Impact of COVID-19 countermeasures on the energy and water consumption and CO$_2$ concentration of municipal buildings

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Abstract. As a disease, COVID-19 has shaken the world in 2020/21. Countermeasures have been taken by governments to protect against infection, which have also affected the water and energy consumption of buildings. In particular, buildings managed by public authorities (e.g. kindergartens, schools and administrative offices) have been closed and reopened with different concepts. In this paper, the impact of countermeasures on the electrical and thermal energy and water consumption of municipal buildings is investigated using monitoring data of 100 buildings from 2018 to 2021 of a city in the state of North Rhine-Westphalia (NRW) in Germany. Where available, data of CO$_2$ sensors from building automation systems are included in the evaluation. The CO$_2$ concentration is in a range of concern (1500-2000 ppm) for 2% of presence periods. A value in the unacceptable range (>2000 ppm) is not found in the CO$_2$ data. Since only ventilation-conditioned spaces are equipped with CO$_2$ sensors, no conclusions can be drawn about non-ventilated buildings. We investigate to which extent the measures taken have changed the energy and water consumption. On total average, the heat demand increased lightly by 5% and water and electricity demand decreased by 15% and 12% respectively.

1. Introduction
The COVID-19 pandemic is keeping the entire world on edge in years 2020/21. Various countermeasures have been taken by local governments. Their influence on the risk of infection has been described in various medical papers. The influence of individual countermeasures on the energy and water consumption of municipal buildings, however, is only investigated in subtropical climate [1]. However, the energy requirements are different from those in moderate climate zones (cooling and heating). Buildings managed by public authorities (e.g. kindergartens, schools and administrative offices) have been closed and reopened with a different concept (different occupancies, other hygiene concept, different ventilation).

In this paper, the impact of countermeasures such as the closure of public buildings on the energy and water consumption of municipal buildings is investigated using monitoring data with 15-minute resolution (water, electrical and thermal energy, and fuels) of an exemplary city in the state of North Rhine-Westphalia (NRW) in Germany. Here, presence data from CO$_2$ sensors for an estimation of the risk of infection from building automation systems are included in the evaluation. We investigate to which extent the measures taken have changed the media (thermal energy, electrical energy, water) consumption.
2. Data set
The data set is limited to one city in North Rhine-Westphalia, Germany. Overall, a period from Jan 2018 to Mar 2021 with data from 122 buildings and 490 monitoring points is considered. Only 100 buildings had consistently high data quality.

Kindergartens and elementary schools account for the majority of the available buildings, with 41 and 29 buildings, respectively. High schools with 21 and administrative buildings with 13 conclude the list. Administration buildings are to be seen as a comparison for an office environment with partial homeworking. In total, 122 electrical meters, 36 heating meters (district heating), 87 gas meters and 118 water meters are considered.

In four kindergartens, two elementary schools and one secondary school, each room or part of the rooms is tempered and ventilated with the help of mechanical ventilation. A total of 36 CO$_2$ sensors were included in the analysis. The sensors measure include 13 group rooms of kindergartens and 23 classrooms in schools. The CO$_2$ data was recorded starting 01.01.2020. This gives two months outside of the COVID-19 pandemic that can be used as a comparison.

3. Considered time periods
Six different time periods were considered in different seasons (see table 1). The opening/closing states were not always completely present. Especially in the closing state, different exceptions were granted over time. The opening state describes when the main part of the considered building types were fully open.

The countermeasures have an impact on energy and water consumption. Thus, all citizens have been urged to wash their hands more frequently. However, as sports lessons and club sports were also cancelled, this measure reduces water consumption in school buildings with sport halls.

At the end of summer 2020/21 until Christmas holidays, schools were kept open. For this, the recommendation was given that window opening for ventilation should be significantly more frequent (every 20 minutes for 5 minutes). This should increase thermal energy demand.

The years 2018 and 2019 are used as the "normal" comparison period. From these years, an averaged consumption is calculated for each of the periods under consideration. For normal operation (all 5 periods) the following consumptions were determined as median: kindergartens: electrical (E): 56 MWh, thermal energy (T): 4339.5 MWh, water (W): 1553.7 m$^3$; elementary schools: E: 181 MWh, T: 11 757.8 MWh, W: 2324.4 m$^3$; high schools: E: 498.8 MWh, T: 4651.3 MWh, W: 1582.4 m$^3$; administration buildings: E: 167.3 MWh, T: 11018.8 MWh, W: 1940.9 m$^3$.

