DTU Library

Heat Flexibility as A Function of The Outdoor Climate: A Study of Danish Dwellings.

Li, Rongling; Chen, Y. ; Rode, Carsten

Published in:
Proceedings of 4th International Conference On Building Energy, Environment

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Heat Flexibility as A Function of The Outdoor Climate: A Study of Danish Dwellings

R. Li [1], Y. Chen [1,2] and C. Rode [1]

[1]Department of Civil Engineering
Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
[2] Department of Built Environment
Eindhoven University of Technology, 5600 MB Eindhoven, the Netherlands

SUMMARY

To limit the need for peak load heat plants and to reduce greenhouse gas emission in district heating grids, we investigated the heat flexibility of different buildings in Denmark and how district heating grids can be better utilized. In this study, the flexibility of Danish residential dwellings from different time periods was modelled using the TABULA database. The thermal response of these dwellings was simulated for each day of the entire heating season and daily heat flexibility was calculated and analysed statistically. As a result, daily heat flexibility was formulated as a function of outdoor temperature and solar irradiance. This way, heat flexibility can be used in practice based on weather forecasts.

INTRODUCTION

District heating supplies 63% of dwellings and amounts to 37% of household energy consumption in Denmark (Danish Energy Agency 2014). Heat demand in district heating grids is mainly dependent on outdoor temperature but is also affected by solar gains and wind chill (Frederiksen and Werner 2014). It is also influenced by the behaviour of users (Kensby et al. 2015)., which causes peak demand primarily in mornings and evenings. During these periods, peak load heat plants are required to generate heat. These plants generally operate on fossil fuel with high costs and high green-house gas (GHG) emission. Currently, in Danish district heating grids, 24% of the heat was produced from coal, natural gas and oil (Danish Energy Agency 2014). In order for Denmark to reach their energy targets of a complete phase-out of coal by 2030 and 100% renewable energy in electricity and heating by 2035 (The Danish Government 2013), a reduction of peak demand in district heating systems is essential.

In demand side management, the use of building thermal inertia is a common strategy for short-term thermal energy storage. This is because the total thermal mass of a building is substantially larger than alternative heat buffers, e.g. hot water tanks, and use of the building thermal mass does not require extra investment (Vanhoudt et al. 2017). A pilot test in five residential buildings in Sweden (Kensby et al. 2015) has shown that heavy buildings could tolerate relatively large variations in heat supplies with less than 1°C temperature variation in a 21 h test cycle. A simulation study revealed that a poorly insulated building could maintain thermal comfort for 2-5 h without heating, while a well-insulated building could have the heating system switched off for more than 24 h (Le Dréau and Heiselberg 2016). These studies have shown the great potential of using building thermal inertia in demand side management. However, in order to use it to reduce the peak load of district heating systems, building thermal inertia and thermal response must be investigated systematically for most building types. This is because in a district heating grid, a distribution network connects to hundreds of buildings and the heat flexibility of single buildings must be aggregated across all distribution networks.

The goal of the present study was to determine how to use building thermal inertia to provide heat flexibility for district heating systems, to reduce or avoid the operation of peak load heat plants. For the operation of district heating systems, the heat flexibility of buildings must be represented in a simple form to be useful in practice. We therefore formulated heat flexibility in a straightforward manner and developed a methodology to estimate heat flexibility based on the weather forecast. This method was applied to several representative Danish single family houses, and the heat flexibility of these building types was investigated towards the utilization in the operation of a district heating grid.

METHODS

The flexibility of Danish residential dwellings built in different time periods was modelled in TRNSYS 17 software based on building parameters from the TABULA database (Wittchen and Kragh 2012, TABULA WebTool). As Single Family Houses (SFH) account for 60% of Danish dwellings in terms of heated floor area (BBR 2012) we have chosen SFH as the focus of this study. Table 1 shows the specifications of the selected building types. The construction year is significant as it relates to different building regulations with different requirements for building energy performance. In the selected building types, those constructed in 1961-1972 and 1850-1930 are the most common in Denmark and represent 22% and 20% of Danish dwellings, respectively (BBR 2012). The dwellings built after 2007 have a high standard of thermal insulation and represent new buildings. Although the majority of Danish dwellings (81%) were built before the 1980s with relatively low thermal insulation, most of these buildings have been renovated or retrofitted to some extent. There are only limited data indicating what percentage of buildings have been renovated and to what standard this was done. In order to take into account the renovated buildings, we included a renovation case that fulfils the minimum requirement of the most recent Danish Building Regulations 2015 (BR15) (BR 2015). In the modelling, dwellings built after 2007 were considered to use floor heating, while the older types were assumed to use radiator heating.

