Energy analysis and energy planning for kindergartens based on data analysis

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Energy analysis and energy planning for kindergartens based on data analysis

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Abstract. The aim of the study was to utilize different building data for prediction of development in energy use of a typical building type. In this study, energy use and its future development for kindergartens in Trondheim, Norway, were analyzed. The energy use data were retrieved from the energy monitoring platform of Trondheim Municipality. The total area of all the kindergartens was about 76 000 m^2, where the area of each kindergarten was ranging from 100 – 4 471 m^2. Firstly, typical heat and electricity duration curves per m^2 of kindergartens in Trondheim within six years were identified. Secondly, the kindergartens were divided into two cohorts based on their connection to district heating (DH). The average total annual energy use was 177 kWh/m^2 for kindergartens without DH, and 168 kWh/m^2 for kindergartens connected to DH. The peak load values were similar for both cohorts, about 140 W/m^2. Analysis of the duration curves showed a bigger electricity load variation for the kindergartens without DH connection. Within the building cohort with DH, three cases were found depending on the energy share from DH; i.e. DH high share, DH average share, and DH low share. By following different background data for CO_2 factors of electricity and local DH, the kindergarten with DH high share had almost the lowest annual CO_2 emission. Contrarily, the annual CO_2 emission of a kindergarten with lower share of DH, or without DH, usually had a wider range of emissions due to its dependence of the electricity production mix. Finally, a prediction was made by assuming 14.2 % growth rate of kindergartens on the ground of the average six-year total kindergarten area. The result showed that if more than 50- 67 % of the new building area would be connected to DH, a smaller increase of CO_2 emission from the projected area could be achieved, depending on the relevant CO_2 factors. This proved that buildings with DH were more robust than the one without DH concerning CO_2 emission. The suggested analysis method and identified duration curves could be used to as a reference example for defining energy profiles of other building types. These profiles are necessary for diversifying and upgrading local energy supply pathways, infrastructure sizing, and improving urban energy planning.

1. Background

Approximately 36-40 % of energy is consumed in building service around the world each year, and it is responsible for nearly 40 % of direct and indirect CO_2 emissions [1]. Therefore, urban building stocks are expected to make high contribution for low energy use and reduction of greenhouse gas emissions. In Norway, due to cheap and green electricity power from the abundant hydro-power, coverage rate of district heating (DH) system is small. DH only contributes approximately 11 % of total heating demand in Norway [2]. Norwegian residential and service buildings are highly reliant on electricity for space heating (SH) and domestic hot water (DHW). Whereas, driven by the motivation of economic and environmental benefits of DH, relevant regulations and investment subsidies have been introduced to expand the build-up of DH system in Norway. As the third largest city in Norway, Trondheim municipality has been committed improving urban plans for better living environment under the pressure of urbanization, population growth, and mitigation of anthropological carbon footprint [3].

The aim of this article was to identify energy profiles of one typical building type in Trondheim. Typical profiles of energy use can be used as input to building simulations and model calibration. The historical energy use data of kindergartens from 2013 to 2018 was retrieved from the energy monitoring platform of Trondheim Municipality [4]. The outdoor weather data and energy use was given in hourly resolution. Besides kindergarten, school, heath/nursing center, sports center and others are also monitored.

2. Methods

2.1. Building general information

During the six years, numbers of total kindergartens have been increased from 83 to 99. Based on the connection to DH, the kindergartens were divided into two cohorts, Cohort 1 and Cohort 2. In Cohort 1, the buildings are not connected to DH, and supplied by electricity only, and in Cohort 2, the buildings are connected to DH. The yearly building numbers and building area of the two cohorts were compared in Table 1. In total, there were 559 hourly files of kindergartens being used in the analysis.

Table 1. Building numbers and area of Cohort 1 and Cohort 2.

		2013	2014	2015	2016	2017	2018
Building numbers (-)	Cohort 1	66	66	68	68	71	71
	Cohort 2	21	23	26	27	28	28
	Total	83	89	94	95	99	99
Building area (m^2)	Cohort 1	36979	38855	40890	40890	43259	43259
	Cohort 2	24623	26317	30105	31766	32768	32768
	Total	61602	65172	70995	72656	76027	76027

It shows that generally the share of Cohort 2 is smaller than Cohort 1 but growing, especially when it comes to the building area. As shown in Figure 1, the blue square stands for Cohort 1 and the red for Cohort 2, and the green line demonstrates the percentage of Cohort 2, Cohort 2 covers around 43 % of total building area till 2018. This can be explained in Figure 2 by plotting the relation between building area and weekly-based load needs. Most of the kindergartens in Cohort 1 were built within small to medium size (in blue stars), while kindergartens in Cohort 2 were within medium to large size (red circles). The area of each kindergarten varies largely from 100 to 4471 m^2.

2.2. Energy duration curve per m^2

There is a big variety of the building area of each kindergarten, hence, the load duration curves were analyzed based on energy demand per m^2. For buildings in Cohort 1, the duration curves were made only by electricity use. For buildings in Cohort 2, the duration curves of electricity and DH were analyzed separately. Yearly duration curve of each building was obtained by sorting annual load hourly profile from highest to lowest values, and average duration curve was made by the mean values of all the curves. From the average energy use under its outdoor temperature, energy signature was established to imply the relation between energy demand per m^2 and outdoor temperature. MATLAB was used for energy data analysis.

