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Heat analysis for energy management in neighbourhoods: case study of a large housing cooperative in Norway

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Abstract. As a basis for energy management in apartment blocks, this paper characterises heat use in a large housing cooperative in Norway, with in total 1,058 apartments. Heat measurements with hourly resolution are available from 20 heating substations. Average specific heat delivery is 139 kWh per heated floor area. A linear regression model is described, modelling specific heat delivered to the apartments. Models are also used for separating heat to domestic hot water (DHW) from the total heat delivery, with a modelled DHW heat delivery of 34 kWh/m^2. Daily heat load profiles are presented, for delivered heat during weekdays and holidays in the annual seasons. The study shows a potential for shifting heat loads in time on a neighbourhood level.

1. Introduction

In zero emission neighbourhoods, thermal and electric energy should be managed in a flexible way [1], to achieve reduced power peaks, reduced energy use, reduced CO_2-emissions and increased self-consumption of locally produced energy. As a basis for energy management in apartment blocks, this paper characterises heat use in a large housing cooperative in Trondheim, Norway, built in the 1970s.

In Risvollan housing cooperative, there are 1,058 apartments with in total 93,713 m^2 heated floor area, distributed on 121 similar apartment blocks. 2,321 residents live in the apartments: 53% female and 47% male residents [2]. 24% are under 20 years old, 40% between 20 and 50 and 33% above 50 years old. District heating (DH) provides space heating and domestic hot water (DHW) to the apartments, as illustrated in Figure 1. DH is distributed to 20 heating substations (SUBs) through three distribution lines (DL), with a supply set point temperature of 76°C all year. The 20 SUBs cover from 25 to 74 apartment units per SUB. The DHW set point temperature is 60°C. The temperature in the space heating system can be changed on SUB-level, by changing the outdoor temperature compensation curves in the SD-system. The applied settings for these temperature curves are similar for all the SUBs, as shown in Figure 1.

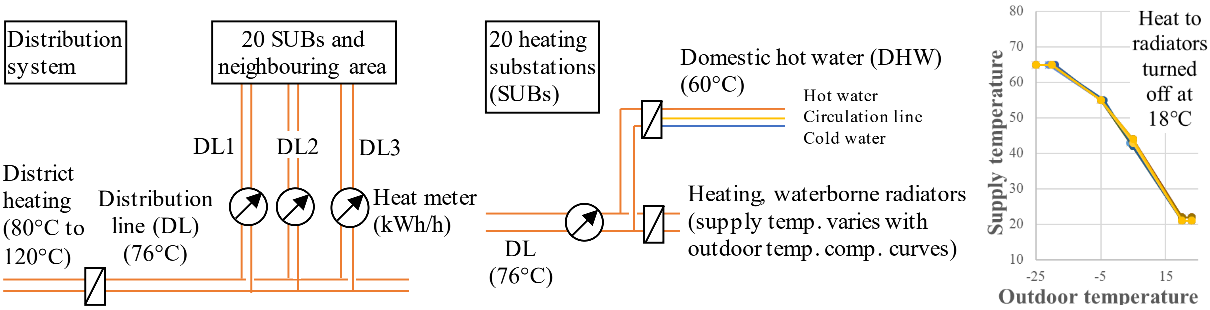

Figure 1. Heat distribution (left) and delivery of DHW and heating from the 20 SUBs (middle) to the 1,058 apartments in Risvollan. Right: Outdoor temperature compensation curves for the 20 SUBs.

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Residents can also adjust the valves on the waterborne radiators in the apartments. However, O&M staff experiences that most resident do not frequently manually regulate their heat supply. When the outdoor temperature exceeds 18°C, the heating circulation to radiators is automatically turned off.

