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The Impact of Data Granularity of Indoor Temperature Measurements on the Calculation of Degree Days

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Abstract **– Degree-days are to normalise energy consumption data and furthermore can generate forecasting predictions for energy demand being used to compare between different properties across different location and years. The base temperature is the main factor to consider the accuracy of degree days. The aim of this study was to evaluate the impact of data granularity to understand its effect on a correlation between energy consumption and Degree Days. Degree Days were calculated using the standard 18.3 °C base temperature as taking in the United States of America and compare the Degree Days calculations against the calculation based on hourly, daily and monthly data for base temperature. The methodology followed is based on the analysis of 23 houses located in Texas, Austin. The properties under study are from different construction periods and with a variety of total floor areas. This study had demonstrated the effect of the granularity of the data collected to generate Degree Days and its impact on the correlation between energy consumption and degree-days for different base temperatures. While the higher correlations are achieved using a monthly granularity, this approach is not recommended due to the small number of data points and a much more preferred approach that should be taken is a daily approach, which would generate a much more reliable correlation. In this study, higher correlation values were achieved when using the standard 18.3 °C base temperature for the Degree Days calculations, 70 % correlation in daily approach versus 56.67 % using indoor temperature, showing better results across the board against the use of indoor temperature at all granularity levels.**

Keywords **– Base temperature; data granularity; degree-day; indoor temperature; energy consumption**

Nomenclature		
T_a	Ambient temperature	°C
T_b	Base temperature	°C
T_{min}	Minutely temperature	°C
T_{hour}	Hourly temperature	°C
T_{day}	Daily temperature	°C
T_{month}	Monthly temperature	°C
Q	Gas energy	kWh
Q_{min}	Minutely gas energy	kWh
Q_{hour}	Hourly gas energy	kWh

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Q_{day}	Daily gas energy	kWh
Q_{month}	Monthly gas energy	kWh
M	Minutely meter reading	kWh

1. INTRODUCTION

The use of Degree Days are widely employed to predict energy demand, through forecasting tools [1], and furthermore, they are used to normalize energy consumption data to be able to compare retrofit performance across different years to assess its success [2]. The concept of Degree Days and its calculation process are well known and described in the literature [3], [4]. Several other uses should be highlighted for the use of Degree Days, such as the opportunity to predict energy use at community level [5] and to assess the severity of weather on the energy consumption for domestic properties [6].

Several authors have pointed out the opportunities of using Degree Days to assess energy performance indicators [7] and for climate classification and heating and cooling loads [8].

The most important factor to calculate Degree Days is the base temperature [9]. For the correct base temperature a straight line correlation between energy consumption and degree-days will be achieved [10]. Several methodologies have been generated to calculate the base temperature because of the influence on the degree-days results [11]. An approach is to select the base temperature as the heat balance point of the building at which no heating will be required, in the case of this paper for the United Stated of America, the base temperature selected is 18.3 °C [12]. A different approach is through the energy signature methodology [13] with the main limitation of the need of high resolution data to perform an accurate calculation, implying the requirement of higher granularity in the data. Furthermore, Jimenez-Bescos [14] presented an approach to use indoor temperature as a base temperature for degree-days calculations based on the use Internet of Things sensors to increase the accuracy of predictions and normalization. While the use of the balance temperature of a building should provide a better approach for base temperature, as the point when heating is not required, Oregi and Jimenez-Bescos [15] showed that there was not a significant different versus the use of a standard base temperature, which would not require extensive calculations for the balance temperature.

The most important aspect is that having different approaches for the calculation of Degree days, the actual values are mean to oscillate [16] and as such, errors can happen due to the wrong base temperature selection in calculating the Degree Days [17].

As presented in this introduction, degree days is highly used to assess building energy performance and the precision of the assessment is influenced by the degree day base temperature. The gap in knowledge of this study is the investigation on the impact of different data granularity to calculate degree-day base temperatures and its effect on energy use by means of correlation between energy consumption and degree-days when using the standard base temperature and the indoor temperature.