Building thermal mass as considered in this study consists of internal thermal mass, including interior furniture and indoor air, and structural thermal mass. The wall thermal mass for the 1850-1930 SFH, the 1961-1972 SFH and the renovated 1961-

1972 SFH was 30 cm brick, while for the 2007-2010 SFH it was 40 cm brick (TABULA WebTool). The thermal capacity of interior furniture was estimated as 2 kJ/K per unit of dwelling volume, based on our own observations in Danish dwellings. This value is equivalent to twice the indoor air thermal capacity. In the TRNSYS building model, the air capacitance was therefore multiplied by a factor of three to account for the thermal capacity of both the furniture and the indoor air. This coefficient of three is also the value recommended by TRNSYS (2013). The daily dynamics of infiltration was not considered in this study and the infiltration rate was fixed at 0.8 ACH, which fulfils the minimum requirement of 0.5 ACH for residential buildings in BR15. It was assumed that a family with two adults and two children was living in the dwelling. The occupancy and internal heat gains were assumed to be the same for all the building types in order to compare the influence of outdoor climate on building heat flexibility.

Table 1. Characteristics of Danish single family houses

Construction year	U-value (W/m^{2}K)				Heating type
	Floor	Wall	Ceiling	Window	
1850 – 1930	0.60	1.60	1.50	2.70	Radiator
1961 – 1972	0.30	0.60	1.30	2.80	Radiator
2007 – 2010	0.11	0.16	0.12	1.50	Floor heating
1961 – 1972 Renovated	0.20	0.30	0.20	1.40	Radiator

The Building thermal response was studied by setting the heating signal to zero (heat cut-off). In this study, we tried to reduce morning peak load by cutting off the heat supply from 6 am and we then examined building thermal response to this intervention. Each building type was therefore investigated for each day with the indoor operative temperature setting at 22°C before the cut-off at 6 am. The time it takes for the indoor operative temperature to decrease from 22°C to 20°C we defined as the heat flexibility. The temperature of 22°C is the value recommended by Tommerup et al. (2007) based on measurements in Danish detached houses. For each building type, the simulations were run on a day-by-day basis from 0 am to 24 pm for a typical heating season, i.e. from the beginning of October to the end of April. In this way, a total of 212 days were calculated. Table 2 shows the monthly average outdoor temperatures in Copenhagen during the heating season. According to Danvak (1992), the heating season in Denmark starts each autumn when the daily average outdoor temperature has fallen below 12 °C for three consecutive days. It ends in spring when the daily average outdoor temperature has remained above 10 °C for three consecutive days. Normally, in Denmark the heating season lasts from 25 September to 8-14 May. However, it varies from year to year, and some years it may not end until the beginning of June.

Table 2. Average outdoor temperature in Copenhagen during heating seasons from 2006 to 2015 (DMI 2016)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Mt (°C)	10.3	6.8	3.4	1.7	1.5	4.1	8.7
Mxt (°C)	13.3	8.6	5.1	3.4	3.5	7.6	13.4
Mnt (°C)	7.4	4.8	1.5	-0.3	-0.6	1.0	4.7

Notes: Mt stands for daily mean temperature, Mxt stands for the mean of daily maximum temperature and Mnt stands for the mean of daily minimum temperature.

Statistical analysis was applied to the daily heat flexibility and outdoor weather conditions to generate models for the prediction of daily heat flexibility based on weather forecasts. RStudio was used for this analysis. For each building, the 212 calculated values of daily heat flexibility formed the dataset for this analysis. The data points included both daily and morning (from 6:00 to 12:00) values of average outdoor temperature and accumulated global horizontal solar irradiance. Regarding solar irradiance, it was assumed no shading on these SFHs during the heating season. Multiple variable regression analysis was chosen, as all the variables were continuous.

