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Heat recovery ventilation system heating energy weather normalization – calculation method and case study

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Abstract

Today, we have measured energy consumption or used data from utility bills and standard weather normalization methods (heating degree days (HDD)) to easily calculate the energy performance certificate (EPC) for existing building. However, normalization methods must be upgraded to be more accurate for weather. This study uses analytical model for weather normalization of air handling unit heating consumption. The models derived from measurements of the ventilation system in a real building were conducted and the normalization aspects were analysed. A new analytical weather normalization calculation method for ventilation heating is compared with heating degree day normalization.

Introduction

The weather normalization of metered energy use is important for energy labelling and comparison, as well as, to improve the energy performance of existing and future buildings. However, today there are few methods to weather normalize the energy performance of different building services. Dynamic simulation-based weather normalization will give us good accuracy. However, considering bigger scale weather normalization, it is slow method. For faster calculation we have heating degree day (HDD) method that can be done with easy calculation. Berggren et. al. used in their study the static and dynamic method for weather normalization of space heating. The static method is easier to use, and from a weather normalization perspective, it is as accurate as dynamic normalization. (Berggren and Wall 2017) Furthermore, C. Tam et al. proposed new HDD based method with weighting exponent. (Tam, Liao, and Poh 2021) Considering the HDD method, Meng and Mourshed show that the base temperature should be estimated carefully. (Meng and Mourshed 2017)

However, today, the HDD method is mainly used for space heating, but there are few studies about methods in particular for ventilation air heating weather normalization. This study will develop a new analytical model for weather normalization of heating consumption for the air handling unit with regenerative rotor heat exchanger. New method is compared with traditional HDD method and normalization aspects are analysed. The real capacity calculation that is calibrated with hourly measured ventilation heating and electricity energy data is used to imitate real AHU heater energy need.

Method

Reference building

The reference building was 3 046 m^2 school building built on 1980. The renovation was done on 2020 and new ventilation system was constructed with 11 air handling units (AHU) with heat recovery.

In this study, only one AHU with rotor heat exchanger is analysed. That will service one part of school building classrooms and will have high quality metered electricity and heating energy data from August 2020 to April 2022.

Figure 1: Reference building

Metered energy data, cleaning and preparation

The accumulative metered AHU heat coil heating and fans electricity energy data was obtained from energy meters hourly from August 2020 to April 2022. Data from 2021 was mainly used in this study. Electricity and heating power were calculated with subtracting the hourly metered energy consumption row by row. Outliers and errors in electricity power was made even with previous hour data. The operation rate of AHU heating coil was generated from electricity power. Equation 1 was used for the calculation of the operation time.

$$\tau_i = \sqrt[3]{\frac{\Phi_{el,i}}{\Phi_{el,max}}} \qquad (1)$$

where τ_i is the operation rate in specific hour, $\Phi_{el,i}$ is electricity power (kW) in specific hour and $\Phi_{el,max}$ is

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the maximum electricity power (kW) during calculation period. During 8. May - 18. Nov the AHU heating coil operation rate was zero. (Figure 2)

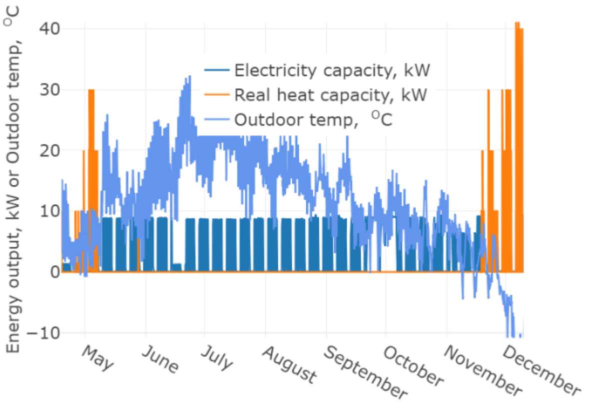

Figure 2: Comparison of heating and electricity power

AHU heater energy need calculation model

In this study, we used the AHU heater energy need calculation model that uses equations 2-6. The model takes hourly outdoor temperature data T_{out}, given parameters (Table 1), and will calculate the AHU heating coil heat output (power) in kW per every hour for one year. The ventilation air flow rate Q_v was multiplied with operation rate composed by real electrical data of AHU fans described previously. Fan temperature rise was set 0 K.