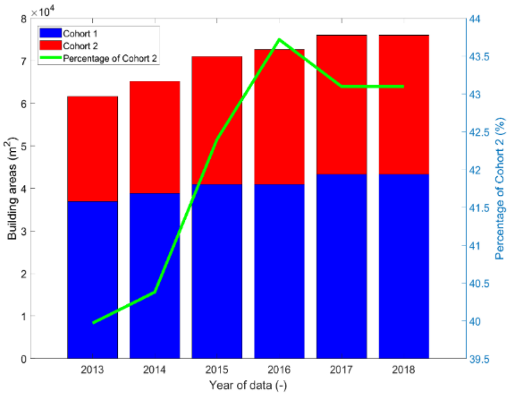

Figure 1. Building area comparison of Cohort 1 and Cohort 2.

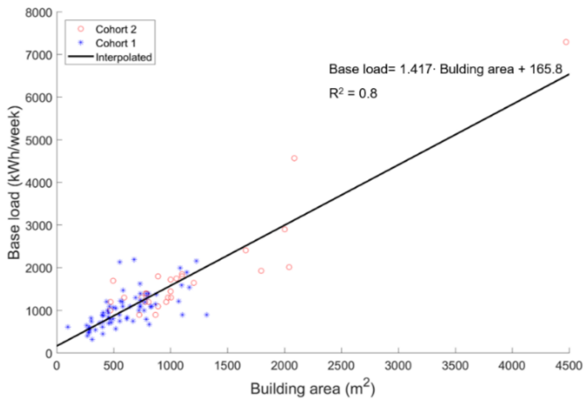

Figure 2. Building area vs Building weekly base load of Cohort 1 and Cohort 2.

2.3. *Energy coverage rate in Cohort 2*

In Cohort 2, heating demand was provided by DH and the other energy demand by electricity. In order to see the contribution from the two energy supply ways, Figure 3 demonstrates the energy coverage rates from DH and electricity in Cohort 2. In Figure 3, DH was marked in red and electricity in blue, each bar stands for the average energy use situation of one kindergarten from 2013 to 2018, and all the 28 kindergartens were included. From the bar chart, three cases were defined, they were named as DH average share, DH high share and DH low share. In the case of DH high share, nearly 76.9 % of total energy use comes from DH, 31.4 % higher than the case of DH low share. On average, DH supports 60.0 % of total energy use, as listed in Table 2.

Table 2. Energy coverage rate of three cases in Cohort 2.

	From DH (%)	From electricity (%)
DH average share	60.0	40.0
DH high share	76.9	23.1
DH low share	45.5	54.5

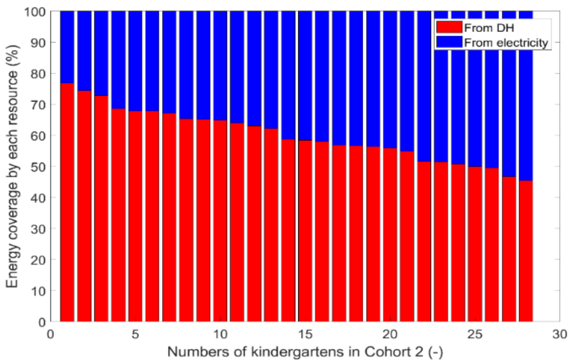

Figure 3. Energy coverage rates of DH and electricity in Cohort 2.

2.4. *CO_2 factors of electricity and DH production*

Benefitting from the modern transmission technology and the characteristic of electricity, electricity is capable of long-distance transmission with less than 5 % of loss. Norway is connected in the Nordic power grid and further expanded into the wider European grid, and electricity is traded in the free market. Within the Norwegian border, CO_2 factor of electricity can be as low as 10 gCO_2/kWh (named as $CO_{2\text{-}EL1}$), which is mainly contributed by the abundant hydro-power, however this factor can be high up to 110 gCO_2/kWh ($CO_{2\text{-}EL2}$) in the Nordic region since fossil fuels are involved in the electricity production mix. Distinguished from electricity, the transmission loss of heating can be quite high, which makes DH not suitable for long-distance transport. Therefore, the equivalent energy and environmental factors of DH is mostly locally specified. From the information of Norsk Fjernvarme, during 2010 to 2018 most of the DH in Trondheim has been provided by waste incineration, followed by fossil gas with the contribution of around 10 %, and the small rest comes from flexible electricity, bio-energy, ambient heat, and fossil oil [5]. In Norway, in accordance to NS 3720-2018, the CO_2 emission from waste-to-energy for energy production (electricity and DH) has been allocated to the sector of waste management instead of energy sector [6]. The CO_2 factors of DH production in Trondheim were calculated based on the annual production composition of energy sources. Three typical CO_2 factors of DH were found, they are the average value from 2010 to 2018, value of 2015 as the 9-year lowest, and value of 2010 as the 9-year highest. These factors were used as background data for the assessment of CO_2 emission, respectively. The CO_2 factors of DH production in Trondheim are listed in Table 3, and the CO_2 data of fossil gas, bio-energy and fossil oil can be found in Norsk Energi [7].

Table 3. CO_2 factors of DH production in Trondheim.