The aim of this study was to evaluate the impact of data granularity to understand its effect on correlation between energy consumption and Degree Days. Degree Days were calculated using the standard 18.3 °C base temperature as taking in the United States of America [12] and compare the Degree Days calculations against the calculation based on hourly, daily and monthly data for base temperature.

2. Methodology

The methodology employed in this paper is generated from the study of 23 single family houses situated in Texas, Austin, in the United States of America. The houses have a range of construction year between 1941 and 2008, with a total floor area ranging from 74.5 m^2 to 360.18 m^2. The selected houses were chosen on the basis of continuous availability of gas used data and indoor temperature of the property with a granularity of data of every minute. Furthermore, weather data for the location was available on an hourly basics and was used to calculate the Heating Degree Days.

For each house, the gas and indoor temperature data had to be matched to each other to create a dataset matching periods in which both, gas and indoor temperature, were available. This meant that the total period of the study presented range from July 2014 to September 2017 but no house would have data for the whole period but an average of 527 days of data across the whole period, with a minimum of 123 days for house 18 and a maximum of 703 days for house 8.

Firstly, the data for each house had to be rearranged into hourly data as a starting point. Secondly, the data using in the calculation should including the whole day in a whole month. Therefore, the useful minutely data starts at 0:00 at the first day of one month to 23:59 at the end date of the last month including gas and indoor temperature data.

Regarding the calculation for Heating Degree Days, the base temperature is based on a simplified method [18] and taking for the location of interest as 65 °F (18.3 °C) [12]. The degree day was calculated in accordance to Eq. (1), as the difference between the base temperature (T_b) and the ambient temperature (T_a).

$$\text{Degree day} = T_b - T_a \tag{1}$$

When processing the temperature data, both ambient and internal mean temperature data in hourly, daily, and monthly period were calculated based on the temperature data collected in minutely intervals from the data website, and it should be noted that the data is calculated in hierarchical order. Specifically, the hourly temperature data was calculated from minutely data, the daily data was based on the hourly data, and the monthly data was based on the daily data. Therefore, the hourly, daily, and monthly mean temperature were calculated by Eq. (2), Eq. (3), and Eq. (4):

$$T_{\text{hour}} = \frac{1}{60}\sum_{n=1}^{60} T_{\text{min}} , \tag{2}$$

$$T_{\text{day}} = \frac{1}{24}\sum_{n=1}^{24} T_{\text{b,hour}} , \tag{3}$$

$$T_{\text{month}} = \frac{1}{m}\sum_{n=1}^{m} T_{\text{b,hour}} , \ m = \text{number of month.} \tag{4}$$

Once the indoor temperature was arranged in hourly, daily and monthly basis, the Degree Day for each interval period was calculated with an hourly, daily and monthly base temperature accordingly to Eq. (1) for each house data period.

Regarding the minutely weather data for the location, the same process as for the indoor temperature was follow with Eq. (2), Eq. (3), and Eq. (4) to determine the hourly, daily and monthly ambient temperature to use with Eq. (1) for the calculation of the Degree Day.

For the actual energy consumption in each house, the minutely gas data was calculated based on the energy meter reading by subtracting the new meter reading from the previous reading, which was shown in Eq. (5).

$$Q_{\mathrm{min,c,f}} = M_{\mathrm{min}} = M_{\mathrm{one\,minute\,ago}} \tag{5}$$

The gas data in each period was also calculated in a hierarchical order, so the gas data in each time period was calculated by Eq. (6), Eq. (7), and Eq. (8):

$$Q_{\mathrm{hour}} = \sum\nolimits_{n=1}^{60} Q_{\mathrm{min}} \ , \tag{6}$$

$$Q_{\mathrm{day}} = \sum\nolimits_{n=1}^{24} Q_{\mathrm{hour}} \ , \tag{7}$$

$$Q_{\mathrm{month}} = \sum\nolimits_{n=1}^{m} Q_{\mathrm{day}} \ . \tag{8}$$

Degree-days were generated on an hourly, daily and monthly basis for each house during the period of data available for each house, as the base temperature minus the average external daily temperature, as presented in Eq. (1) and considering only positive values.