RESULTS

Heat flexibility of different building types

The heat flexibility of each building type during heat cut-off was investigated for each day of the entire heating season. Figure 1 shows the daily heat flexibility of all four building types for the entire heating season. It can be seen that the SFH constructed in 2007-2010 and the renovated 1961-1972 SFH have heat flexibility values that can be as high as 24 hours. The heat flexibility in the first and last month of the heating season was very high with the majority of the days having 16 hours of flexibility. For the 2007-2010 SFH, the daily heat flexibility during the middle months of the heating season (from day 30 to 180) was between four and ten hours on most of the days. In comparison, during the same period, the renovated 1961-1972 SFH had daily heat flexibility values of only two to five hours.

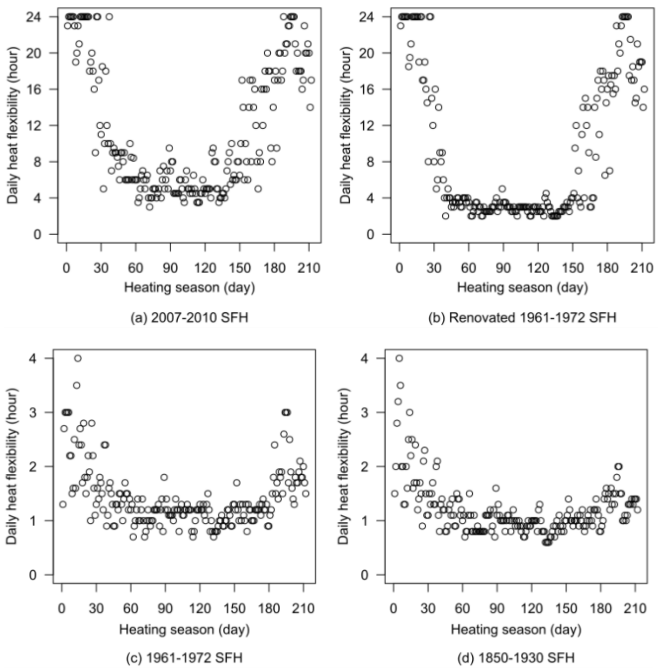

Figure 1. Daily heat flexibility of the four building types during the heating season

In comparison with the above two building types, the 1961-1972 SFH and the 1850-1930 SFH had lower values of flexibility with a maximum of four hours. On a few days at the beginning and the end of the heating season, the daily heat flexibility was between two and four hours, while on most days of the heating season, the heat flexibility was between 30 minutes and two hours. The similarity in the performance of these two building types is due to the similarity of their thermal insulation values.

The most flexible building type was the one constructed in 2007-2010. It provided flexibility for three to 24 hours on different days in the heating season. It may also be observed that the daily variation in flexibility was higher for the 2007-2010 SFH and the renovated 1961-1972 SFH, which are better insulated in comparison with the older buildings.

Regression model of heat flexibility based on weather conditions

For the 2007-2010 SFH and the renovated 1961-1972 SFH, multiple regression analysis was performed on the heat flexibility of the 212 days of the heating season against the daily mean outdoor temperature (T_{od}) and the integral value of daily global horizontal solar irradiance (I_{sol}). The daily mean outdoor temperature was chosen as we found that heat flexibility was longer than six hours (i.e. past noon) on a substantial number of days. For the 1961-1972 SFH and 1850-1930 SFH, the morning values from 6:00 to 12:00 were used instead of the daily value. This was because for these two building types, the daily heat flexibility was no more than six hours.

A summary of the multiple linear regression for 2007-2010 SFH is shown in Table 3 and the quantile-quantile plot (q-q plot) of the residuals is shown in Figure 2 (a). The q-q plot shows that the residuals follow a Normal distribution, which indicates that the regression analysis is valid. From Table 3 it can be seen that both outdoor temperature and solar irradiance have statistically significant impacts on the daily heat flexibility.

Table 3. Summary of regression analysis of 2007-2010 SFH

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	2.91	0.288	10.10	<2e-16 ***
I_{sol}	2.84	0.144	19.78	<2e-16 ***
T_{od}	1.17	0.045	25.83	<2e-16 ***

Significance codes: 0 = ***, 0.001 = **, 0.01 = *
Residual standard error: 2.53, Multiple R-squared: 0.87