		2010-2018: $CO_{2\text{-DH1}}$	2015: $CO_{2\text{-DH2}}$	2010: $CO_{2\text{-DH3}}$
Composition of energy sources (%)	Waste incineration	74.0	83.1	61
	Fossil gas	10.8	5.9	20
	Flexible electricity	8.5	5.0	6
	Bio-energy	4.0	4.0	5
	Ambient heat	0.8	1.0	1
	Fossil oil	1.9	1.0	7
CO_2 factors (gCO_2/kWh)		41.66	23.5	76.3

2.5. Annual CO_2 emission of one typical kindergarten and future prediction

From Figure 2, a typical kindergarten in Trondheim was determined at 700 m^2 concerning the main size ranges the two cohorts. For the buildings in Cohort 1, as addressed above regarding the difficulty of splitting energy share from heating and electricity, therefore, the annual CO_2 emission comparison of one typical kindergarten between Cohort 1 and Cohort 2 was made based on the annual average energy demand of Cohort 1. For Cohort 2, the three cases regarding DH shares were considered separately.

After the annual CO_2 emission calculation of one typical kindergarten was made and compared, the impact of new building area was predicted. In this article, 10 000 m^2 of new building area of kindergarten (A_{new}) was assumed to be added in Trondheim. The building area growth rate (r) was defined as the ratio between (A_{new}) and the annual average total building areas of kindergarten throughout the six years, which is 70 413 m^2. The increasing building area rate is 14.2 %. This growth rate was used as the reference line, and compared with the CO_2 growth rate based on different background data by varying the percentage of new building area connected to DH (x). For simplicity, the annual CO_2 emission was calculated based on the CO_2 factor of Nordic electricity ($CO_{2\text{-EL2}}$) and the three DH production factors. Meanwhile, for the new area connected to DH, the case of DH average share was used. In Function (1), as the denominator, the average annual average CO_2 emission of all the kindergartens ($\overline{CO_2}$) was calculated from the annual average energy use of Cohort 1 and Cohort 2 within the six years. The comparison between growth rates of building area and CO_2 can be explained as:

$$r - \frac{CO_{2-added}}{\overline{CO_2}} \cdot 100\% \tag{1}$$

$$CO_{2-added} = [A_{new} \cdot (1-x) \cdot E_{EL} + A_{new} \cdot x \cdot E_{DH-EL}] \cdot CO_{2-EL2} + A_{new} \cdot x \cdot E_{DH-DH} \cdot CO_{2-DHi}$$
$$(i = 1, 2, 3)$$

When Function (1) = 0, there is a break-even point that the increasing rates of CO_2 emission and new building area are same. When Function (1) < 0, it means if increasing new building area by 14.2 %, more than 14.2 % more CO_2 emission would be produced. On the contrary, when Function (1) > 0, it implies that slower CO_2 emission growth could be achieved.

3. Results

3.1. Results of energy duration curve and Energy signature per m²

The annual average duration curves were presented in Figure 4, Figure 5, and Figure 6, and the annual energy demand were summarized in Table 4. Average duration curves were plotted in black thick lines. The peak load for the two cohorts are almost same. The maximum deviation from the average curves are 27.2 % in Cohort 1 and 24.3 % in Cohort 2. The deviation considers 0- 4000 hour in the duration curve. Energy loads during the last 4760 hours are small, and have minor influence of the grid and plant sizing. Moreover, peak load for Cohort 1 can only expect from electricity; while the peak load for Cohort 2 can be satisfied by DH and electricity, it releases the maximum demand of power grid. Although electricity use in Cohort 2 has weak relation with outdoor temperature, the duration curves of six years have similar pattern except higher use in 2013. It may be explained that fewer kindergartens were used for the analysis, and it caused the large deviation. The detailed annual duration curves can be found in Appendix Figure A 1 to Figure A 6, and there were several unknown high peak loads in Cohort 1.

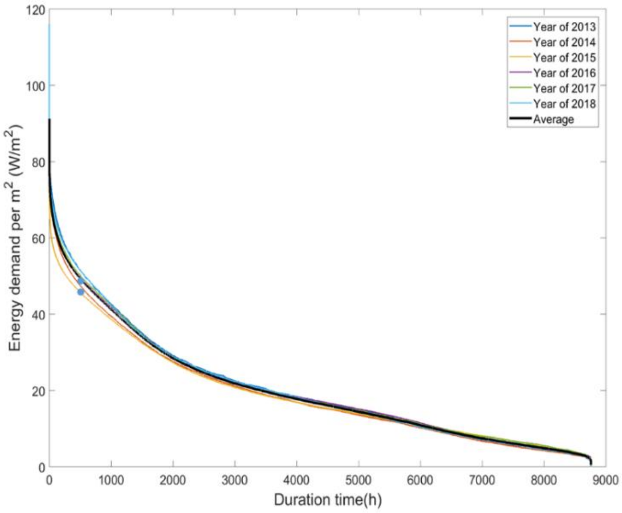

Figure 4. Average total energy duration curves of Cohort 1.

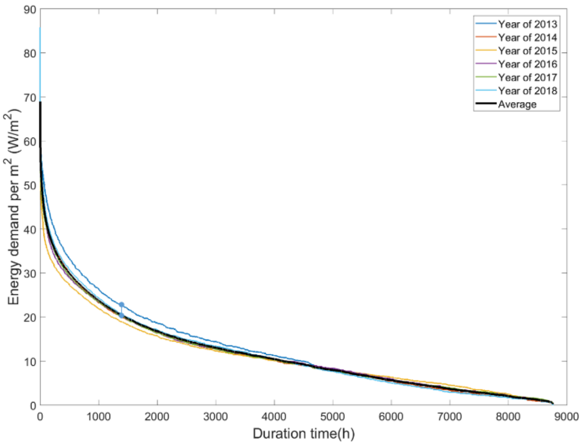

Figure 5. Average heating energy duration curves of Cohort 2.