$$\Phi_v = \rho \cdot c \cdot \Delta T_h \cdot q_v \cdot \tau_i \qquad (2)$$

where, ρ is the density of air 1.2 kg/m^3, c is the specific heat capacity of air 1.006 kJ/(kg·K), q_v is air flow rate m^3/s multiplied with AHU operation rate τ_i; ΔT_h is temperature difference the heater should cover:

$$\Delta T_h = \mathrm{MAX}(T_{supply} - T_{after,hx}, 0) \qquad (3)$$

where, T_{supply} is supply air setpoint temperature in °C, and was considered as constant; $T_{after,hx}$ is the air temperature in °C after heat exchanger and calculated with equation:

$$T_{after,hx} = \eta_{hx,lim} \cdot (T_{extract} - T_{out}) + T_{out} \qquad (4)$$

where, $T_{extract}$ is the extract temperature that is equal to room temperature in °C; T_{out} is the outdoor temperature in °C and $\eta_{hx,lim}$ is calculated:

$$\eta_{hx,lim} = \frac{T_{extract} - T_{exhaust}}{T_{extract} - T_{out}} \qquad (5)$$

where, $T_{exhaust}$ is the temperature in °C after heat exchanger that is limited and was calculated with equation:

$$T_{exhaust} = \mathrm{MAX}(T_{extract} - \eta_{hx,const} \cdot (T_{extract} - T_{out}), T_{exhaust,lim}) \qquad (6)$$

However, in this case, as the rotor did not significantly increase heating energy use despite outdoor temperatures below -30 °C, the $\eta_{hx,lim}$ was always constant $\eta_{hx,const}$.

Air handling unit heat recovery and control parameters

Second part of this study was to detect the AHU heat recovery parameters that reference building will have (Table 1). The minimum exhaust temperature was taken as lowest temperature -30 °C, because we detected frost protection did not significantly increase heating energy use. However, the real heat exchanger heat recovery efficiency, extract and supply air temperature are not known and were detected by parameter optimization with minimizing the CV(RMSE) between real metered and AHU heating coil heat output calculated with Equation 2 (separately for Jan, Feb, Mar, Nov, Dec). Optimization was in limits: supply air temperature 16-21 °C, extract air temperature 22-24 °C and heat exchanger efficiency 0.75-0.9. The optimization was done with real operation rate described previously. Final parameters were generated by averaging optimized parameters of these months (Table 1).

Table 1: AHU parameters

Parameter	Abbreviation	Value
Minimum exhaust air temperature, °C	$T_{exhaust}$	-30
Extract air temperature, °C	$T_{extract}$	21.75
Ventilation air flow rate, l/s	q_v	4749
Supply air temperature, °C	T_{supply}	20.26
Heat recovery efficiency	$\eta_{hx,const}$	0.809

Analytical model for weather normalization with mean temperature (MT) and parameters

The model was composed by the difference in ventilation air heat capacity between real and test reference year (TRY) climate (Kalamees and Kurnitski 2006), where corrected ventilation air heat capacity is

$$\Phi_{h,corrected} = (\Phi_{h,real} + \Delta\Phi_{h,TRY,Real})^{+} \qquad (7)$$

The difference was calculated with

$$\Delta\Phi_{TRY,Real} = \rho \cdot c \cdot q_v \cdot \tau_i \cdot (\Phi_{h,Real} - \Phi_{h,TRY}) \qquad (8)$$

, where

$$\Phi_{h,Real} = T_{out,Real} + \mathrm{MIN}\left(T_{extract} - T_{exhaust,lim};\ \eta_{hx} \cdot (T_{extract} - T_{out,Real})\right) \qquad (9)$$

$$\Phi_{h,TRY} = T_{out,TRY} + \mathrm{MIN}(T_{extract} - T_{exhaust,lim};\ \eta_{hx} \cdot (T_{extract} - T_{out,TRY})) \qquad (10)$$

where the $T_{out,Real}$ and $T_{out,TRY}$ are outdoor temperatures in every hour respectively in 2021 and in TRY. Other parameters are in Table 1.