2. Data

2.1. Data collection and quality assurance

Heat measurements from 20 SUBs are available from an energy monitoring system, starting from 2018 [3]. The meters measure space heating and DHW combined, where each measurement gives accumulated heat delivery the previous hour. In this research, the data are analysed using the statistical computing environment R [4]. The data quality is analysed with visual inspection and by studying peak- and zero-values. For 13 SUBs, the heat measurements have a resolution of 10 kWh per hour, while the remaining 7 SUBs have a resolution of 100 kWh per hour. Low measurement resolution may affect load profiles by shifting the load to the subsequent hour [5], which is the case especially for the 100 kWh-resolution measurements. After evaluating the measurement resolution and data quality, all the 7 SUBs with 100 kWh and 3 SUBs with 10 kWh resolution were excluded from the detailed analysis, analysing daily heat load profiles and peak values. The measurements are still used when evaluating annual heat delivery. The 10 SUBs used in the detailed analysis, cover about half of the housing cooperative: 536 apartment units with a heated floor area of 46,030 m^2 and 1,161 residents.

The climate data are collected from eKlima [6]. The outdoor temperatures (code TA) are mainly from a weather station at Risvollan, where a few missing values are replaced with data from weather station Voll, 2.5 km away. The wind data (code DD and FF) are also from Voll, while the global radiation (code QSI) and minutes of sunshine each hour (code OT) are from the weather station Gløshaugen, 3 km away.

Holidays are identified as days where the primary schools are closed in Trondheim [7], including national bank holidays. If the schools are closed on a Friday or Monday, the weekends are marked as holiday-weekends. The annual seasons have three months each, where the spring season starts in March.

Table 1. Heat delivery to the 121 apartment blocks in Risvollan housing cooperative in 2018.

	Area	**Bldg**	**Apt**	**Res**	**Heat deliv.**	**Heat pr. res**	**Specific heat deliv.**	**If incl. garages**	**Max hourly**	**Max daily**
	m^2	Nr.	Nr.	Nr.	MWh/yr	kWh/res/yr	kWh/m^2/yr	kWh/m^2/yr	kWh/m^2/h	kWh/m^2/h
SUB-1	5,258	6	56	137	770	5,624	147	147	0.059	0.83
SUB-2	4,758	5	56	128	483	3,775	102	102	0.048	0.61
SUB-3	3,790	5	44	99	492	4,971	130	130	0.053	0.71
SUB-4	4,663	5	54	122	653	5,352	140	140	0.056	0.92
SUB-5	3,680	6	43	98	506	5,161	137	137	0.052	0.73
SUB-6	4,887	6	62	115	650	5,654	133	133	0.053	0.71
SUB-7	4,197	5	45	107	770	7,192	183	110	0.086	1.10
SUB-8 *	6,139	5	74	139	830	5,974	135	115	0.052	0.72
SUB-9	4,507	5	54	116	605	5,216	134	134	0.053	0.73
SUB-10	4,150	4	48	100	578	5,776	139	139	0.055	0.81
SUBs									Accumulated	
in analysis	46,030	52	536	1,161	6,337	5,458	138	127	0.051	0.75
SUBs remaining *	47,684	69	522	1,150	6,698	5,825	140	111		
Total	93,713	121	1,058	2,311	13,036	5,641	139	118		

* Heat delivery is estimated for 3 months for SUB-8 and 1 month for two of the remaining SUBs. However, only actual measurements are included in model development and for load profile analysis.

Abbreviations: Bldg: Buildings. Apt: Apartments. Res: Residents. Deliv: Delivery. SUB: Heating substation.

2.2. Heat delivery to the Risvollan apartments in 2018

Table 1 shows heat delivery to Risvollan in 2018. The average specific heat delivery from the 20 SUBs is 139 kWh/m^2. SUB2 and SUB7 stand out, with a low heat delivery of 102 kWh/m^2 and a high heat delivery of 183 kWh/m^2. Heated garage area is the main reason for these differences, as shown in the table. Garages are not included in the heated floor area, but heat delivered to garages is included in the measurements. Other explanatory variables may be differences in heat losses and occupant behaviour. The average heat delivery per resident is 5,641 kWh per person. The max hourly value for the 10 SUBs in the analysis vary from 0.048 to 0.086 kWh/m^2/h, where most of the SUBs have a max value from 0.05 to 0.06 kWh/m^2/h. Variations are also to be expected within each SUB, on apartment level [8].

