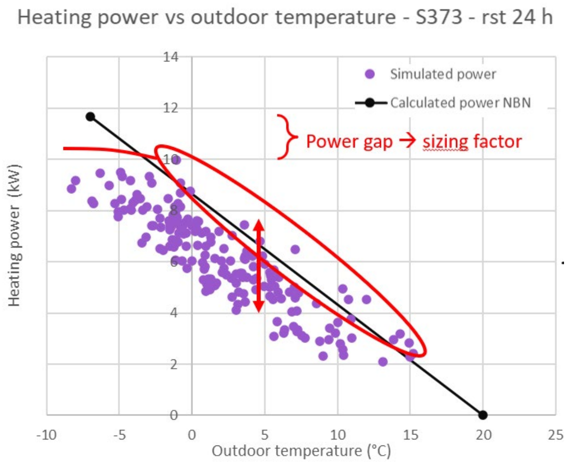

Figure 8: Simulated heating power (building) versus outdoor temperature - variant S373-rst 24h

When applying the same polynomial regression as for monitoring (see § 4), Figure 9 is obtained. We observe some power variation at the same outdoor temperature, as a result from wind and solar influence and some modelled variation in the user behaviour regarding temperature set point and internal heat gain profiles. Lower "wind power" below -5°C, and to a smaller extend the presence of some solar gains, lead to a downward power curve deflection, and, for this variant, to a small power gap.

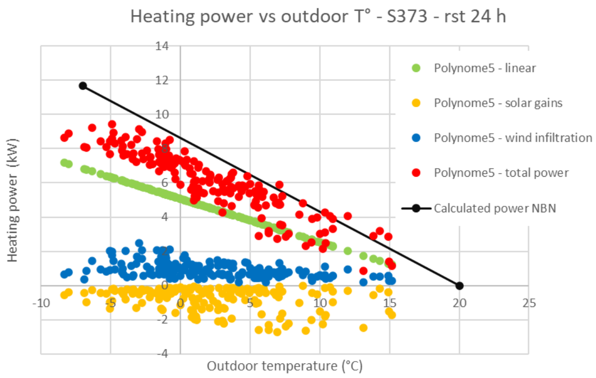

Figure 9: Simulated power breakdown to weather factors - variant S373 – rst 24h

In average a sizing factor of about 0.8 is obtained from the simulations, which is considerably higher compared to the average measured value. The simulated daily average loads are thus higher than the daily measured heat loads and closer to the calculated values following the Belgian annex. Moreover, for quite some variants, the simulated power even exceeds the calculated heat load, suggesting that the standard could underestimate the required power, as can be observed in Figure 10 for the variants with sizing factors above 1.

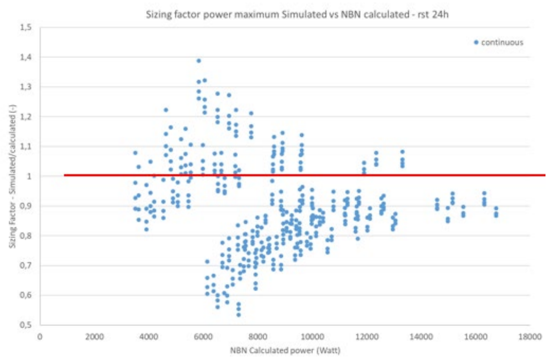

Figure 10: Sizing factor of simulated variants (continuous heating only, well insulated dwellings)

The highest differences in sizing factor are obtained for the different ventilation systems, suggesting that some of the ventilation parameters are not well taken into account in the standard. However, since the interactions between infiltration and ventilation flows was not easy to model, it could be due to modelling issues as well. Further research and analysis should help to scrutinize these results. We can also notice that when the infiltration rates increase, leading to higher NBN calculated heat loads, the sizing factors approaches 1.

While in Figure 10 all dwellings had a good insulation quality, in Figure 11 this insulation quality is varied from a passive standard (Uva – light blue, the lowest heating powers at the left) until non insulated dwellings (Uvi – dark blue – highest heat loads at the right). For the three building types (row house, semi-detached and lowrise dwelling) the same trend is clearly showing; the sizing factor evolves from circa 1 for the best insulated dwellings to circa 0.55 for the worst insulated dwellings.