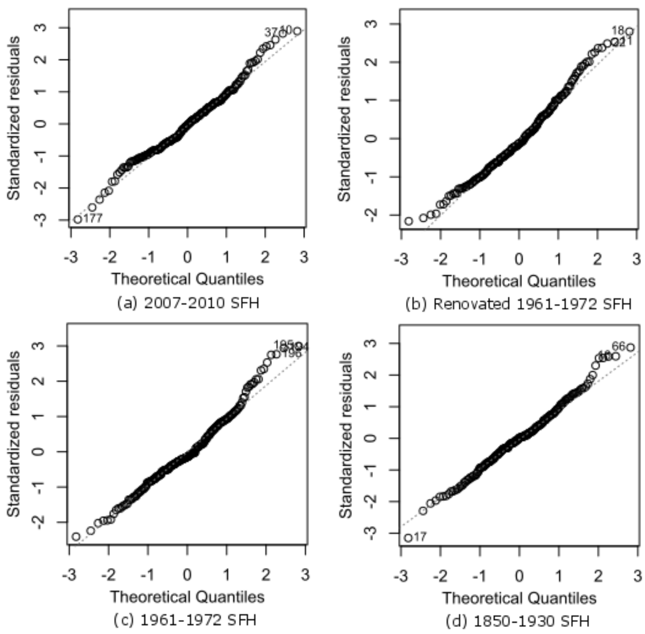

Figure 2. Normal q-q plot of the regression analysis for the four building types

Based on the estimates shown in Table 3, the regression equation of daily heat flexibility for 2007-2010 SFH was formulated as:

$$Daily\ heat\ flexibility = 2.91 + 1.17T_{od} + 2.84I_{sol} \quad (R^2 = 0.87) \tag{1}$$

where T_{od} is the daily mean temperature (°C) and I_{sol} is the daily integral value of global horizontal solar irradiance (kWh/m^2). The coefficient of determination also called r squared (R^2) indicates that the fraction of the total variation in the daily heat flexibility explained by the regression was 0.87.

The regression model of Equation 1 and the daily heat flexibility are plotted in Figure 3. The light blue area denotes the prediction results of the regression model, which crosscuts the observations illustrated by orange circular markers.

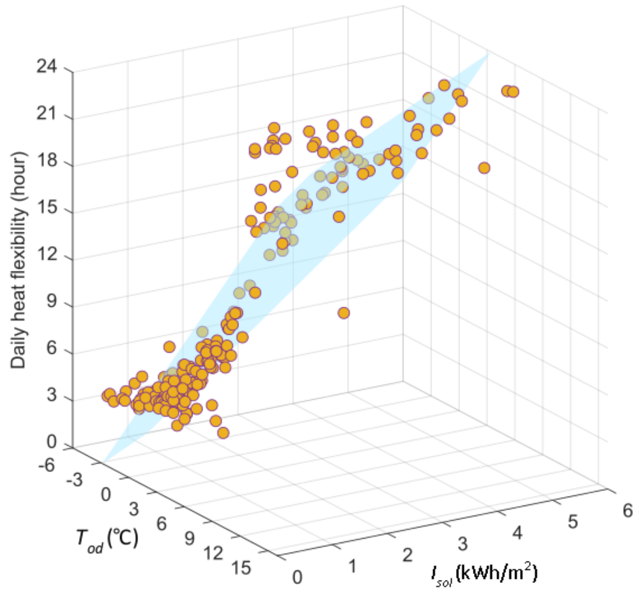

Figure 3. 3D plot of daily heat flexibility (circular markers) and its regression model (blue area) for 2007-2010 SFH

The analysis of renovated 1961-1972 SFH (Table 4) revealed that the influence of outdoor temperature and solar irradiance on the daily heat flexibility was also statistically significant. Its q-q plot (Figure 2) again indicates a Normal distribution of the residuals.

Table 4. Summary of regression analysis of renovated 1961-1972 SFH

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	-0.44	0.201	43.12	<2e-16 ***
I_{sol}	3.74	0.166	22.48	<2e-16 ***
T_{od}	1.06	0.056	19.00	<2e-16 ***

Significance codes: 0 = ***, 0.001 = **, 0.01 = *
Residual standard error: 2.86, Multiple R-squared: 0.86

The daily heat flexibility of the renovated 1961-1972 SFH was formulated as:

$$Daily\ heat\ flexibility = -0.44 + 1.06T_{od} + 3.74I_{sol} \quad (R^2 = 0.86) \tag{2}$$

where the variables are the same as in Equation 1. This equation might show the possibility of a negative daily heat flexibility. In fact, the value of heat flexibility was positive on every day.