Figure 2a) shows specific heat delivered from the 10 SUBs included in the analysis. The figure also shows duration curves for specific heat, delivered 1) each hour and 2) daily average energy per hour. The difference between the duration curves illustrate the potential for reducing peak values, if a heat storage was available for 24 hours heat delivery. Figure 2b) illustrates an example of daily coincidence curves, for March 2nd, 2018. The figure shows 10 SUBs individually, the 10 SUBs accumulated, and three DL heat meters accumulated. This date is chosen since it has the highest 2018-hourly peak for *all* the three DL heat meters. The curves show a morning and afternoon peak in the heat delivery.

The coincidence factor for the 10 SUBs is 0.90, based on hourly values. This factor is defined as the ratio between maximum load for the accumulated measurements studied and the sum of each SUBs maximum load [5], and is always less or equal to unity. As a comparison, [5] found district heating coincidence factor for clusters with app. 10 buildings (single family houses and apartment blocks) to be 0.711. The coincidence factor is dependent on the number of customers served, and if the customers represent a homogeneous or heterogeneous group [5]. At Risvollan there is a rather large and homogeneous customer group and buildings per SUB, which can explain the high coincidence factor.

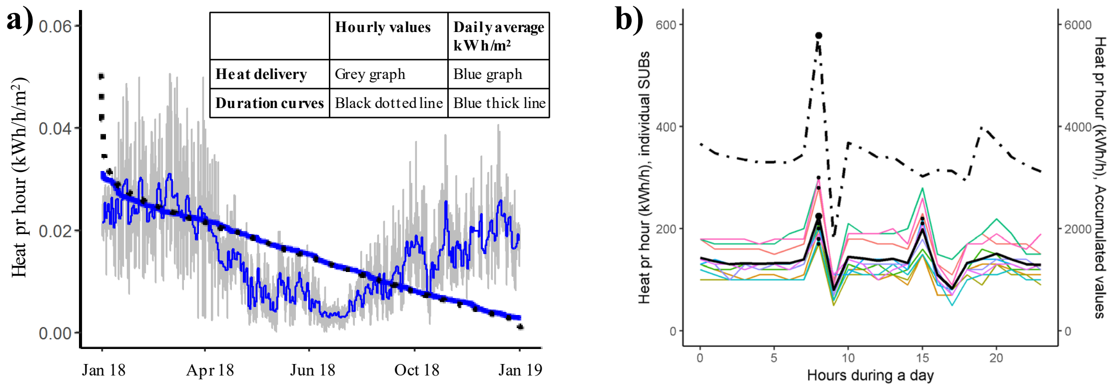

Figure 2 (a). Specific heat delivered from 10 SUBs each hour and daily average energy per hour. Lines show duration curves for specific heat delivered each hour and daily average energy per hour. **(b).** Coincidence curves for March 2nd, 2018, with hourly heat and max points for 1) 10 SUBs (coloured), 2) total heat for 10 SUBs (black line), 3) total heat for 3 DL meters (dotted).

3. Methods

Linear regression models [9] are developed based on data from 2018, for predicting heat delivered to space heating and DHW. For the heat modelling, only the high-quality data from the 10 SUBs are included. Measurements from three days in April and October are removed, since the water temperature was raised these days to prevent legionella growth.