Four base temperatures were analysed in this research:

- Hourly indoor temperature for each house;
- Daily indoor temperature for each house;
- Monthly indoor temperature for each house;
- Standard base temperature of 18.3 °C for the United States of America [12].

As presented by Oregi and Jimenez [15], the purpose of Degree Days is to normalise energy consumption data, in our case gas consumption data used for heating and domestic hot water. By correlating Degree Day versus gas data consumption, the ideal outcome should be a coefficient of determination, R^2, of value 1, which would indicate that the gas consumption of the house can be fully explained by the degree-days [19]. The coefficient of determination, R^2, will varied between 0 and 1 values, with those values closer to 1 indicating a strong correlation and values closer to 0 showing no significant correlation between gas consumption and Degree Day. It must be noted that a coefficient of determination showing a strong correlation does not imply cause and effect [20].

A similar approach was used by Oregi and Jimenez [15] to evaluate the impact on Degree Day calculation for different base temperatures, based on thermostat, balance temperature and the default base temperature in Spain.

In this paper, as the degree-days are calculated based on three different base temperatures according to the data granularity in hourly, daily and monthly basis, the coefficient of determination, R^2, is used to evaluate the correlation according to the different granularity approaches to calculate degree-days and its fitness to explain the energy consumption.

3. RESULTS

Fig. 1 shows an example of the process followed for each house calculating the coefficient of determination to assess the correlation between energy consumption and degree days on an hourly basis using the indoor temperature and the standard base temperature as base temperatures for the calculations for House 1. This data was calculated for house 1 with 13 128 data points based on the number of hours, where data was available for gas consumption and indoor temperature.

House 1 is a single family house with two occupants built in 1975 with a total floor area of 159.142 m^2. House 1 has a complete set of data for gas consumption and internal temperature from November 2014 to April 2016.

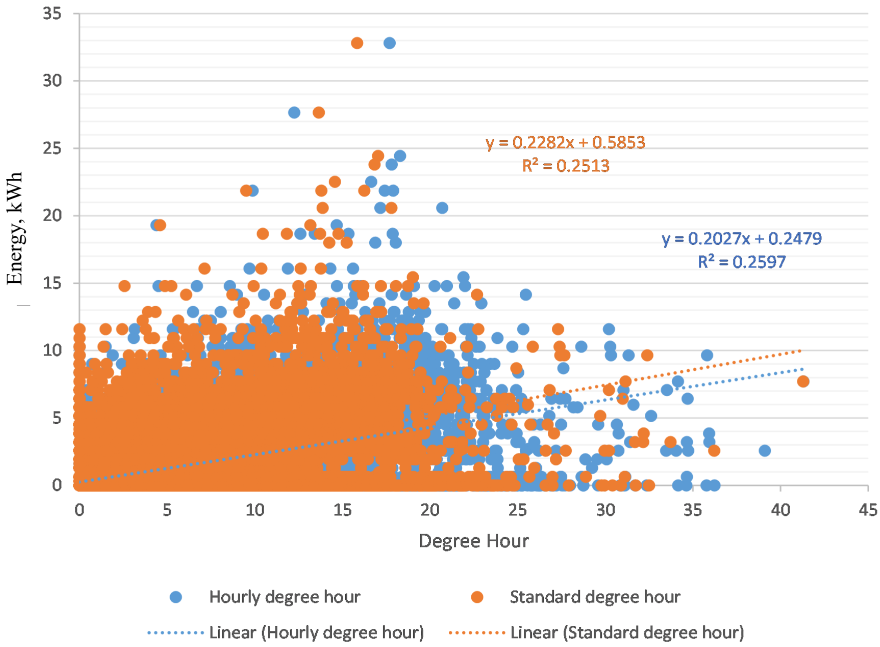

Fig. 1. Energy consumption versus degree-days for house 1 with hourly approach.

Fig. 2 presents the correlation for house 1 on a daily basis using the indoor temperature and the standard base temperature as base temperatures for the calculations. This data was based on 541 data points according to days with full data available. When the Degree Day and Energy use is considered in a daily basis, the improvement in correlation is observed graphically. This is a combination of having less granularity, less data points as we are accounting for the whole degree days and more importantly, the whole gas consumption for a full day. This allows to reduce the issues in Fig. 1 with hourly data, when we can have none or little gas consumption in an hour.