Furthermore, the model will consider two limitations. First, the outdoor temperature was limited with the base temperature that is the outdoor temperature, when no heating is needed. This is calculated with the equation:

$$T_{out,lim} = \frac{T_{supply} - \eta_{hx} \cdot T_{extract}}{1 - \eta_{hx}} \quad (11)$$

The outdoor temperature was taken as minimum temperature between T_{out} and $T_{out,lim}$.

$$T_{out} = MIN(T_{out}, T_{out,lim}) \quad (12)$$

Secondly, the $\Phi_{v,corrected}$ was calculated only when the result is positive, otherwise the heating power is zero.

The AHU heat coil heating power of the TRY climate was calculated hourly with equations 1-5 and then aggregated daily, weekly, monthly and yearly.

Calculations and comparisons of two methods

The AHU heat consumption of the TRY climate was compared with two methods: mean temperature (MT) and HDD method. In the MT method, the corrected consumption was calculated with the daily, weekly, and monthly average outdoor temperature when AHU fans speed (operation rate) was over 54%. Secondly, the MT method was compared with HDD method. The base temperature (Tb) was identified with change-point method (Rohdin et al. 2018), where the linear regression line meets x-axis. Furthermore, the Tb was calculated for different boundary conditions, with Equation 11 or randomly selected (

Table 2). Thereafter, the R^2, CV(RMSE) and NMBE was calculated to identify the Tb that will have the best correlation for HDD normalized and TRY daily consumption.

HDD weather normalization was done by Equation 13, where Q_v is real AHU heating energy consumption and HDD is heating degree days in test reference year and real year. Calculations were performed from January to December 2021.

The comparison between two normalization methods was done with data, where operation rate was over 54%.

$$Q_{v,HDD,corrected} = Q_v \cdot \frac{HDD_{TRY,}}{HDD_{Real}} \quad (13)$$

The daily average outdoor temperature was calculated with two methods for HDD normalization:

1) All 24h outdoor temperature was included (except may-nov);
2) Outdoor temperature during fans minimum speed 54%;

Results and Discussion

Model uncertainty

The accumulative consumption of all year calculated with optimized parameters is compared with measured consumption in Figure 3 and Figure 4. The CV(RMSE), and R^2 of this comparison for hourly accumulative consumptions are in limits of model calibration (ANSI/ASHRAE 2002), respectively <30% and ≥75%. NMBE is 8% over the limit ±10 % (Figure 3).

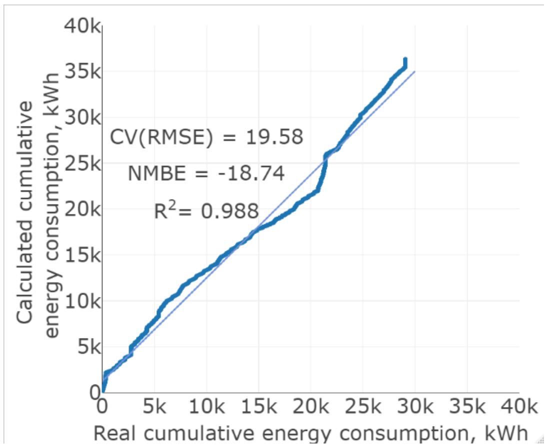

Figure 3: The accuracy of consumption calculated with optimized parameter

Base temperature for HDD normalization

Best fitting base temperature 14.4 °C was identified with cleaned datapoints during 2021 with minimum fan speed 54%. However, from

Table 2 can see that other data selection conditions had good correlation as well. The linear fitting of final base temperature is shown in Figure 5.