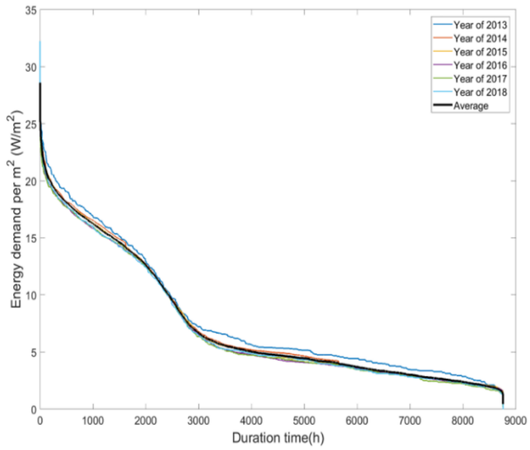

Figure 6. Average electricity duration curves of Cohort 2.

Table 4. Average annual energy use of Cohort 1 and Cohort 2.

		2013	2014	2015	2016	2017	2018	Average
Cohort 1	E_{EL} (kWh/yr)	182.3	169.6	169.6	180.9	180.8	179.8	177.2
Cohort 2	E_{DH-DH} (kWh/yr)	111.6	100.9	98.8	102.2	101.6	102.9	103.0
	E_{DH-EL} (kWh/yr)	69.9	65.4	64.6	62.9	62.5	63.1	64.7

Moreover, to see if the energy use followed the outdoor temperature (t_{od}), heating degree days (HDD)/ heating degree hours (HDH) and energy signature were adopted as rough measurements.

Firstly, heating degree days (HDD)/ heating degree hours (HDH) is the integral of difference between indoor and outdoor temperatures, and is robust tool of predicting space heating. 12- 18 °C are commonly used as the effective indoor temperature to avoid oversizing of heating plants [8]. In this article 18 °C was chosen to roughly estimate the colder and milder weather conditions. The HDH of the six years can be found in Table 5. The average annual heating use of Cohort 2 (E_{DH-DH}) better followed the outdoor temperature (t_{od}) than the average annual energy use of Cohort 1 (E_{EL}).

Table 5. Heating degree hours of six years.

	2013	2014	2015	2016	2017	2018
°C·h	107562.4	94982.4	99146.4	106567.2	105487.2	106156.8

Secondly, energy signature curve can be used as a function of t_{od} to describe and predict heating energy demand [8] [9]. Figure 7 and Figure 9 were made by average hourly energy demand of six years (105 168 hourly data). For buildings in Cohort 1, it is rather difficult to draw one interpolation curve to describe the relation between energy demand $P(t_{od})$ and (t_{od}) in the whole temperature range. There was a break around 5 °C, and energy demand turning back and forth with t_{od}. The appearance of break has been discussed before in caused by changing of heating equipment under different t_{od} [10]. In this article, it can be explained that some electric heating equipment may be shut down during off- work hours in Cohort 1. For example, electric resistant heater has little thermal inertia, which makes it unnecessary to keep on with non-appearance of occupants. Since electricity is used both for heating and other electric appliances, it is not easy to make accurate calculation of energy consumption share for heating and other electric uses. To know the daily operation routine of these buildings is needed. For buildings in Cohort 2 of hydronic DH system, SH and DHW are measured in one meter. The DHW use of one kindergarten was assumed as constant as its six-year average use, and its annual use followed the Norwegian statistic data [12], which is around 9 kWh/m^2 in most of Norwegian kindergarten. Figure 8 presents the distribution of the ratio between the annual hot water use and total heating needs within the six years. Clearly, DHW accounted for less than 9 % of total heating demand in most of the kindergartens and had a small influence in the whole picture. In this article, to describe the relation between SH and t_{od} more accurately, DHW use was deducted from the total DH needs. DHW use profile was roughly assumed as the DH use when t_{od} higher than 18 °C (the effective indoor temperature) in May, June, and August (kindergartens are mostly closed in July). For weekends, coefficient of 0.2 was considered. As shown in Figure 9, it is relatively easy to establish the energy demand function of t_{od} in polynomials through the entire outdoor temperature range. The function was written as:

$$P(t_{od}) = p_1 {t_{od}}^i + p_2 {t_{od}}^{i-1} + p_3 {t_{od}}^{i-2} + p_4 \qquad (2)$$

$$(i = 1,2,3. If\ i-2 < 0, p_{3,}\, p_4 = 0;\ if\ i-2 = 0, p_4 = 0\ )$$

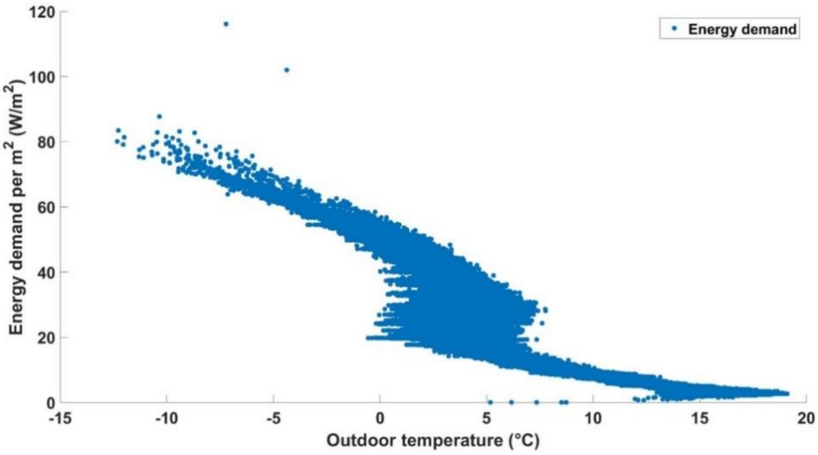

Figure 7. Energy demand vs Outdoor temperature of Cohort 1.