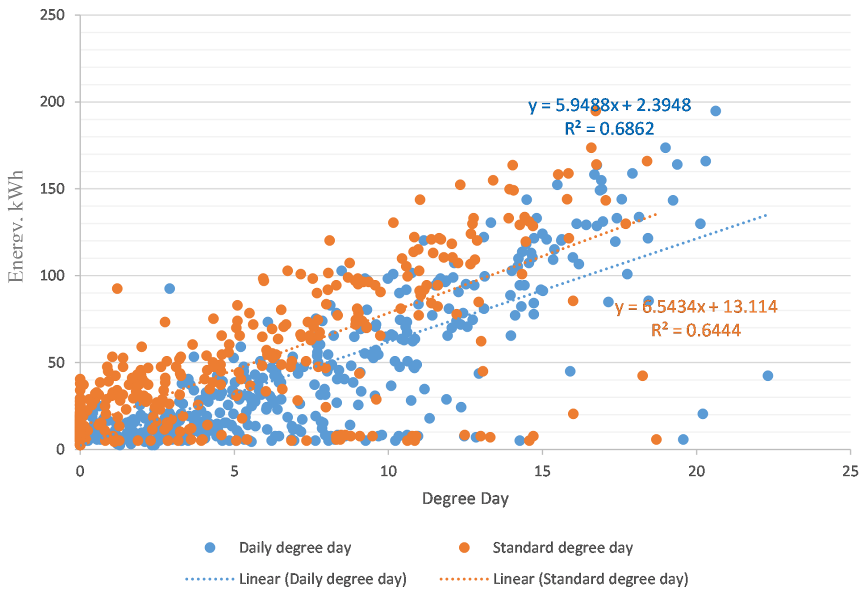

Fig. 2. Energy consumption versus degree-days for house 1 with daily approach.

Fig. 3 presents the correlation for House 1 on a monthly basis using the indoor temperature and the standard base temperature as base temperatures for the calculations. This data was based on a small sample of full months for which the full data available.

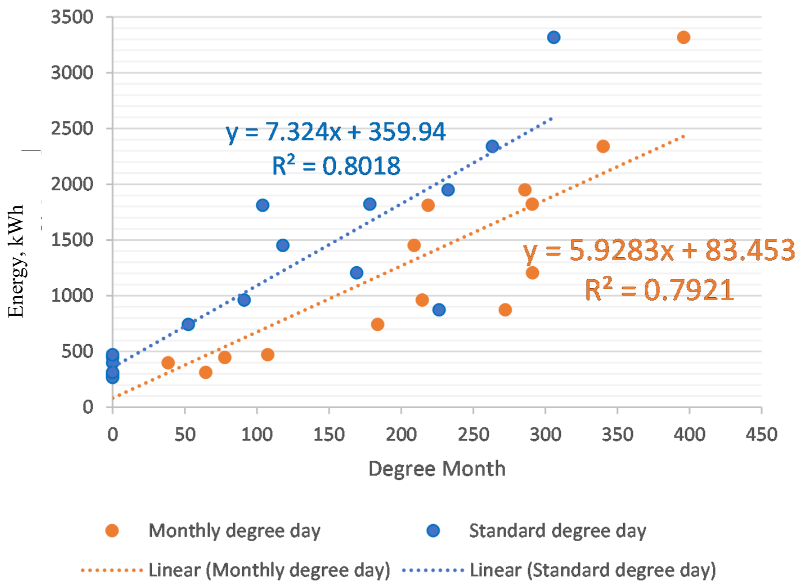

Fig. 3. Energy consumption versus degree-days for house 1 with monthly approach.

Fig. 4 presents the gas consumption for each house in kilowatts per meter square (kWh/m^2) from July 2014 to September 2017, which shows as expected a concentration around winter for the increase use of gas and an important level of variability of kWh per meter square, suggesting that perhaps the indoor temperature may have a big influence on the gas consumption.