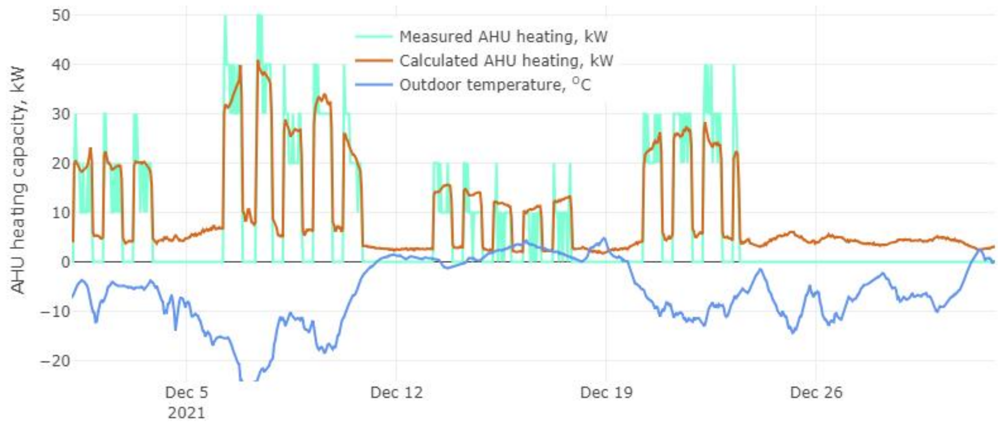

Figure 4: AHU real measured and model calculated energy consumption with outdoor air temperature in December

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Table 2: The identification of base temperature of AHU heater

Tb	R^2	CV(RMSE)	NMBE	Tb calculation method	Boundary conditions for datapoint selection
11.0	0.987	16.63	-0.27	random selection	-
12.9	0.996	8.70	1.40	Linear fitting	All datapoints during Aug. 2020-2021
13.1	0.996	8.79	1.47	Linear fitting	cleaned datapoints during 2020-2021 (may-nov is removed)
13.3	0.996	8.91	1.50	Calculated eq. 11	optimized parameters in Table 1
14.4	**0.997**	**8.82**	**1.42**	Linear fitting	cleaned datapoints during 2021 with minimum fan speed 54%
15.1	0.994	11.26	1.57	Linear fitting	cleaned datapoints during 2021 (may-nov is removed)
16.0	0.991	14.12	1.62	random selection	-
17.0	0.987	16.90	1.59	random selection	-

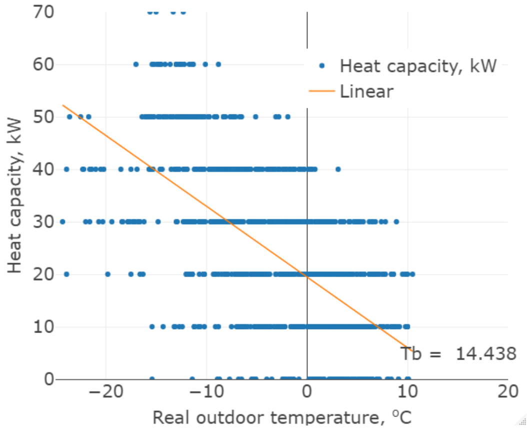

Figure 5: Base temp. calculated with heat capacity and outdoor temperature in operation time over 54%

Calculation method analysis for daily average outdoor temperature

Two calculation methods for the daily average outdoor temperature was analysed for HDD normalization. The monthly degree day analysis between both methods in Figure 6 show that the correlation in between datapoint selection method is significant. However, calculating CV(RMSE) and NMBE between daily HDD normalisation and TRY AHU heating consumption for two methods, can see that second method is more accurate (Table 3).