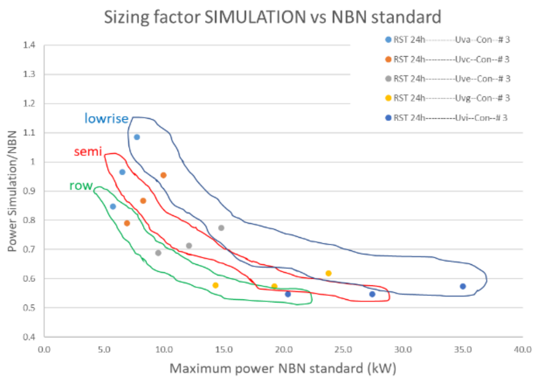

Figure 11: Sizing factor of simulated variants (continuous heating only, varying insulation quality with an average U-value of 0.2 W/m^2K for Uva, until 2 W/m^2K for Uvi)

This trend is in line with the “physical rebound”, which describes that non-heated rooms (or in the philosophy of the heat load standard the rooms that are kept at 10 or 16°C) are only that cold in the worst insulated dwellings, but reach a (much) higher equilibrium temperature for the variants that are better insulated. The better the insulation of the outdoor envelope, the higher average temperatures will be reached in the protected volume. These higher (average) indoor temperatures will cause extra heat losses and therefore also a (relative) higher heat load which is not taken into account for in the standard calculation. Thus, it seems that this ‘power rebound’ effect is counterbalancing for the best insulated variants other effects that cause the much lower sizing factor becoming apparent for the worst insulated dwellings:

- In reality there are always some internal heat gains so they are included in the measurements and estimated in the dynamic simulations but are not included in the standard calculation
- solar heat gains (idem)
- non-simultaneity of all worst weather conditions and user behaviour

With respect to the resampling time, where the standard assumes that the building mass absorbs hourly variations in heat load, Figure 12 shows that the heat load on 1h basis surpasses the heat load on 24 h average. This is limited from 10 to 40 % for the continuously heated variants, caused by hourly variability during the day (mostly outdoor temperature fluctuation related, but also heat gains vary throughout the day).

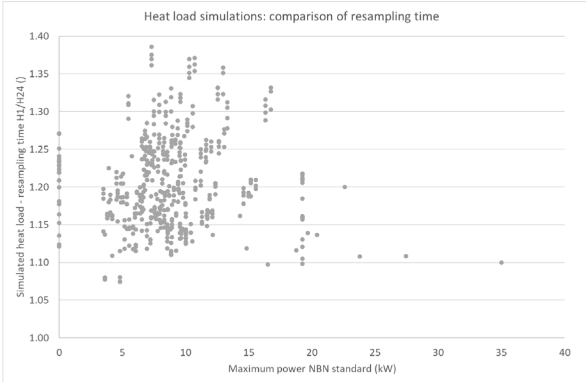

Figure 12: Heat load simulations- comparison of resampling times 1h vs 24h - continuously heated variants only

For the variants with setback schedules and reheat power, however, the simulated sizing factors are much higher, reaching values up to 4 (no figure shown). Since these simulations are run with instantaneous ideal heaters with unlimited heating capacity, this is not a realistic value, though. More simulations have been set up and run with limited emitter capacities, so that the reheat power can be found in relation to realistic reheat times (and building related parameters). Further work is needed to complete this analysis, but the first results show a high non-linearity, so the authors wonder if a small table with reheat values as used in the EN12831-1 is probably an oversimplification of the reality and whether simplified RC models could provide better results.

7. Conclusions

The research was oriented towards possible improvements of the Belgian standard annexe and eventually the European standard EN 12831-1.

Monitoring of real dwellings in use reveal a certain oversizing of the standard on building level, with a 24h horizon. This oversizing can partly be explained by some weather effects, but an important part of this oversizing is probably due to other factors, such as occupant behaviour, without having a method to address it in the standard. Leak infiltration is characterized by a high variability, but new factors couldn’t be proposed.

Based on the dynamic simulations we believe that the time horizon of 24h should be reduced, at least for dwellings with lower thermal inertia. This could increase the heat load with 10 to 40 % again, counterbalancing the observed oversizing of the standard on daily base. In addition, the desired flexibility towards smart grids, e.g. as active demand response, can demand extra heating power.

Contrary the actual Belgian standard that assumes the generator capacity as the sum of all room emitter capacities, a distinction should be made between calculations at room and at building level. That will enable to take into account the increased infiltration and reheat factors on room level (emitter sizing) and the non-simultaneous use of ventilation in all rooms, without increasing the heat load on building level (generator sizing).

Other elements of the standard need clarifications: the definition of temperature comfort and the effect on the air temperature, the definition of ventilation design flow rates and indoor air quality assumptions.

Finally control schedules for heating system operation (e.g. outdoor temperature based heating curves) should take into account the high variability of the required power and the absence of a pure linear relationship between required power (or distribution temperature regime) and the outdoor temperature.

8. Future work

Future research will focus on a simplified RC modelling method to introduce the dynamic behaviour of building and system in the standard calculation. In addition, a more statistical sound method will be investigated in order to avoid oversizing due to the actual simultaneity of all worst case conditions, but enable a more sound choice of parameters that are still on the severe side, but deliver, also when combined, more realistic heat loads.

9. Acknowledgement

This research was partly funded by the Belgian Federal Public Service Economy.

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The full dataset generated and/or analysed during the current study is not publicly available because of GDPR and property issues (most of the cases are measured by HVAC or building companies). However, the authors can be contacted and in function of the research need, a selection of the data can be made available