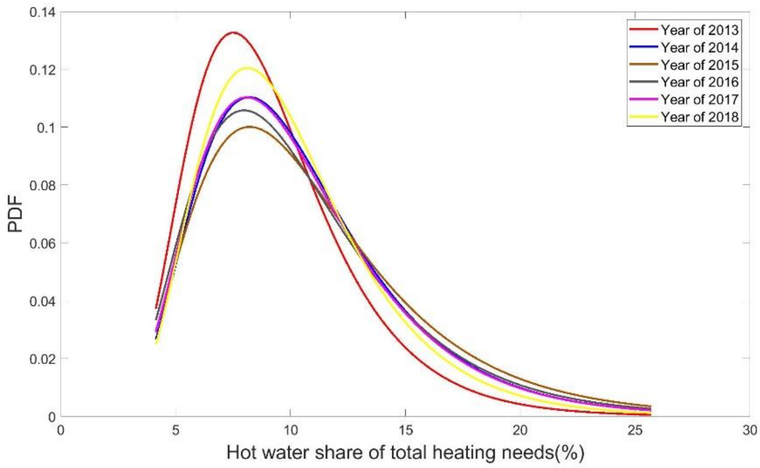

Figure 8. Distribution of hot water use in total DH needs of six years.

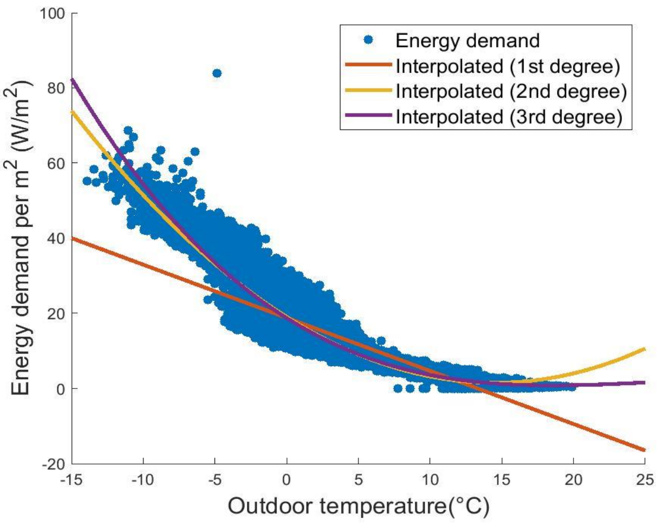

Figure 9. Energy signature curve of DH demand of Cohort 2 under 1st degree, 2nd degree, and 3rd polynomial.

To make sure of the goodness-of-fit of the model, the coefficients of determination R^2 was used. The value of R^2 should not be less than 0.75 as a rule of thumb in the analysis of building energy [12]. The coefficients of Function (2) and R^2 of each polynomial were shown in Table 6. It can be seen that even the simplest 1st degree polynomials satisfies the requirement of R^2 and fulfil the prediction of energy demand. This can be used to predict hourly heating load in the accordance with reference weather year, which is developed based on decades of weather data and can be found in database library [13]. The load profile can be used as input to energy system modelling, such as EnergyPLAN [14].

Table 6. Coefficients of Function (2) and R^2

	p_1	p_1	p_3	p_4	R^2
1st degree	-1.414	18.82	/	/	0.7927
2nd degree	0.08309	-2.412	19.02	/	0.8977
3rd degree	-0.001359	0.1027	-2.403	18.72	0.8995

3.2. Calculation of CO_2 emission of one typical kindergarten

In Figure 10, the stand-alone two bars at right side represent the building without DH. The annual CO_2 emission can be hugely increased from 1.2 tCO_2/yr to 13.6 tCO_2/yr when CO_2 factors of electricity changed from 10 to 110 gCO_2/kWh by making it the worst case. In the green square, three cases of different DH shares were compared, and their combinations regarding CO_2 factors were made as: blue bars of Norwegian electricity ($CO_{2\text{-EL1}}$) with average DH production ($CO_{2\text{-DH1}}$), orange bars of Nordic electricity ($CO_{2\text{-EL2}}$) with average DH production ($CO_{2\text{-DH1}}$), yellow bars of $CO_{2\text{-EL2}}$ with DH production of 2015 ($CO_{2\text{-DH2}}$), and purple bars of $CO_{2\text{-EL2}}$ with DH production of 2010 ($CO_{2\text{-DH3}}$). All the blue bars still gave the smallest values in each case since CO_2 factor electricity was 10 gCO_2/kWh. From the results, it can be seen that if electricity shoulders more energy supply, the total annual CO_2 emission can be varied a lot depending on the CO_2 factor of electricity. While in the case of DH high share, the variation of CO_2 emission under different background data was relatively small. Generally speaking, in the comparison of building with and without DH by using the same total energy demand, even in the case of DH low share under the highest DH production factor ($CO_{2\text{-DH3}}$), the total annual CO_2 emission (11.7 tCO_2/yr) can still be lower than the case without DH (13.6 tCO_2/yr) by 14 %.