The methodology used for modelling is mainly based on methods described by [5, 10]. Quantitative and categorical explanatory variables are tested, to specify a linear regression model for the response variable "heat per area per hour". The quantitative variables tested are outdoor temperature, average outdoor temperature (TMA) the last 3, 6, 9, 12, 15, 18, 21 and 24 hours, wind speed, solar radiation, minutes of sun each hour and residents per area. The categorical variables tested are hour of the day, weekdays / weekends, holidays, SUBs and wind direction. Weekdays, weekends and holidays are tested in both separate and joined models. In the joined model, the categorical variable "hour of the day" is divided in weekday (wd), weekend (we), weekday holiday (wd_h), weekend holiday (we_h), with 24 values per category, in total 96 values. Also, interaction between temperature and daily hours are tested in the model, giving different slope and intercept for each line [11]. Lastly, models are tested with a break point, with segmented relationships between the response and the explanatory variables [12, 13]. When comparing the models, the adjusted R^2 and the significance of the terms are considered. For the most promising models, predictions and residuals are analysed. The chosen model is tested on data from January to February 2019. When estimating energy for DHW, revised models are used (Named A and B). The DHW models are based on heat data from 2018 until May 2019, setting the outdoor temperature to the approximate break-point temperature of the model. The DHW estimation is compared with a DHW measurement period of one months in one of the SUBs, during May 2019.

4. Results

An excerpt of the linear regression models evaluated are shown in Table 2, with the chosen model 8 in equation 1. Model 8 is chosen instead of nr. 9, since hourly predictions for wind and solar data are not sufficiently reliable for Risvollan. This would affect the result if using the model for prediction. The chosen model has a break point for outdoor temperature of 19.0°C. Adjusted R^2 is 0.8438. Model A and B-8 are used for DHW estimation, where model A is for Risvollan while model B-8 is for SUB-8 only.

Table 2. An excerpt of the linear regression models evaluated for heat delivery to Risvollan.

	Variables						*Interactions*		Sub:	T:h:	T:h:sub:	Break-	df	Adjusted
Mod	T	h	sub	TMA18	W	S	T:h	T:sub	TMA18	sub	TMA18	point T		R^2
1													107	0.8149
2													202	0.8196
3													211	0.8345
4													1066	0.8357
5													220	0.8379
6													1075	0.8389
7													1067	0.8306
8												19.01°C	222	**0.8438**
9												17.96°C	224	0.8515
A												18.77°C	212	**0.7973**
B-8			SUB-8									20.60°C	194	**0.7744**

$$y_t = \beta_0 + \beta_T T_t + \beta_h D_h + \beta_{sub} D_{sub} + \beta_{TMA18} \mathrm{TMA18}_t + \beta_{Th} T_t D_h + \beta_{Tsub} T_t D_{sub} + \beta_{subTMA18} D_{sub} \mathrm{TMA18}_t + \gamma_{t,T>bp} + \varepsilon_t \tag{1}$$

Table 3. Variables and symbols / indexes used in Table 2 and equation 1.

Variables	Description	Symbols	Description
t	Any hour t throughout the year (1-8760)	β_0	Fixed time independent effect
y_t	Specific heat delivered in hour t (kWh/m²/h)	β_h	Effect on hour-of the day (1-96)
D	Dummy variable for categorical variables, h and sub	β_{sub}	Effect on SUB (1-10)
T_t	Outdoor temperature in hour t	β_{TMA18}	Effect on TMA18 in hour t
h	Hour-of the day (1-96, as wd, we, wd_h and we_h)	β_{Thsub}	Effect on interaction between T, h and sub
$\mathrm{TMA18}_t$	18 hour moving average of T_t	$\gamma_{t,T>bp}$	Effect when T_t is above break-point temp.
sub	Heating substation	ε_t	Error term of regression
W	Wind speed in hour t	df	Degrees of Freedom: Measure in statistics of how many values can vary
S	Global radiation (QSI) in hour t		

The modelled value of specific heat delivered to the 10 SUBs is 138 kWh/m² in 2018, which equals the measured value. When testing the model for January and February 2019, the specific heat modelled for 9 SUBs these two months is 32.2 kWh/m², while the measured value is 33.2 kWh/m². Delivered heat to DHW is estimated by setting the outdoor temperature to 19°C all hours. With this method, delivered energy to DHW is 34 kWh/m² or 1,360 kWh per resident in 2018, equivalent to 24% of the heat delivery.

The energy signature reflects the relationship between energy use and different outdoor temperatures. For most of the hours the slope is similar, but for hour 8, representing the time slot from 7 to 8 in the morning, the slope is steeper, illustrating that delivered heat is higher this hour, see Figure 3.