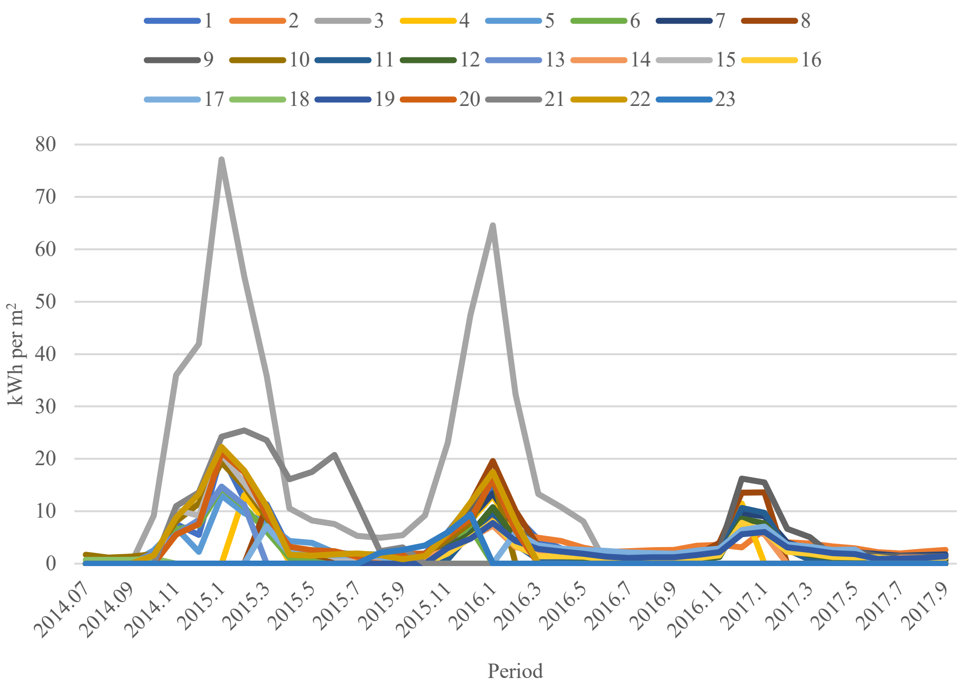

Fig. 4. Energy consumption in kWh per meter square for all houses.

Table 1 shows the number of data points that were used to generate the hourly, daily and monthly indoor temperature and gas consumption data. From Table 1 and Fig. 4, it can be appreciate it the range of indoor temperature and gas consumption data that was available for each of the 23 houses that were analysed in this study. Furthermore, there is a wide range of construction years from 1941 to 2008 and total floor area, which will add to different ranges of data points available to carry out the study.

Table 2 and Fig. 5 provides the coefficient of determination (R^2) analysing the correlation between Degree Day and gas consumption for all 23 houses in accordance to the hourly, daily and monthly method. The results show that when using hourly data to generate Degree Day based on indoor temperature to correlate to energy consumption, the correlation is very weak with an average for all 23 houses of 0.1718. This suggests that only 17.18 % of the time, the energy consumption can be explained by Degree Days. In contrast, when a daily and monthly approach is used for the indoor temperature, the average correlations are 0.5667 and 0.7076, respectively. A similar effect on the correlation when using the standard base temperature of 18.3 °C is appreciated regarding the granularity of the data as hourly, daily and monthly.

TABLE 1. DATA POINTS FOR HOURLY, DAILY AND MONTHLY GENERATION OF INDOOR TEMPERATURE AND GAS CONSUMPTION DATA

			Hourly	Daily	Monthly
House	Year	Area	Data Points	Data Points	Data Points
1	1975	159.14	13 128	547	18
2	1977	147.90	16 800	700	23
3	1967	74.51	14616	609	20
4	1958	153.47	16 800	700	23
5	2007	248.93	7297	305	10
6	1961	140.47	10 224	426	14
7	1967	268.67	16 800	700	23
8	1994	225.38	16 872	703	23
9	1950	179.67	16 800	700	23
10	2008	143.44	13 920	583	19
11	2007	217.39	16 800	700	23
12	2007	264.12	16 800	700	23
13	1967	172.98	3624	151	5
14	1966	250.74	16 152	673	22
15	1941	87.05	5808	242	8
16	1968	360.18	16 800	700	23
17	1985	116.78	16 800	670	22
18	2007	159.79	2952	123	4
19	1973	199.55	16 800	700	23
20	1949	98.29	11 664	486	16
21	1981	150.41	7992	333	11
22	2008	203.83	12 408	517	17
23	1957	111.11	3673	153	5
Average			12 675.2	527	17.3