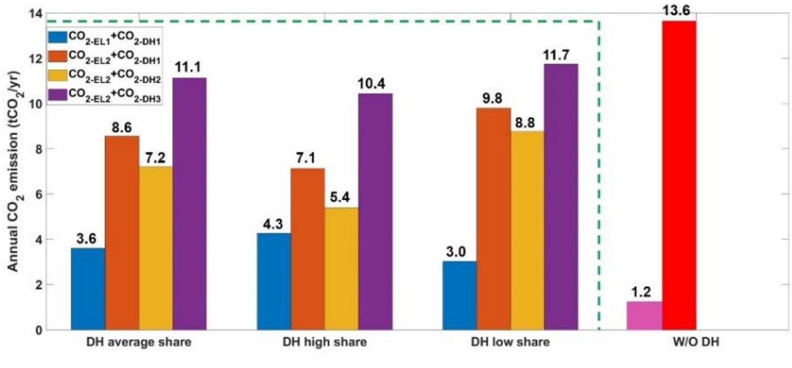

Figure 10. Annual CO_2 emission of one kindergarten of 700 m^2.

3.3. Assessment of CO_2 impact of new building area

After 10 000 m^2 of new building area of kindergartens was assumed to be built in Trondheim, the calculation of annual CO_2 emission regarding the new area was made. Through changing the penetration rates of new building area supplied by DH (x) between 0 % and 100 %, three kinds of growing trends of added annual CO_2 emission were calculated by following each DH production factor. As plotted in Figure 11, when all new buildings had only electricity, the added annual CO_2 emission would be 194.9

tCO_2/yr, and this is same for the three growing trends. When half of the new building area being connected to DH system, annual CO_2 reduction would be between 22.5 and 49.7 tCO_2/yr. Since it was predicted to follow linear CO_2 reduction with variation of DH penetration, the annual CO_2 emission would be double if all the new building area being connected to DH. The orange line represents the best case since DH production factor in 2015 was smallest, while the yellow line has mildest reduction slope due to the choice of highest DH production factor, and the blue line of the average DH production factor is in between.

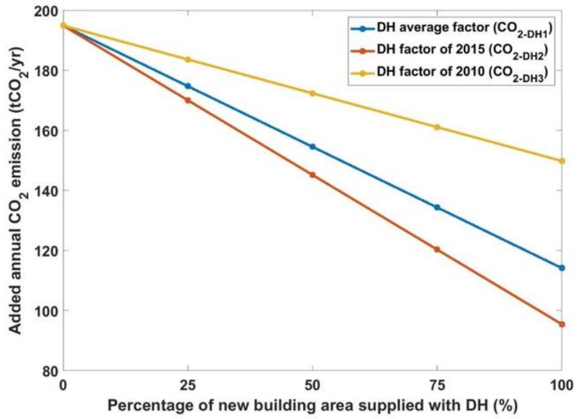

Figure 11. Annual CO_2 addition of 10 000m^2 new building area.

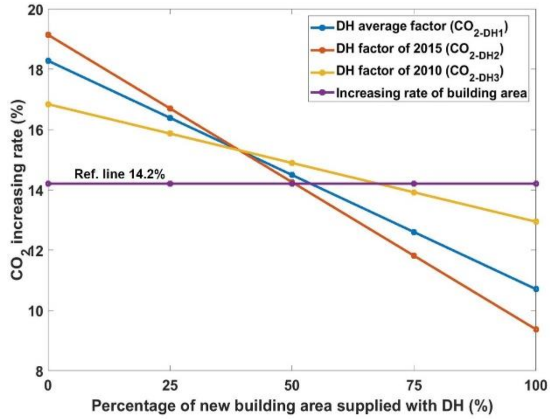

Figure 12. CO_2 increasing rate of 10 000m^2 new building area.

On the ground of the 6-year average annual area, the growth rate of building area, 14.2 %, was shown as the purple reference line in Figure 12. The region above the horizontal line had higher increasing rate of CO_2 than that of building area. It means if 14.2 % more building area being introduced, more than 14.2 % more CO_2 would be emitted; while the region below the line had smaller CO_2 increasing rate than the building area increasing rate, and this is what is expected to happen in the future to slower carbon footprint growth. The orange line representing the smallest DH production factor ($CO_{2\text{-}DH2}$) had the steepest slope. After more than half of new building area using DH, slower CO_2 increasing rate can be realized. When using the highest DH production factor ($CO_{2\text{-}DH3}$), the break-even point can reach at 67 % as shown in the yellow line of the mildest slope. Therefore, the breaking point located between 50 % and 67 % of new building area connected to DH under different CO_2 background data.