Figure 4 shows daily heat load profiles for delivered heat during weekdays and weekends in the summer and winter season, with holidays separated. For the daily heat load profiles, the hourly values are the sample mean values. The figure shows the fit between the modelled hourly means and the 2018-measurements. The daily heat load profiles show a morning peak from 7 to 8 during working days and a delayed morning peak during weekends. The peaks are primarily linked to DHW use. During holiday periods the heat delivery is reduced. The modelling result of DHW is shown in Figure 5, together with available DHW measurements from SUB-8 during May 2019.

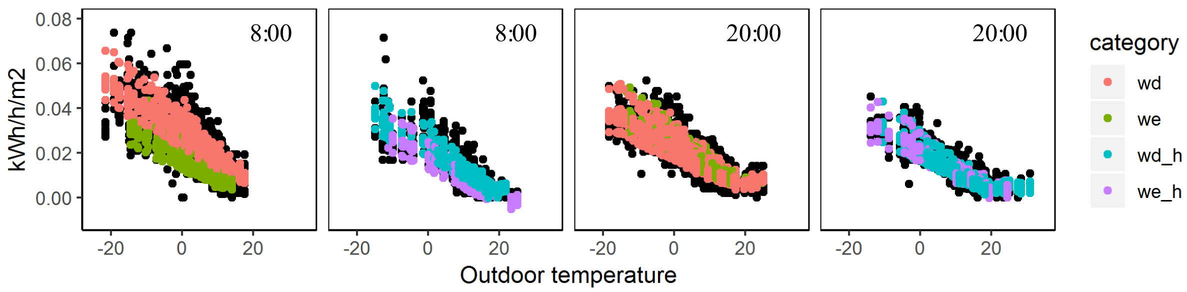

Figure 3. Hourly energy signatures of Risvollan, at the hour 8:00 and 20:00, divided on working days and holidays. The modelled data points are coloured, while the 2018-measurements are black dots.

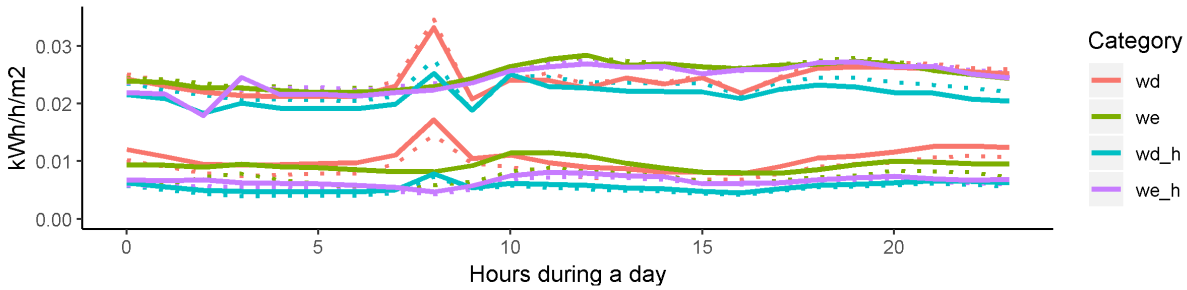

Figure 4. Average daily heat load profiles at Risvollan during summer (Jun-Aug, lower plots) and winter (Dec-Feb, higher plots). Modelled hourly means (lines) are based on 2018-data (dotted).