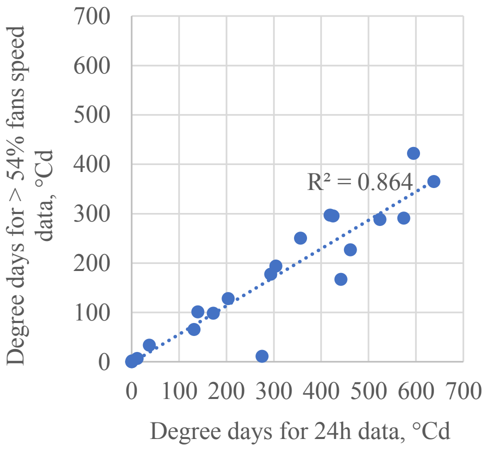

Figure 6: Correlation between two method monthly degree days

Table 3: Uncertainty calculations for data selection methods for temperature averaging

Method	CV(RMSE)	NMBE
24h data	3.95	0.46
> 54% data	2.05	0.21

Normalization methods comparison

The result of analysis is shown in the following Figures 7-9 daily, weekly and monthly. On a linear regression graphs, the horizontal axis is the AHU heat energy calculated with hourly TRY outdoor climate. On the vertical axis is the heat output/heating energy normalized with MT (upper/left) and normalized with HDD method (lower/right).

Daily and weekly analysis (Figure 7 and Figure 8) shows, that MT method will normalize just a little more accurate than HDD method. However, in monthly normalization there is no difference. Hence, the HDD normalization is more reasonable, as it does not need parameters detection.

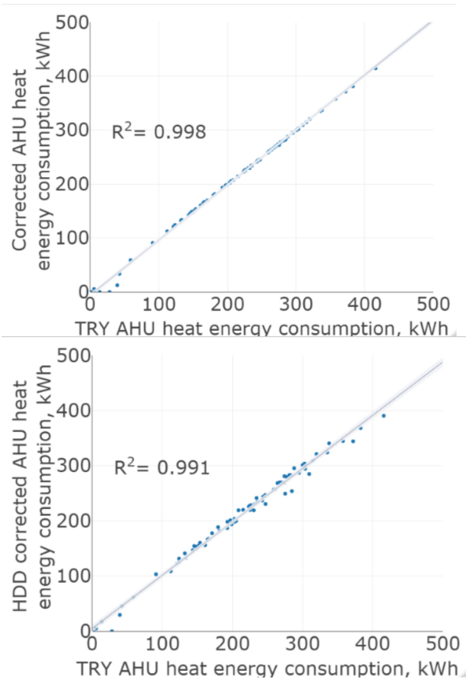

Figure 7: Comparison of daily TRY, MT (left) and HDD normalized (right) energy consumption

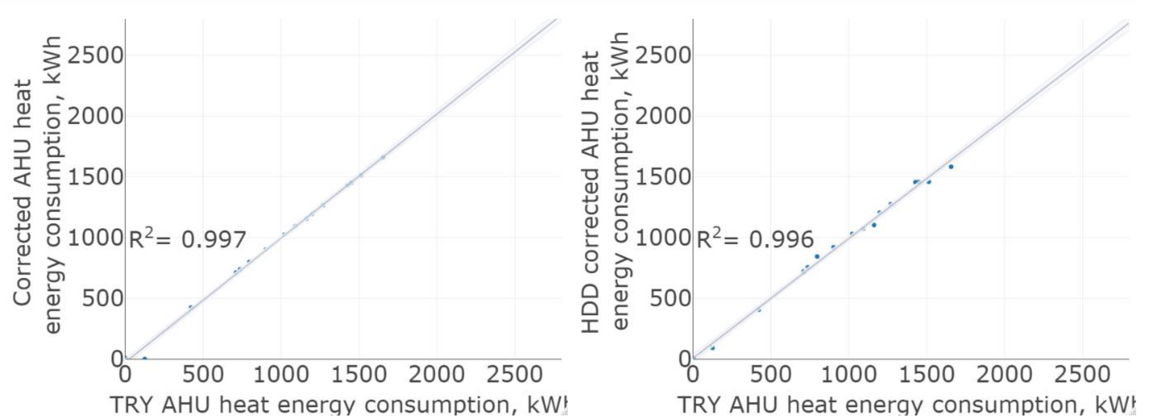

Figure 8: Comparison of weekly TRY, MT (a) and HDD normalized (b) energy consumption