| Number | Start         | End           | Regulation                                          |
|--------|---------------|---------------|-----------------------------------------------------|
| 1      | 16.03.2020    | 10.05.2020    | Closing of schools and kindergarten (spring)        |
| 2      | 11.05.2020    | 29.06.2020    | Opening of schools and kindergarten (spring/summer)  |
| 3      | 29.08.2020    | 18.12.2020    | Opening of schools and kindergarten (summer/autumn) |
| 4      | 11.01.2021    | 14.03.2021    | Closing of schools and kindergarten (winter)        |
| 5      | 15.03.2021    | 25.04.2021    | Opening of schools and kindergarten (spring)        |

4. Method
4.1. Energy and water
The measured values of natural gas are converted to heating values with a conversion factor of 11.5 $\text{kWh/m}^3$ (H-Gas). Heating energy consumption is made comparable on the basis of degree-day
values based on outdoor temperature according to VDI Guideline 4710[2] with the recommended heating limit temperature of 15 °C. In the case of electrical consumption, no trend direction of energy consumption can be identified a priori, except for a reduction in energy consumption due to lower use of the building.

It is being investigated whether more frequent hand washing during the pandemic also means that there is an increased demand for water in buildings. Two opposing measures must be considered here. First, school sports and club sports were banned or restricted during large periods of the period under consideration. In buildings with sports halls, the water demand in the sports halls is decreased compared to pre-COVID-19. In many buildings, the sports hall is not measured separately. Therefore, we examine the effect of changing water demand in school buildings having no sports hall. Figure 5 shows the total consumption across all months from 2018 to 2021.

4.2. CO\textsubscript{2} measurements
The transmission risk of SARS-CoV-2 can be estimated from CO\textsubscript{2} measurements [3, 4]. However, this calculation requires additional metadata (e.g., room size, number of people, and filtration efficiency of coverings) which is not available. Therefore, CO\textsubscript{2} limits are calculated that were generally determined within school buildings of [3]. We check if three limits (1000 ppm, 1500 ppm and 2000 ppm) were not exceeded. 2000 ppm was set by Robert-Koch-Institut (RKI) as a limit that is not acceptable [5]. All CO\textsubscript{2} levels below 1000 ppm are considered safe. 1500 ppm was set as point between safe and not acceptable. These values are derived similarly in [3]. These values are independent of SARS-CoV-2 infections also for defining pupils performance decline due to poor air quality. Only rooms with mechanical ventilation were considered. Thus, no conclusions can be made regarding the effectiveness of window opening for infection incidence in schools.

4.3. Comparison
The consumptions of the buildings were compared with the average value of the years 2018 and 2019 in the respective periods as a "baseline". Attention was given to ensure that there were no different vacation times in the periods. Any comparative value >1 means that more media, a value <1 says that less media was consumed during the countermeasures and a value =1 indicates that the same value was consumed in both periods.

Average consumption values are calculated over building types based on the average comparative value of each building and not on the average consumption in the building type. This avoids excessive bias from larger and smaller buildings.

In the case of CO\textsubscript{2} measurements, these are compared with January/February 2020. Here the buildings were in normal operation without special measures.

5. Results
The results are divided separately into media consumption during considered time periods and CO\textsubscript{2} measurements. For comparison of periods, mainly Fig. 4 can be used.

5.1. Media consumption
5.1.1. Period 1 (closed, spring) In period 1, average media demand decreased in all building types except for the administrative buildings in electrical demand. The reduction of electric energy demand was 33-40% in schools and kindergartens. In the administration 9% more electric energy was consumed. Possibly, the air handling units were adjusted to a higher air flow rate. Heating demand decreased by 10-37%. The reduction of water consumption was 60-68% in schools and kindergartens. In the administration this was only 16%.
5.1.2. Period 2 (open, spring/summer) Electrical energy demand decreased from 1% (administration) to 28% (elementary schools) despite normal usage in all buildings. The opening of the schools and more frequent ventilation resulted in increased thermal energy demand, which was 30-31% in the schools. Such an effect could not be observed in the kindergartens. The administration also had a 15% higher heating demand. As a tendency, water consumption also decreased in this period. Only the administration had a 10% higher water demand. In particular, the elementary and high schools had a 38% and 45% decrease in water demand.

5.1.3. Period 3 (open, summer/autumn) This period provided a 8% (kindergarten and high school) to 17% (elementary school) increase in average in thermal energy consumption compared to the reference period. Only in the mainly mechanically ventilated administration buildings, the heating demand fall by 5%. More than 30% of the buildings studied have heat demand below the comparison period. Elementary schools with a sports hall and elementary schools without a sports hall showed no significant differences in the comparison of thermal demands. The electrical demand fluctuated around the reference value (from -3% to +5%). Elementary schools increased water demand by 27%. High schools had the same water demand (sport was allowed again).