TABLE 2. ENERGY CONSUMPTION AND DEGREE-DAYS FOR BUILDING 6

	Hourly		Daily		Monthly	
House	Indoor base temp	Standard base temp	Indoor base temp	Standard base temp	Indoor base temp	Standard base temp
1	0.2597	0.2513	0.6862	0.6444	0.7921	0.8018
2	0.0217	0.0329	0.4058	0.4401	0.7364	0.6649
3	0.2103	0.2843	0.6362	0.8334	0.7354	0.9597
4	0.3155	0.4328	0.8574	0.73	0.8678	0.9693
5	0.1208	0.158	0.4891	0.5584	0.5036	0.5565
6	0.4175	0.4915	0.7891	0.8949	0.8931	0.9495
7	0.1894	0.2789	0.6106	0.7918	0.7836	0.9713
8	0.1944	0.2483	0.717	0.831	0.8301	0.9523
9	0.2556	0.2907	0.6312	0.7509	0.7056	0.8739
10	0.0736	0.1078	0.5228	0.8011	0.5734	0.9508
11	0.1246	0.2027	0.5182	0.673	0.638	0.8542
12	0.1719	0.2782	0.4548	0.7445	0.6039	0.9545
13	0.2538	0.3234	0.7103	0.8105	0.7665	0.8804
14	0.024	0.0445	0.1897	0.3057	0.4203	0.5351
15	0.1944	0.3293	0.6513	0.7934	0.7823	0.8807
16	0.085	0.1266	0.536	0.694	0.7134	0.9139
17	0.0598	0.1072	0.3867	0.661	0.4739	0.853
18	0.0002	0.0003	0.1333	0.0352	0.7883	0
19	0.0961	0.1367	0.6176	0.7398	0.8163	0.9197
20	0.2026	0.2211	0.6333	0.6997	0.7826	0.821
21	0.1467	0.2321	0.3303	0.3816	0.2525	0.2504
22	0.4618	0.4677	0.8644	0.9015	0.9356	0.9549
23	0.0737	0.0912	0.6649	0.696	0.8821	0.9719
Average	0.1718	0.2233	0.5667	0.6700	0.7076	0.8128
SD	0.1196	0.1342	0.1886	0.2057	0.1684	0.2495

In all 69 cases, the correlation achieved between Degree day and Energy consumption is higher when using the standard base temperature, apart from 6 instances. This can be easily appreciated in a graphical way in Fig. 5.