The difference between the regression model and the daily heat flexibility of renovated 1961-1972 SFH is illustrated in Figure 4. The prediction results of Equation 2 are illustrated by the light blue area and the observations are illustrated by orange circular markers.

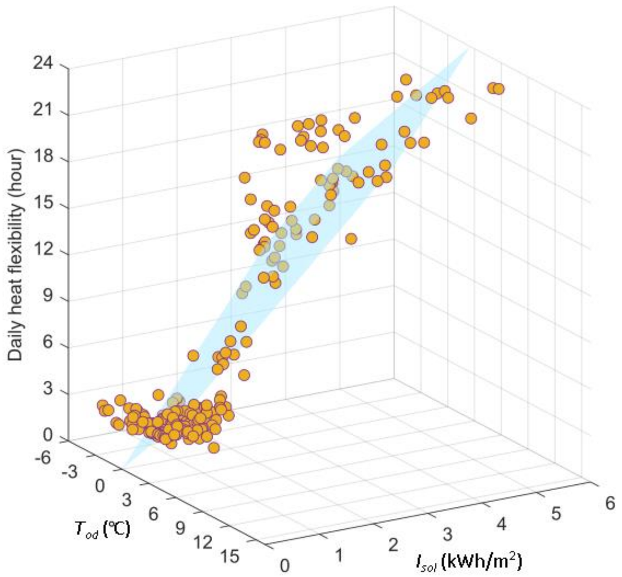

Figure 4. 3D plot of daily heat flexibility (circular markers) and its regression model (blue area) for renovated 1961-1972 SFH

For the analysis of 1961-1972 SFH and 1850-1930 SFH, the observations include the accumulated global horizontal solar irradiance ($I_{sol,6/12}$) and the average outdoor temperature ($T_{od,6/12}$). The results of the regression analysis of 1961-1972 SFH are shown in Table 5 and the residual normality is shown in Figure 2 (c). The value of R^2 was not as high as for the previous two regression models, probably due to the fact that the variation in heat flexibility for old buildings is much smaller than for the newer ones. It can also be seen in Figure 1 that the values of heat flexibility are unevenly distributed, with most of the data points located between 0.5 and 1.5.

Table 5. Summary of regression analysis of 1961-1972 SFH

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	0.92	0.029	31.53	<2e-16 ***
$I_{sol,6/12}$	0.11	0.031	3.67	0.0003 **
$T_{od,6/12}$	0.11	0.005	3.67	<2e-16 ***

Significance codes: 0 = ***, 0.001 = **, 0.01 = *
Residual standard error: 0.26, Multiple R-squared: 0.77

The daily heat flexibility of the 1961-1972 SFH was therefore formulated as Equation 3.

$$Daily\ heat\ flexibility = 0.92 + 0.11T_{od,6/12} + 0.11I_{sol,6/12} \quad (R^2 = 0.77) \quad (3)$$

Where $T_{od,6/12}$ is the average outdoor temperature from 6:00 to 12:00 and $I_{sol,6/12}$ is the accumulated global horizontal solar irradiance between 6:00 and 12:00.

The model prediction and the observations of 1961-1972 SFH are shown in Figure 5. The yellow circular markers are the observations while the light blue area is the prediction by the regression model of Equation 3.

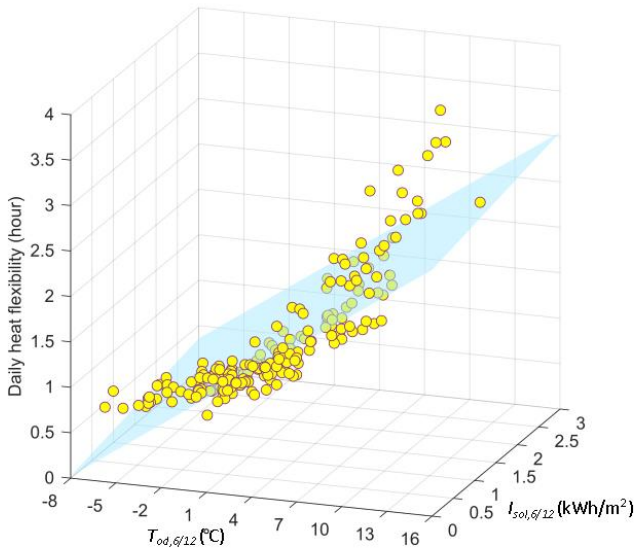

Figure 5. 3D plot of daily heat flexibility (circular markers) and its regression model (blue area) for 1961-1972 SFH

For the analysis of 1850-1930 SFH, the solar irradiance was found to have no impact on the daily heat flexibility. A polynomial regression analysis was therefore conducted with outdoor temperature as the only variable. The results are shown in Table 6 and Figure 2 (d).