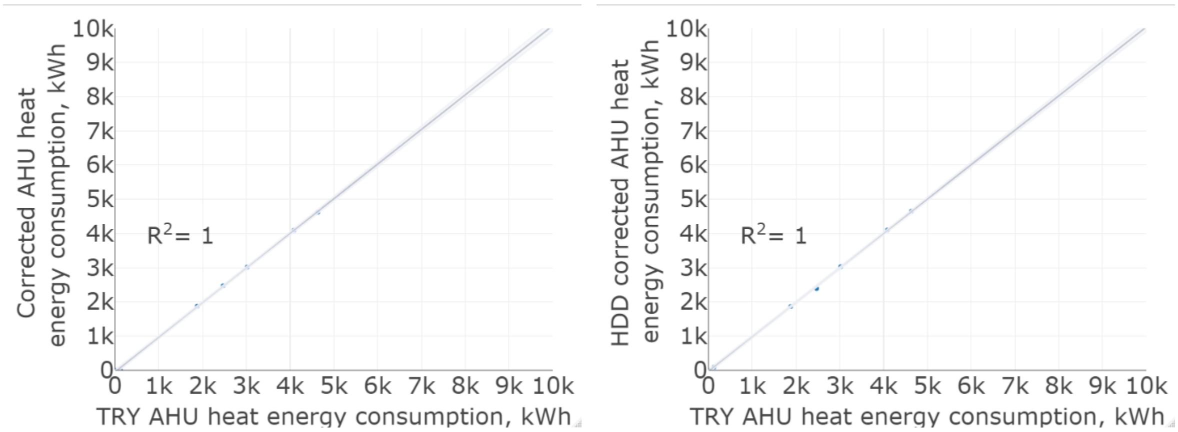

Figure 9: Comparison of monthly TRY, MT (a) and HDD normalized (b) energy consumption

Metered heat consumption normalization

Finally, the actual metered AHU heating energy consumption was normalized with HDD method from Aug-2020 to April-2022. The normalization was done with two data selection:

1) All 24h outdoor temperature was included (except may-nov);
2) Outdoor temperature during fans minimum speed 54%;

The difference between two method is not big, but varies more from Nov-2020 to Mar 2021 (Figure 10). However, another thing to notice in Figure 10 is that the energy consumption in 2021-2022 winter is low, even though the degree days are similar or even more than 2020-2021 winter. For example, the Nov-20 and Nov-21 energy consumptions are totally different, but degree days are similar. Looking to BMS of the AHU we can see, that the air flow has changed and therefore the heat recovery efficiency was improved and heating demand is lower.

