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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 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 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. The kindergartens were divided into two cohorts based on their connection to district heating (DH). Typical heat and electricity duration curves per m^2 of each cohort within six years were identified. The average total annual energy use was 177 kWh/m^2 for kindergartens without DH, and 168 kWh/m^2 for the ones 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. Among 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 has almost the lowest annual CO_2 emission. Finally, a prediction was made by assuming 14.2 % growth rate of kindergartens on the ground of the average 6-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 predicted area could be achieved. This proved that buildings with DH were more robust than the ones 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.

Keywords: kindergarten, district heating, electricity, building area, CO_2

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 (in)direct 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 green electricity power from the abundant hydro-power, coverage rate of district heating (DH) system is rather small. DH only accounts for approximately 11 % of total energy use for building heating in Norway, under high reliance on electricity [2]. Whereas, driven by the motivation of economic and environmental benefits of DH, regulations and subsidies have been introduced to expand the build-up of DH in Norway. As the third largest city in Norway, Trondheim municipality has been committed improving urban plans for better living environment under pressure of urbanization, population growth and mitigation of carbon footprint [3]. 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. The historical energy use data of kindergartens from 2013 to 2018 was retrieved from the energy monitoring platform of Trondheim Municipality [4]. School, heath center, sports center and others are also monitored in the platform.

2. METHODS

2.1 Building general information

From 2013 to 2018, number of kindergartens has been increased from 83 to 99. Based on the connection to DH, the kindergartens were divided into two cohorts, Cohort 1 (unconnected to DH) and Cohort 2 (connected to DH). The yearly building numbers and building area of the two cohorts were compared in Table 1. There were 559 hourly files of kindergartens used in the analysis.

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

	Building numbers (-)		Building area (m^2)	
	Cohort 1	Cohort 2	Cohort 1	Cohort 2
2013	62	21	36979	24623
2014	66	23	38855	26317
2015	68	26	40890	30105
2016	68	27	40890	31766
2017	71	28	43259	32768
2018	71	28	43259	32768

It shows that the share of Cohort 2 is smaller than Cohort 1 but growing, especially when it comes to the building area, Cohort 2 covers around 43 % of total building area till 2018. Most of the kindergartens in Cohort 1 were built within small to medium size (100 to 1000 m^2), while kindergartens in Cohort 2 were within medium to large size (500 to 2000 m^2). 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, 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 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.

2.3 Energy coverage rate in Cohort 2

In Cohort 2, heating demand was provided by DH and the other energy demand by electricity. To see the contribution from the two energy supply ways, Figure 1 demonstrates the energy coverage rates from DH and electricity. 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, named as DH average share, DH high share and DH low share. On average, DH supports 60.0 % of total energy use, as listed in Table 2.

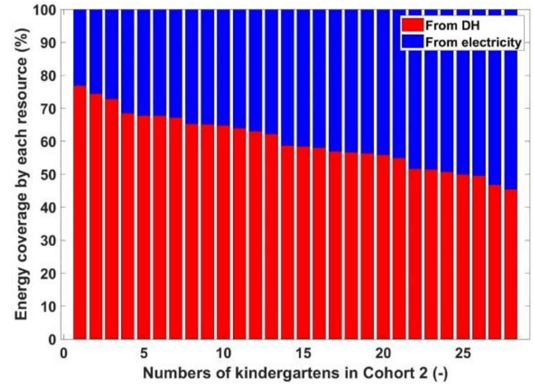

Figure 1. Energy coverage rates of DH and electricity in Cohort 2.

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

2.4 CO_2 factors of electricity and DH production

Norway is connected in the Nordic power grid and further expanded into the wider European grid under the free market of trading electricity. Within the Norwegian border, CO_2 factor of electricity can be as low as 10 gCO_2/kWh ($CO_{2\text{-}EL1}$), which is mainly contributed by the hydro-power, however this factor can be increased to 110 gCO_2/kWh ($CO_{2\text{-}EL2}$) in the Nordic region since fossil fuels are involved in the production mix. Distinguished from electricity, mostly energy and environmental factors of DH production is specified locally. From 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 10 %, the small rest share comes from electricity, bio-energy, ambient heat, and oil [5]. In Norway, in accordance to NS 3720-2018, the CO_2 emission from waste incineration for energy production has been allocated to waste management instead of energy sector. 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 ($CO_{2\text{-}DH1}$), value of 2015 as the 9-year lowest ($CO_{2\text{-}DH2}$), and value of 2010 as the 9-year highest ($CO_{2\text{-}DH3}$). These factors were used as background data for the assessment of CO_2 emission, respectively. The CO_2 factors of DH production were 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. CO2 factors of DH production in Trondheim.