Table 6. Summary of regression analysis of 1850-1930 SFH

Coefficients	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	0.83	0.011	71.85	<2e-16 ***
$T_{od,6/12}$	0.05	0.004	12.58	<2e-16 ***
$T^2_{od,6/12}$	0.01	0.0004	16.65	<2e-16 ***

Significance codes: 0 = ***, 0.001 = **, 0.01 = *
Residual standard error: 0.12, Multiple R-squared: 0.92

The daily heat flexibility of the 1850-1930 SFH was therefore formulated as Equation 4.

$$Daily\ heat\ flexibility = 0.82 + 0.05T_{od,6/12} + 0.01T^2_{od,6/12} \quad (R^2 = 0.91) \quad (4)$$

where $T_{od,6/12}$ is the average outdoor temperature from 6:00 to 12:00.

Figure 6 shows the model prediction and the daily heat flexibility of 1850-1930 SFH with the light blue area showing the predictions from the regression model and the yellow circular markers showing the observations.

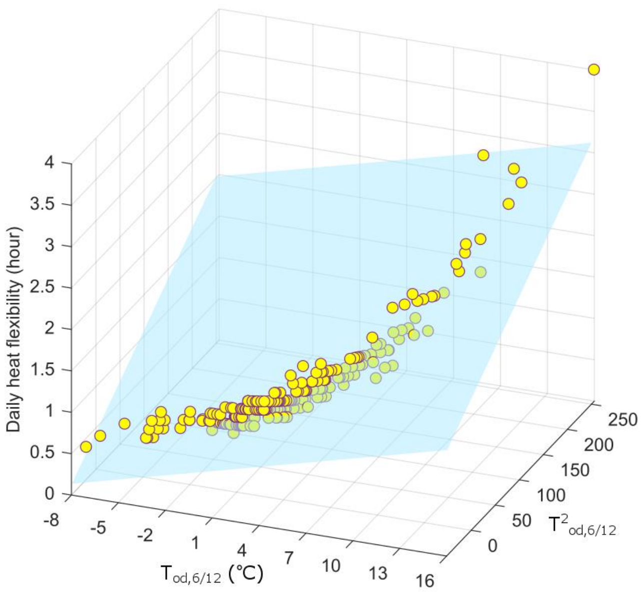

Figure 6. 3D plot of daily heat flexibility (circular markers) and its regression model (blue area) for 1850-1930 SFH

DISCUSSION

This study shows that the difference in heat flexibility of different building types must be considered in the operation of a district heating grid, as new buildings have longer periods of flexibility and old ones have rather short flexibility. It is also found that heat flexibility, as defined in this paper, correlates with outdoor temperature and solar irradiance (except for the oldest dwellings) and should be predictable based on these two parameters. The heat flexibility is thus a relevant parameter for the operation of a district heating network, which can be optimized based on the same-day weather forecast. However, in the implementation of the results, the following limitations of this study need to be emphasised. The initial condition of the indoor operative temperature was 22°C with 0.3°C variation, which is not always realistic as indoor temperature in some buildings may have larger variation. In addition, user behaviour such as window opening was not considered in the model, and might have affected the results.

The results of this study are in line with two previous studies. Kensby et al. (2015) found that in a 21 h test cycle the temperature decrease in heavy buildings was less than 1°C. The same phenomenon was found in our study for the well-insulated modern buildings both at the beginning and at the end of the heating season. Le Dréau and Heiselberg (2016) reported that the heat flexibility was 2-5 h for a poorly insulated building, while it could be more than 24 h for a well-insulated building. These results cannot be compared at a detailed level with our study as in these two studies, the building models were different. Nevertheless, the flexibility results in our study have the same magnitude, and the difference between the poorly insulated buildings and the well-insulated ones was also found in our study.