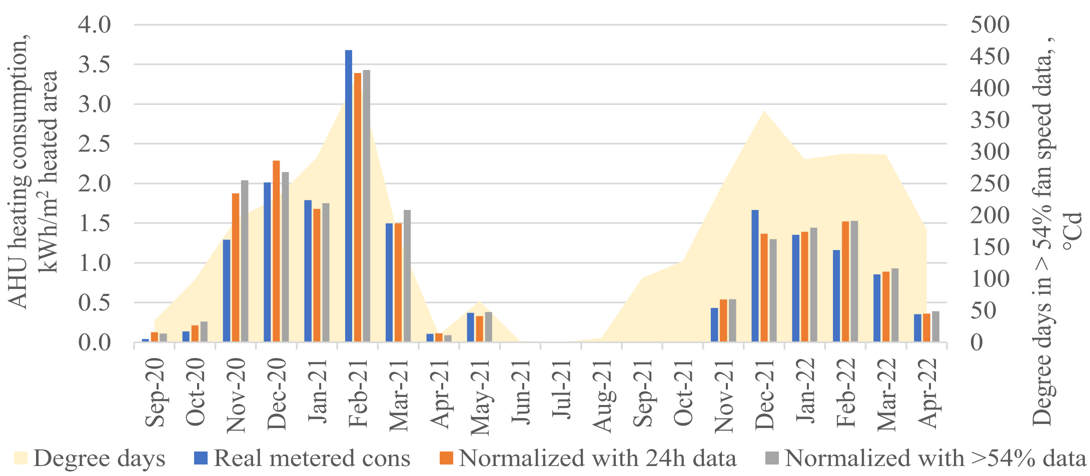

Figure 10: Comparison of monthly metered and HDD normalized energy consumption

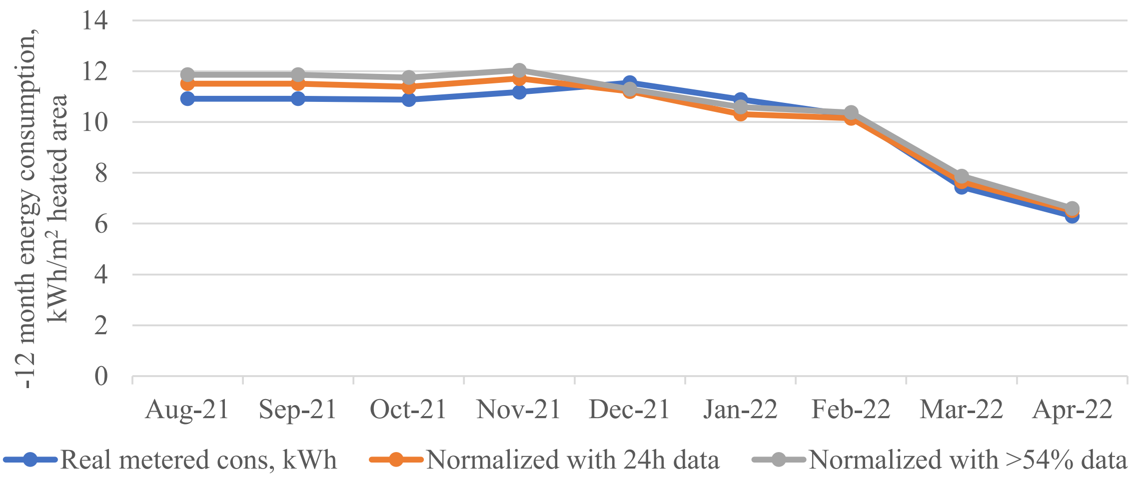

Figure 11: Yearly energy consumption calculated from 12 previous months

Figure 11 will show the 12 previous months (one year) total energy consumption calculated each month. There can see, that the real metered energy consumption will vary compared to normalized consumption. Furthermore, with this graph we can find out that from Nov-2021 something changed and should be investigated. In this case, on Nov-2021 the AHU air flow was changed.

Conclusion

This study compares two AHU heat coil heating consumption weather normalization calculation methods for the of one school building AHU with rotor heat exchanger. The mean temperature method is slightly more accurate than heating degree day method. However, there should consider that the MT method will need more data as heat recovery efficiency and AHU supply and extract temperature. Therefore, the HDD method will be more reasonable to use together with correct base temperature calculation in monthly normalization.

In AHU heat coil heating consumption analysis and normalization, the operation time should be considered as it will influence the results. Furthermore, the weather normalization is essential to erase weather influence and then predict some faults and setpoints changes.

However, it should be considered, that these analyses do not include possible frost protection and defrosting energy use. Therefore, future studies should include to the analysis some frost sensitive heat exchangers as for example, cross-flow plate heat exchanger. Furthermore, future studies should be extended to building level as in actual case, most buildings have data only for whole ventilation heating.

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