5.1.4. Period 4 (closed, winter) Elementary and high schools and administration buildings reduced heat demand by 3%, 5% and 6%, respectively. Kindergarten increased heat demand by 9%. Electrical demand varied from -29% (high school) to -2% (administration). Water demand was at 90% of baseline in kindergartens despite "emergency" operation. In the other unopened buildings, values of 31% to 60% of baseline were obtained.

5.1.5. Period 5 (opened, spring) In period 5, heating demand increased in all five building types. The highest values were reached in all four building types and for all periods (+32% to +49%). Electrical demand decreased in all buildings (-4% to -10%). Water demand remained stable (-1%) for kindergartens. In the other building types, water demand decreased significantly (-11% to -56%).

5.1.6. Sum Over all time periods considered (1-5), kindergarten and elementary schools used 7% and 8% more thermal energy (see Fig.1). Administration buildings and high schools achieved the same heat energy demand. Across all building types, consumption increased by an average of 5%. Only 30% of the buildings consumed less thermal energy. 12 buildings are equipped with (partial) mechanical ventilation. They had in mean 4% less, in opening time 8% more heating energy demand.

Water demand decreased by 5% to 31% in the building types. On average, water consumption across all buildings decreased by 15%. 87% of the buildings had lowered water demand.

Electrical demand decreased at a similar rate as water demand (-11% to -18%), with administration buildings having a 2% higher electrical energy demand (higher ventilation rate). An average reduction of 12% was achieved, with 87% of buildings achieving a reduction.

5.2. CO₂ measurements There were a total of 6,040,277 CO₂ measurements during the periods under consideration (every 5 minutes, weekdays, between 7 am and 4 pm). Of these, only 6,520 measurements are in range between 1500 and 2000 ppm. No measurement is above 2000 ppm. 130,803 measurements are between 1000 to 1500 ppm. In the periods open for all, this corresponds to 2% of the measurements. Values above 1500 ppm were mainly when the ventilation was off. Thus, it
can be postulated that mechanical ventilation prevents extreme ranges of CO$_2$ concentration (>2000 ppm). Overall, good air quality was achieved.

In some buildings, before the COVID-19 measures, CO$_2$ concentrations were more frequently above 2000 ppm (see Fig.6). Data from ventilation show that air exchange rates were increased as a countermeasure. This resulted in the lower CO$_2$ measurements than baseline.

At the beginning of the day, a CO$_2$ concentration of 600-650 ppm (at 420 ppm base concentration) still remained in most measurement locations. For an extra reduction of CO$_2$, an extension of the ventilation time after or before the time of use could help.

6. Discussion/Conclusion
Over the entire considered periods, heat demand increased slightly compared to the reference period (+6 %). The closed periods could not compensate for the higher energy demand due to increased window opening during opening period. Water demand and electrical energy demand decreased across all periods studied (-11 % and -12 %, respectively). More frequently hand washing likely increased water use, but this was also offset by other measures (fewer showers in the sports halls in most of the periods). Although kindergartens were in "emergency operation" most of the time, the media consumption is comparatively stable.

The reductions in consumption due to the measures were lower than in [1] (up to -50 %). However, a complete shutdown was never adopted. In period 4, many exceptions (emergency care) were active, which is why the schools and kindergartens had a permanently supply.

Overall, the energy management of the studied city can be issued a good judgment for
Figure 5. Absolute sum of all consumptions during the years 2018-2021 dissolved monthly. In July/August 2020, there was a disruption in data recording in some buildings (network problems), but this was outside the periods under consideration. Thermal: $1.0 = 28,344 \text{ MWh}$, Electrical: $1.0 = 1049 \text{ MWh}$, Water: $1.0 = 9416 \text{ m}^3$.

Figure 6. $\text{CO}_2$ measurements of kindergarten 2 in 2020. Increased volume flow lowered the $\text{CO}_2$ concentration after week 12.

the management of individual buildings in the countermeasures. The buildings in which in comparison high electrical and thermal energy consumption was observed, especially in the non-used periods (closed), should be studied separately to increase energy efficiency here. In particular, period 4, when the schools were closed, should be investigated more closely, since more thermal energy was nevertheless consumed. The $\text{CO}_2$ measurements showed that mechanical ventilation can maintain air quality at an adequate level. Here, the city reacted correctly by increasing the air flow rate.

The results in this paper will be provided to the City and measures will be created on how to reduce energy consumption for the building types studied. Since vaccination is not yet approved for most school children (especially elementary school children), school energy management based on COVID-19 countermeasures will also play a role for the future.

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