		2010-2018: $CO_{2\text{-}DH1}$	2015: $CO_{2\text{-}DH2}$	2010: $CO_{2\text{-}DH3}$
Composi-tion of energy sources (%)	Waste	74.0	83.1	61
	Gas	10.8	5.9	20
	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

A typical kindergarten in Trondheim was determined at 700 m^2. For Cohort 1, it is difficult to calculate energy share for heating and electricity. Therefore, the annual CO_2 emission comparison of one typical kindergarten between two cohorts was made based on the annual average energy demand of Cohort 1, the building with electricity only. For Cohort 2, the three cases regarding different 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 6-year average annual total building area of kindergarten, 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, regarding the projection of CO_2 from new area, 6-year average annual energy demand of electricity-only building and DH building was used for the calculation. In Function (1), as the denominator, $\overline{CO_2}$ represents the 6-year average annual CO_2 emission of all the kindergartens. The comparison between building area growth rate and CO_2 growth rate can be explained as:

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

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

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 can be achieved.

3. RESULTS

3.1 Results of energy duration curve and Energy signature per m^2

The annual average duration curves were presented in Figure 2, Figure 3 and Figure 4, and the annual energy demand of each cohort were summarized in Table 4. Average duration curves were plotted in black thick lines. The peak loads for the two cohorts were similar. The lower maximum deviations from the average curves are 17.2 % in Cohort 1 and 13.7 % in Cohort 2; the upper maximum deviations are 27.2 % in Cohort 1 and 24.3 % in Cohort 2. The deviation considers 0- 4000 hour in the duration curve, since energy load during the last 4760 hours is usually small with minor influence on the grid and plant sizing. It can be seen that Cohort 1 has larger deviation variation. Moreover, the peak load for Cohort 1 only expects from electricity; while the peak load for Cohort 2 is satisfied by DH and electricity, it releases the maximum demand of power grid. Although electricity use in Cohort 2 had relatively weak relation with outdoor temperature, the duration curves of six years had similar pattern except higher use in 2013. It may be explained that fewer kindergartens were used in the analysis.

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

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

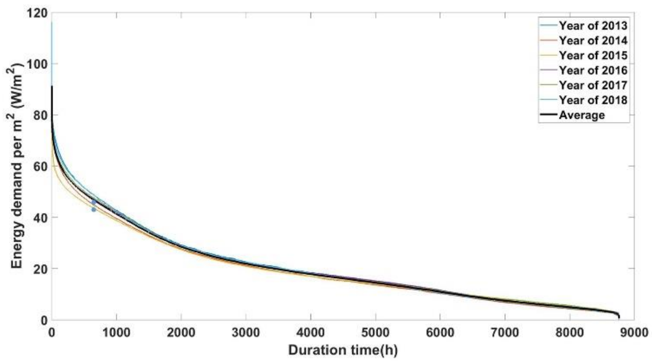

Figure 2. Average total energy duration curves of Cohort 1.

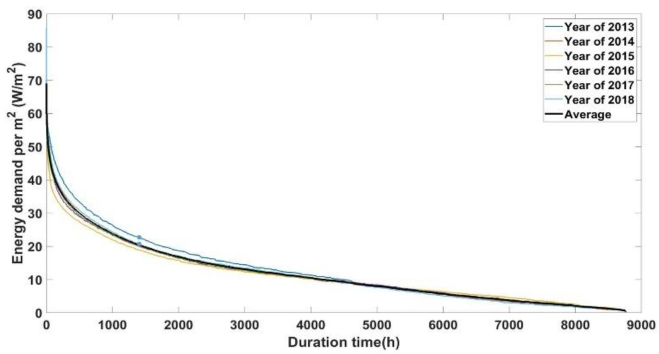

Figure 3. Average heating energy duration curves of Cohort 2.