The present research method and results is clearly of value for district heating grids. By applying the results, peak load heat plants can potentially be shut down and the cost in heat generation would then be reduced significantly. This would eventually benefit district heating companies and the heat consumers. This implementation also means that the GHG emission of a district heating grid can be reduced dramatically as peak load heat plants are the main cause of GHG emission, and there is considerable societal interest in this. There will be some challenges in implementing this study. First, heaters in individual buildings would have to be capable of being switched on or off by the district heating grid operator, which is not permissible at present. New contracts will have to be developed for heat consumers to accept it. This is the first study whose aim was to develop an applicable method for using building heat flexibility in the operation of district heating grids. The study could be improved: 1) the models and results can still be fine-tuned so as to find an equally simple but perhaps better method, 2) other types of operation such as the reduction of heat supply using building heat flexibility at different times of the day should also be investigated.

CONCLUSIONS

This paper presents a methodology for using building heat flexibility for the reduction of GHG emission in a district heating grid. The heat flexibility was formulated as the time period that a building can sustain its thermal comfort conditions without any heat supply. For the district heating grid operators, the multiple linear regression models developed for different building types can be implemented on a daily basis using the weather forecast as input.

The daily heat flexibility varied among different building types with different thermal insulation. For new building (2007-2010 single family house) and renovated old buildings (built 1961-1972 SFH, renovated recently), the daily heat flexibility was from two hours up to 24 hours. However, the daily heat flexibility of older buildings (1961-1972 SFH and 1850-1930 SFH) was between half an hour and four hours, primarily because of their lower thermal insulation. These results indicate that in order to determine the acceptable heat cut-off time when using heat flexibility in the operation of district heating grids, it is essential to know the building thermal characteristics.

The daily heat flexibility of buildings was found to be significantly affected by weather conditions, including outdoor temperature and solar irradiance. It was found that the impact of weather differed between the well-insulated and poorly insulated buildings. For new buildings (2007-2010 SFH and renovated 1961-1972 SFH), outdoor temperature and solar irradiance both had a significant influence on the heat flexibility of the buildings, while for the oldest buildings (1850-1930 SFH), only outdoor temperature could be shown to have any influence.

ACKNOWLEDGEMENT

This study was supported by CITIES project and the EnergyLab Nordhavn project. This work is related to IEA EBC Annex 67 Energy Flexible Buildings.

REFERENCES

Danish Energy Agency 2014. Energy statistics 2013. https://ens.dk/sites/ens.dk/files/Statistik/energystatistics2014.pdf

The Danish Government 2013. The Danish climate policy plan-Towards a low carbon society. https://biobs.jrc.ec.europa.eu/sites/default/files/generated/files/policy/Danish%20Climate%20Policy%20Plan%20Towards%20a%20Low%20Carbon%20Society.pdf

Kensby et al. 2015. Potential of residential buildings as thermal energy storage in district heating systems. Applied Energy 137, 773-781

Frederiksen and Werner 2014. District heating and cooling. Studentlitteratur AB, Lund

Vanhoudt et al. 2017. The use of distributed thermal storage in district heating grids for demand side management. Preprint submitted to Energy and Buildings. https://arxiv.org/abs/1702.06005

Le Dréau and Heiselberg 2016. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 111, 991-1002

Wittchen and Kragh 2012. *SBi 2012:01* Danish building typologies-Participation in the TABULA project. Danish Building Research Institute, Aalborg University

TABULA WebTool, http://webtool.building-typology.eu/#bm

BR 2015. Danish building regulations 2015, http://bygningsreglementet.dk/file/591081/br15_english.pdf

Tommerup et al. 2007. Energy-efficient houses built according to the energy performance requirements introduced in Denmark in 2006. Energy and Buildings 39, 1123-1130

BBR 2012. Danish Enterprise and Construction Authority, The Building Stock Register (BBR - Bygnings- og Bollgregistret)

Danvak 1992. Stampe OB. Varme- og Klimateknik, Grundbog. Editors: Hansen HE, Kjerulf-Jensen P

TRNSYS 2013. TRNSYS 17 Technical Documentation Vol. 5, Multizone Building modeling with Type56 and TRNBuild

DMI 2016. *DMI Report 16-02* Denmark-DMI historical climate data collection 1768-2015 http://www.dmi.dk/fileadmin/user_upload/Rapporter/TR/2016/DMIRep16-02.pdf