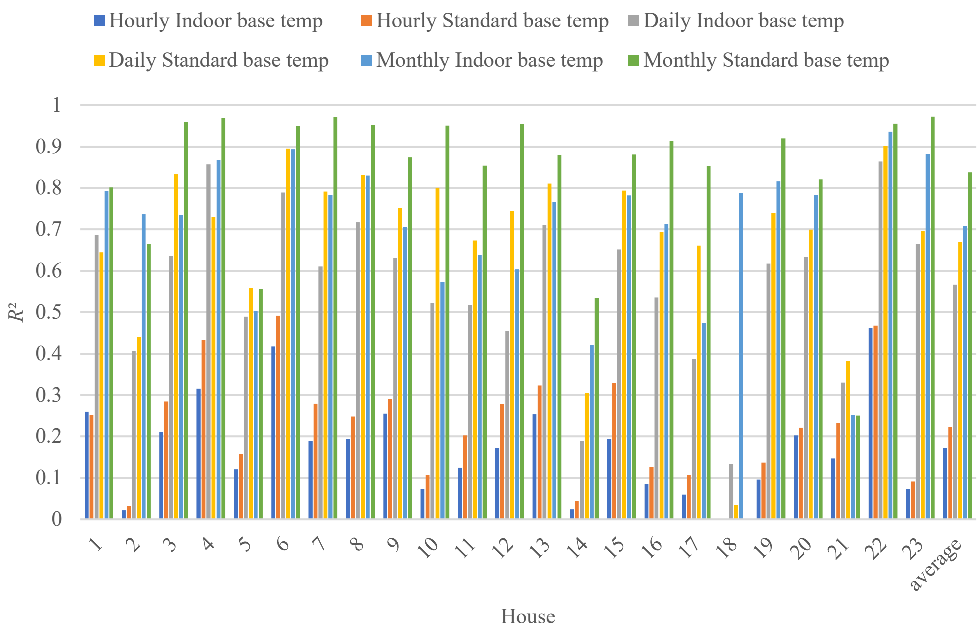

Fig. 5. Coefficient of determination R^2 for all houses at each base temperature in hourly, daily and monthly granularity.

4. Discussion

The aim of this study was to evaluate the impact of data granularity to understand its effect on correlation between energy consumption and Degree Days. Degree Days were calculated using the standard 18.3 °C base temperature as taking in the United States of America and compare the Degree Days calculations based on hourly, daily and monthly data.

The selection of base temperature is a very important aspect to achieve a good correlation with Degree Days, as it was suggested by Layberry [9]. The results presented in Table 2 and Fig. 5 are in agreement with the importance of selecting the appropriate base temperature but furthermore, it highlights that a high granularity of the data, as happening when using hourly data, creates an issue when normalizing the gas energy consumption with a very weak correlation.

The correlation increase as the number of data points decrease with the higher values achieved when using monthly data, but this data could be too course and provide an easier chance to achieve high correlations. The same effect is appreciated using the standard base temperature and the indoor temperature, suggesting that the effect is due to the granularity of the data and not the base temperature selection.

The results show that the number of data points have an influence on the expected correlation, from the point of view that having a small number of data points help to increase the correlation, while a number of data points too large, generates data so finely that the correlation became weak.

The correlation between energy consumption and Degree Days has a higher correlation when using the monthly granularity but the number of data is quite small and in comparison, a daily approach provides a good level of correlation with an average of 0.5667, when using the indoor temperature as base temperature, and 0.67 when using the standard 18.3 °C base temperature.

This research has followed the approach to generate the base temperature independently for each house, as suggested by Day *et al.* [11], to increase the correlation.

The limitations of this research are similar in nature to the study by Krese *et al.* [13], needing a longer data collection period and higher number of properties, where a full set of data is available and for different locations.

While the appropriate selection of base temperature is highly important to avoid errors [16], this research shows that the use of hourly data to generate Degree Day data for energy normalization, generates a weak correlation due to the minimum interval require for Degree Day and energy consumption data. This study recommends that a daily approach is taking as it provides a good compromise between the number of data points and reasonable correlations for energy consumption and Degree Days. Furthermore, the study recommends the use of the standard 18.3 °C base temperature for this location, as it generates stronger correlations with the energy consumption, suggesting that perhaps the selection of base temperature may be influence as well by the climatic conditions of the site of investigation. This is in disagreement of previous research [14], which showed that using the internal temperature as base temperature can provide more accurately correlations but further details are required regarding the effect of the climate.

5. Conclusion

This study had demonstrated the effect of the granularity of the data collected to generate Degree Days and its impact on the correlation between energy consumption and degree-days for different base temperatures. While higher correlations are achieved using a monthly granularity, this approach is not recommended due to the small number of data points and a much prefer approach should be taking using a daily approach, which would generate a much more reliable correlation. In this study, the higher correlation values were achieved when using the standard 18.3 °C base temperature for the Degree Days calculations, 70 % correlation in daily approach versus 56.67 % using indoor temperature, showing better results across the board against the use of indoor temperature at all granularity levels.

The fact of achieving better correlation using the standard 18.3 °C base temperature for the Degree Days suggests that when dealing with a wide range of different properties, a general country approach is the way forward. While when working with similar properties an approach based on indoor temperature may have better outcomes.