4. Summary and Future work

In this article, a typical energy profile of kindergarten in Trondheim was identified. The energy use data was retrieved from energy monitoring platform of Trondheim Municipality in total 559 hourly files. Two cohorts, namely Cohort 1 (not connected to DH) and Cohort 2 (connected to DH) were analyzed and compared. Under various building areas of the kindergartens, energy profile per m^2 of all kindergartens from 2013 to 2018 was defined and the average profile of each cohort was obtained. For Cohort 1, it is difficult to draw a robust energy signature regarding the energy demand and outdoor temperature, other issues and scheduling may be considered. While for Cohort 2, hot water use can be estimated as the only DH use in summer period and deducted from the total heating needs, in order to establish energy signature more accurately. Within the six- year duration curves, the annual average energy use of Cohort 1 was 177.2 kWh/(m^2.yr), and annual average electricity and heating of Cohort 2 was 64.7 kWh/(m^2.yr) and 103.0 kWh/(m^2.yr), respectively. Within Cohort 2, there were three cases depending on the energy contribution from DH and electricity, from DH high share, DH average to DH low share. 700m^2 was chosen as the representative building area of one kindergarten. Its annual CO_2 was compared between with and without DH based on the same total annual energy use. For the background data of electricity, two CO_2 emission were used. The one within Norwegian border gave the best results in all cases; when extended the border to the Nordic region, CO_2 emission jumped to higher level. For the CO_2 factors of DH production in Trondheim, the average factor from 2010 to 2018, the factor in 2015 as lowest, and the factor in 2010 as highest, were used. The kindergarten with DH high share had lowest annual CO_2 emission and smaller CO_2 variation. By using the DH factor in 2015, it supported the lowest emission. For the kindergarten had low share of DH or even without DH, the CO_2 emission had a wider range. This is mainly caused by their higher dependence of the electricity production mix since electricity can be traded in the free market. Moreover, the building with only electricity is more likely to have unknown high peak load. As a mild prediction, 10 000 m^2 was assumed to be built in Trondheim. On the ground of average total kindergarten area within six- year, the growth rate of building area, 14.2 %, was used as the reference line. The growth rate of CO_2 emission could be slower than that of the building area, if more than 50 % and 67 % of new building area would be connected to DH. The break-point locates depending on the energy sources of local DH production, which determines the CO_2 factor.

The results of this article showed that building connected to DH system was more competent than the building of only- electricity concerning the CO_2 emission, and its energy demand easier to be predicted. In the future work, energy data and profiles of other building types and reference weather data in Trondheim shall be defined and analyzed. These profiles can be used to diversify and upgrade energy supply ways and improve urban energy planning.

Appendices

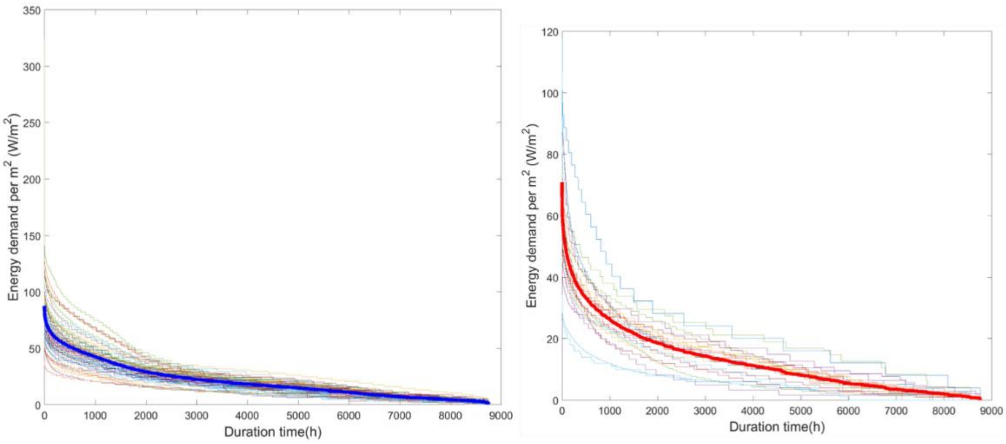

Figure A 1. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2013.

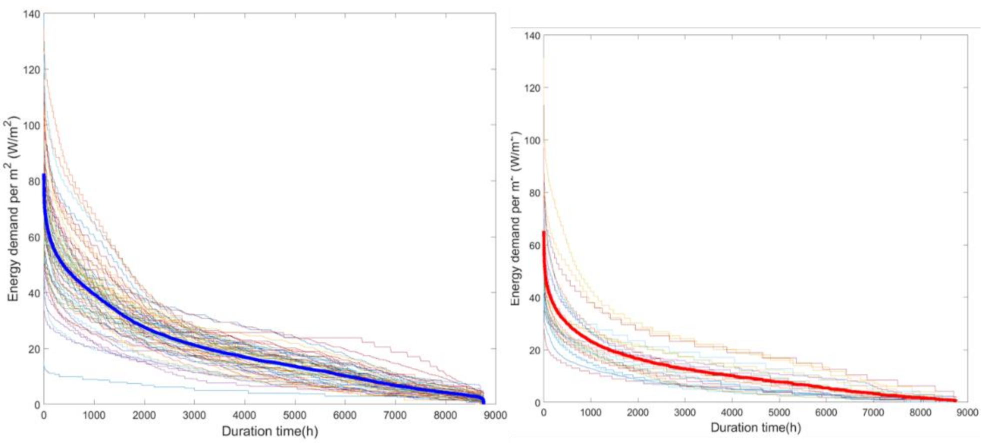

Figure A 2. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2014.