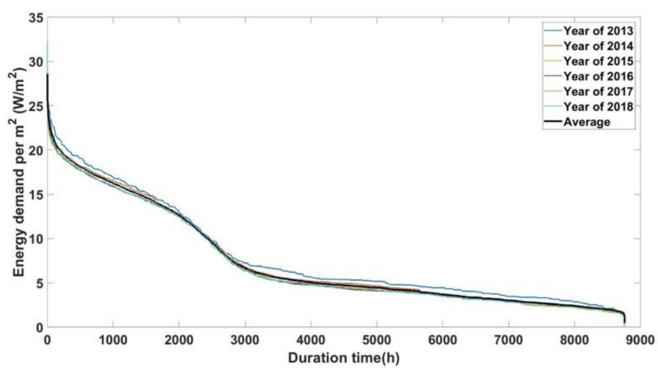

Figure 4. Average electricity duration curves of Cohort 2.

To see if the energy use followed the outdoor temperature, energy signature was adopted as rough measurements [8]. It can be used as a function of the outdoor temperature to depict heating energy demand. Figure 5 and Figure 6 were made by average hourly energy demand of six years (105 168 hourly data). For buildings in Cohort 1, it was rather difficult to draw one interpolation curve to describe the relation between energy demand $P(t_{od})$ and t_{od} from -13 to 19°C. 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 [9]. Here in this article, it can be explained that some electric heating equipment may be shut down during off- work hours in Cohort 1. Since electricity is used both for heating and other electric appliances, it needs to know the daily operation routine. For buildings in Cohort 2, it was relatively easy to establish the energy demand function of outdoor temperature (t_{od}) in polynomials through the entire outdoor temperature range. The function was written as:

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

$$(i = 1,2,3. If\ i-2 < 0, p_3,\ p_4 = 0; if\ i-2 = 0, p_4 = 0)$$

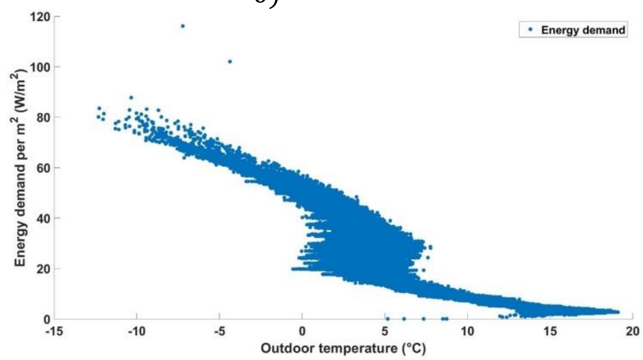

Figure 5. Energy demand vs Outdoor temperature of Cohort 1.

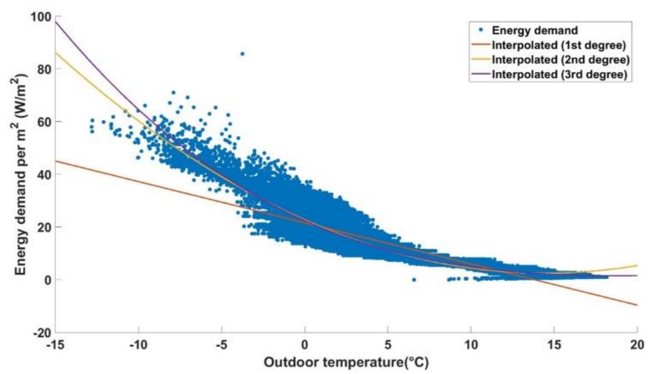

Figure 6. Energy signature curve of DH demand of Cohort 2 under 1st degree, 2nd degree, and 3rd degree polynomial.

To make sure 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 [10]. The coefficients of Function (2) and R^2 of each polynomial were listed in Table 5. It can be seen that even the simplest 1st degree polynomials satisfied the requirement of R^2 and fulfil the prediction of energy demand. It 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 reached in database library [11]. The load profile can be used as input to energy system modelling, such as EnergyPLAN [12].