Further studies should look into reducing limitations related to the effect of construction year, total floor area and thermal performance, which could impact the correlations between degree days and gas consumption.

References

[1] Hong W. *Intelligent energy demand forecasting*. Springer, 2013. https://doi.org/10.1007/978-1-4471-4968-2

[2] Jansson-Boyd C., Robison R., Cloherty R., Jimenez-Bescos C. Complementing retrofit with engagement: exploring energy consumption with social housing tenants. *International Journal of Energy Research*, 2017:41(8):1150–1163. https://doi.org/10.1002/er.3698

[3] Krarti M. Weatherization and energy efficiency improvement for existing homes – an engineering approach. *CRC Press* 2013.

[4] CIBSE. TM41 Degree-days: theory and application. CIBSE Publications, 2006.

[5] Mitchell J. M. Degree-days: Heating and Cooling by the Numbers. *Weatherwise* 2012:40:6:334–336. https://doi.org/10.1080/00431672.1987.9932080

[6] OrtizBeviá M. J., Sánchez-López G., Alvarez-Garcìa F. J., Ruiz de Elvira A. Evolution of heating and cooling degree-days in Spain: Trends and interannual variability. *Global and Planetary Change.* 2012:92–93:236–247. https://doi.org/10.1016/j.gloplacha.2012.05.023
[7] De Rosa M., Bianco V., Scarpa F., Tagliafico L. A. Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach. *Applied Energy.* 2014:128:217–229. https://doi.org/10.1016/j.apenergy.2014.04.067
[8] Bhatnagar M., Mathur J., Garg V. Determining base temperature for heating and cooling degree-days for India. *Journal of Building Engineering.* 2018:18:270-280. https://doi.org/10.1016/j.jobe.2018.03.020
[9] Layberry R. L. Degree-days for building energy management – presentation of a new data set. *Building Services. Engineering Research and Technology* 2008:29(3):273–282. https://doi.org/10.1177/0143624408093886
[10] Layberry R. L. Analysis of errors in degree-days for building energy analysis using Meteorological Office weather station data. *Building Services. Engineering Research and Technology* 2009:30:1:79–86. https://doi.org/10.1177/0143624408098221
[11] Day A. R., Knight I., Dunn G. and Gaddas, R. Improved methods for evaluating base temperature for use in building energy performance lines. *Building Services. Engineering Research and Technology* 2003:24(4):221–228. https://doi.org/10.1191/0143624403bt073oa
[12] Degree Days. [Online]. [Accessed 05.03.2021]. Available: https://www.degreedays.net/base-temperature
[13] Krese G., Prek M., Butala V. Analysis of Building Electric Energy Consumption Data Using an Improved Cooling Degree Day Method. *Journal of Mechanical Engineering* 2012:58(2):107-114. https://doi.org/10.5545/sv-jme.2011.160
[14] Jimenez-Bescos C. Assessing the Impact of Degree Day Base Temperatures on The Development of an Energy Index to Measure Energy Reduction. *Proceedings of the International Conference for Sustainable Design of the Built Environment*, London, 2017:241–246.
[15] Oregi X., Jimenez-Bescos C. Evaluating the Effect of Different Base Temperatures to Calculate Degree-Days. *Environmental and Climate Technologies* 2020:24(2):364–372. https://doi.org/10.2478/rtuect-2020-0079
[16] Walsh P. J. The relation between degree-days and base temperature. *Applied Energy* 1983:13(4):241–253. https://doi.org/10.1016/0306-2619(83)90017-X
[17] Woods J., Fuller C. Estimating base temperatures in econometric models that include degree-days. *Energy Economics* 2014:45:166–171. https://doi.org/10.1016/j.eneco.2014.06.006
[18] Verbai Z., Lakatos L., Kalmár F. Prediction of energy demand for heating of residential buildings using variable degree day. *Energy* 2014:76:780–787. https://doi.org/10.1016/j.energy.2014.08.075
[19] Bryman A. Social Research Methods. Oxford University press, 2004.
[20] Collis J., Hussey R. Business Research. Palgrave, 2003.