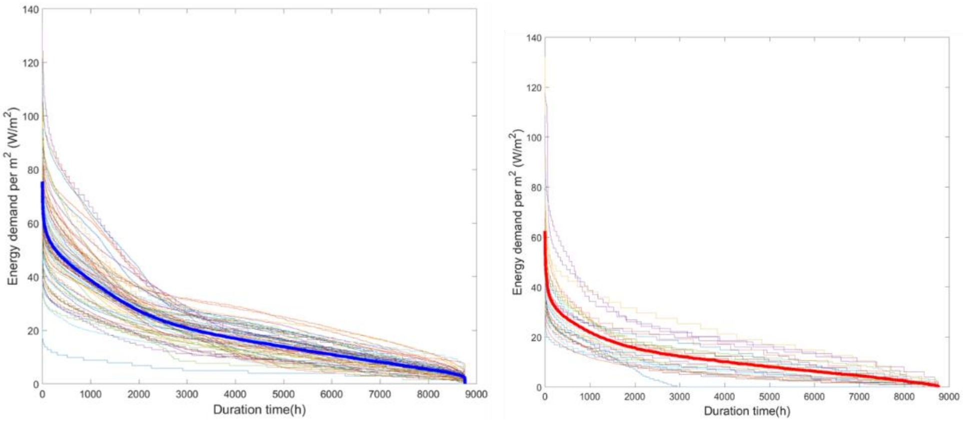

Figure A 3. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2015.

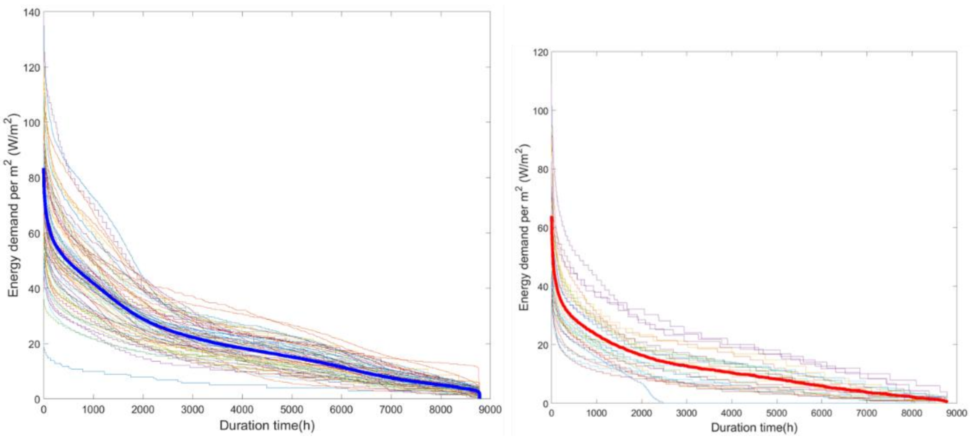

Figure A 4. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2016.

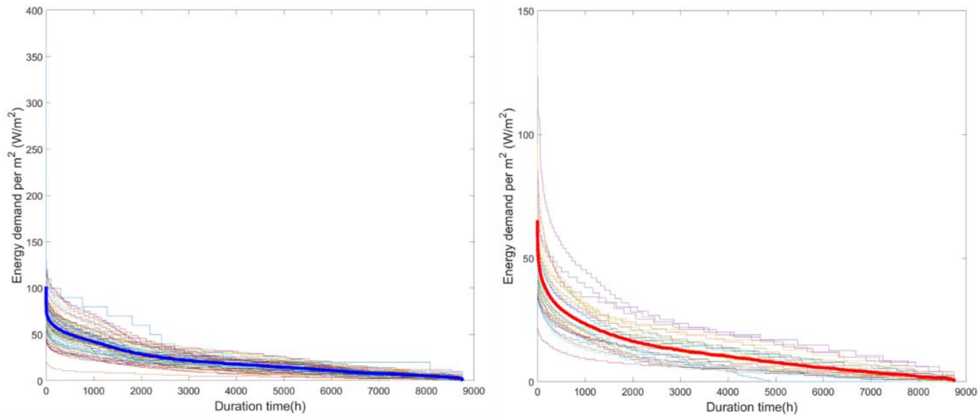

Figure A 5. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2017.

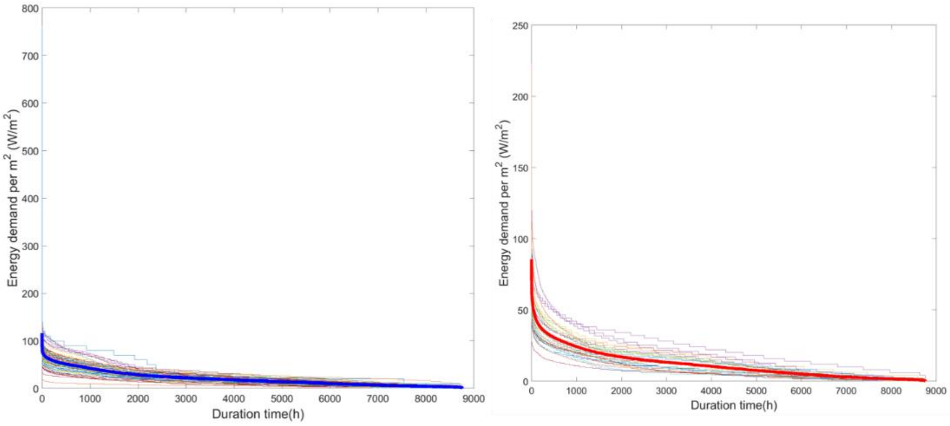

Figure A 6. Annual energy duration curves of Cohort 1 and Cohort 2 (only DH) in 2018.

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