Table 5. Coefficients of Function (2) and R^2

	p_1	p_1	p_3	p_4	R^2
1st deg	-1.563	21.6	/	/	0.7913
2nd deg	0.0962	-2.792	22.71	/	0.8899
3rd deg	-0.0017	0.1227	-2.816	22.4	0.8915

3.2 Calculation of CO_2 of one typical kindergarten

In Figure 7, the right stand-alone two bars represent the building without DH. The annual CO_2 emission can be hugely increased from 1.2 tCO_2 to 13.6 tCO2 when CO_2 factors of electricity changes from 10 gCO_2/kWh to 110g CO_2/kWh. 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 $CO_{2\text{-}EL1}$ and average DH ($CO_{2\text{-}DH1}$), orange bars of $CO_{2\text{-}EL2}$ and $CO_{2\text{-}DH1}$, yellow bars of $CO_{2\text{-}EL2}$ and DH production 2015 ($CO_{2\text{-}DH2}$), and purple bars of $CO_{2\text{-}EL2}$ and DH production 2010 ($CO_{2\text{-}DH3}$). When CO_2 factor of electricity was 10 gCO_2/kWh, each case achieved smallest annual CO_2 undoubtedly. From the results, if electricity shoulders more energy supply percentage, 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. Even in the case of DH low share under the highest CO_2 factor of DH production ($CO_{2\text{-}DH3}$), the total CO_2 emission (11.7 tCO_2/yr) was still lower than the one without DH (13.6 tCO_2/yr) by 14 %.

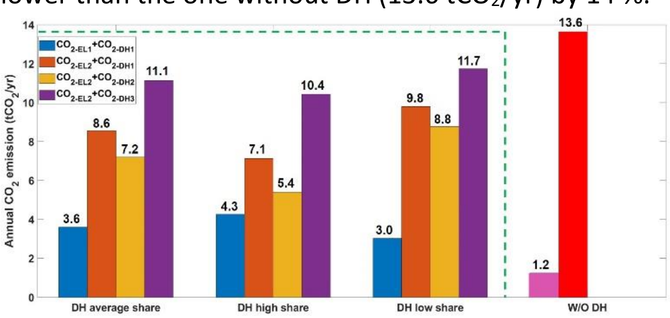

Figure 7. Annual CO_2 emission of one kindergarten in 700 m^2.

3.3 Assessment of CO_2 impact of new building area

By assuming 10 000 m^2 of new building area of kindergartens to be built, 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 CO_2 factor of DH production. As plotted in Figure 8, when all new buildings have only electricity, the added annual CO_2 emission would be 194.9 tCO_2, and this is same for the three growing trends. When half of the new building area is connected to DH system, the annual CO_2 reduction would be between 22.5 and 49.7 tCO_2. Since it is predicted to follow linear CO_2 reduction with variation of DH penetration, the annual CO_2 reduction would be double if all the new building area being connected to DH. The orange line represents the best case since CO_2 factor of DH production in 2015 is smallest, while the yellow line has mildest reduction slope due to the choice of highest CO_2 factor of DH production, and the blue line with the average CO_2 factor of DH is in between.

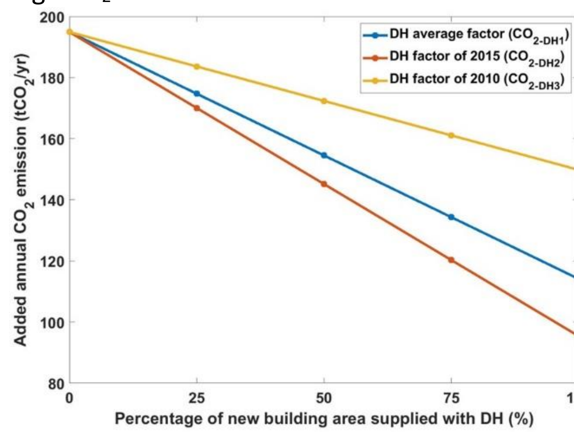

Figure 8. Annual CO_2 addition of 10 000m^2 new building area.

On the ground of the 6-year average annual area, the growth rate of new building area, 14.2 %, was shown as the purple reference line in Figure 9. The region above the horizontal line has higher increasing rate of CO_2 than that of building area. It means if 14.2 % more building area being built, more than 14.2 % more CO_2 would be emitted; while the region below the line has 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 CO_2 factor of DH production ($CO_{2\text{-}DH2}$) still has the steepest slope. After more than half of new building area connecting DH, slower CO_2 increasing rate can be realized. When using the highest CO_2 factor of DH production ($CO_{2\text{-}DH3}$), the break-even point can reach at 67 %, as shown in the yellow line with the mildest slope. Therefore, the breaking point locates between 50 % and 67 % of new building area covered with DH according to each CO_2 background data.