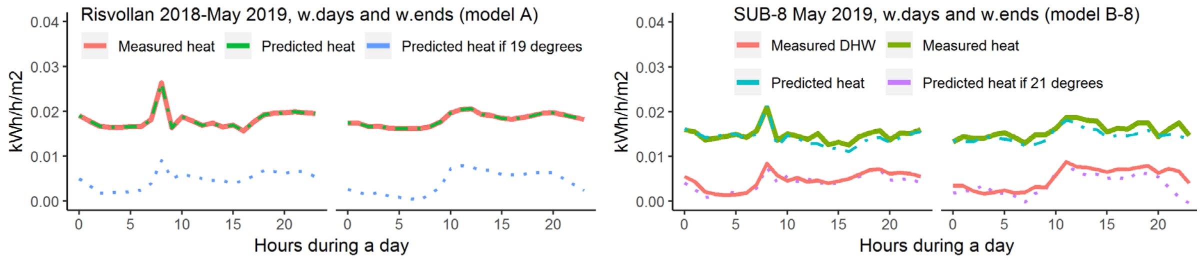

Figure 5. Daily heat load profiles for Risvollan (left) and SUB-8 only (right). The two models are based on measurements from Jan 2018 to May 2019. For DHW estimation, heat prediction is shown for outdoor temperatures above break point temperature (19°C or 21°C), every hour of the year.

5. Discussion

This paper characterises heat use in Risvollan housing cooperative. The linear regression model described, represents well the specific heat delivered in 2018. The testing period of two months in 2019 also give a modelling result close to reality, with modelled heat delivery 3% less than measured heat delivery. The input values of the model are easily available also for predicting heat delivery, since it only includes outdoor temperature as climate data. The model can be developed further, preparing for short-term forecasting in an energy management system, e.g. by analysing the autocorrelation function for the model residuals [14]. When improving the model, also measurements after 2018 are available.

Total delivered heat in 2018 was 138 kWh/m^2 or 5,458 kWh per resident. Compared to low energy buildings the heat delivery per area is high, and the project EBLE measured delivered heat between 23 to 58 kWh/m^2 in 19 passive houses [15]. DHW heat delivery is modelled to 34 kWh/m^2 or 1,360 kWh per resident, by setting outdoor temperature to 19°C all hours. There are few data points above 19°C, especially for non-holidays and night time. When modelling DHW, a temperature close to break-point temperature was therefore used, to make the results as reliable as possible. The DHW result is in the range of the limited DHW measurements available, in SUB-8 during May 2019. The value 34 kWh/m^2 is also comparable with the Norwegian norm value of 29.8 kWh/m^2 [16]. The project EBLE measured energy for DHW in 29 houses or apartments, with values from 18 to 42 kWh/m^2 [15]. Seasonal variations in delivered DHW [17] is not considered in the model, due to few DHW measurements.

The study shows a potential for shifting heat loads in time, on a SUB or neighbourhood level. The following possibilities are identified: 1) Duration curves, coincidence curves and daily heat load profiles show that heat loads can be shifted in time. Especially the morning peak can be shifted from peak hours to the night-time, by installing heat accumulation tanks in the SUBs. On an *average* working day during winter (Dec-Feb, ref. figure 4), the increase to *average* morning peak from 7 to 8 is in the range of 0.01 kWh/m^2, which need a storage volume of app. 0.2 litre/m^2. 2) The peaks are primarily linked to DHW use. If delivered temperature is increased before the peak hours, the need for delivered space heating could be reduced during DHW peak hours. This could be arranged by changing the set-points in the compensation curves. However, if this should be tested in practice, O&M staff needs to be sure that the comfort of the residents will not be reduced. A pilot test in five multifamily residential buildings in Sweden, indicate that buildings with a structural core of concrete can tolerate relatively large variations in heat deliveries while still maintaining a good indoor climate [18]. 3) It may also be possible to increase the temperature in the distribution line. If the temperature set-point is increased during off-peak periods, e.g. during the night, the distribution line can function as a heat storage, reducing the need for district heating delivery during peak hours. When evaluating such an approach, thermal stresses should be taken into account, since there will be a more frequent cycling between higher and lower temperatures [19].

6. Conclusion

This paper characterises heat use in a large housing cooperative in Norway, built in the 1970s, with in total 1,058 apartments. A linear regression model is described, modelling the specific heat delivered to the apartments. The model is also used for estimating the share of heat for DHW. The study shows a potential for shifting heat loads in time on a SUB or neighbourhood level. The analysis and model will be used in further work, together with analysis of electricity use at Risvollan, to address how effective management of power and energy in neighbourhoods can be realized.

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