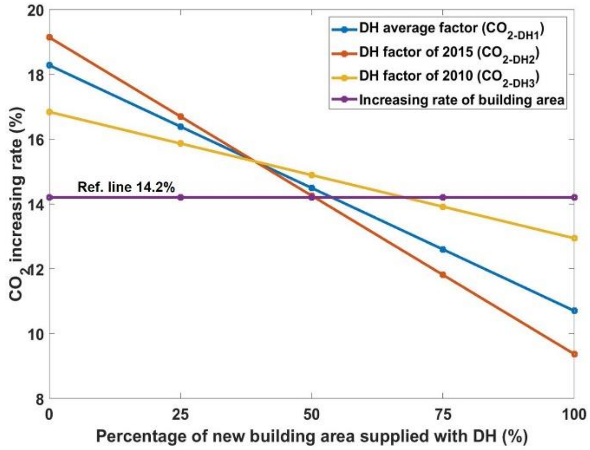

Figure 9. CO_2 increasing rate of 10 000m^2 new building area.

3.4 Comparison with similar building type in other areas

In this article, around half of building energy is consumed for heating purpose due to the cold climate, the highest heating degree hour within the six years is approximately 107562°C·h (year of 2013). It is opposite to the tropical climate, such as the countries in the equatorial belt, where nearly 60 % of building energy is consumed for cooling [13].

In the mild Mediterranean region, the annual cooling and heating demand of school could be as low as 19.6 kWh/m^2 11.0 kWh/m^2 after considering the closing during hot summer period [14]. The total building energy demand is naturally much less than the Nordic case.

Statistically, the average indoor temperature of Northern Europe maintains at 21°C, while in the UK, 18°C is acceptable. It means that the heating energy use also follows the country's custom, as addressed in [15]. It leaves us limited space for reducing the building energy demand.

In Finland, where has similar climatic condition with Norway, the energy use variation of both heating and electricity can be high up to 10- fold between the least and most energy-efficient daycare buildings [16]. It proves important and meaningful to develop average and representative energy profile for one building type for future energy planning.

4. SUMMARY AND FUTURE WORK

In this article, the energy use data of 559 hourly files was retrieved from energy monitoring platform of Trondheim Municipality. Energy profile per m^2 of all kindergartens from 2013 to 2018 was defined and the average profile of Cohort 1 and Cohort 2 was obtained. For Cohort 1, it was rather difficult to draw a single and robust energy signature regarding the energy demand and outdoor temperature, other issues shall be considered. While for Cohort 2, energy signature was relatively easy established. It can be used to predict heating demand and used as input for energy system modelling. Within the 6-year duration curves, the annual average energy use of Cohort 1 was 177 kWh/m^2, and annual average electricity and heating of Cohort 2 was 64.7 kWh/m^2 and 103.0 kWh/m^2, respectively. Within Cohort 2, there were three cases depending on the energy contribution from DH and electricity. 700 m^2 was chosen as the representative building area of kindergarten, and its annual CO_2 was compared between with and without DH. For the background data of electricity, two CO_2 emission were used. The one within Norwegian border gave the best results, when extending it to the Nordic region, CO_2 emission jumped to higher level. For the CO_2 factors of DH production, 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 in general had lowest annual CO_2 emission and smaller CO_2 variation. For the kindergarten had low share of DH or even without DH, the CO_2 emission had a wider range. This was caused by their high dependence of the electricity production mix. 10 000 m^2 was assumed to be built in Trondheim. The growth rate of building area, 14.2 %, was used as the reference line. The increasing 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, depending on the energy sources of local DH.

The results of this article show that building connected to DH system is more competent than the building of only- electricity concerning the CO_2 emission and its energy demand is easier to be predicted. CO_2 factor of DH production is locally specified. In the future work, energy data and profiles of other building types and reference weather data in Trondheim shall be defined and analyzed, such as coincidence factor, utilization rate, etc. These profiles can be used to diversify and upgrade energy supply ways and improve urban energy planning.

ACKNOWLEDGEMENT

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