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ABSTRACT

The COVID-19 pandemic and its associated lockdown have caused significant changes in lifestyle all around the globe. The combined effect of business and school closures as well as restrictions on travel during this period introduced unprecedented changes in occupancy presence and behavioral patterns in buildings. Electricity consumption in residential buildings can be affected by such changes in occupancy. However, the majority of the research activities which have attempted to quantify the aforementioned impacts of the COVID-19 lockdown on electricity consumption have been at the grid level; there have been limited efforts to study the impact of the pandemic on electricity consumption at the building level. Moreover, even fewer studies have focused on analyzing the change in electricity consumption patterns in rural residential buildings. Accordingly, in this study, electricity consumption data from more than 9,000 detached single-family homes in Cedar Falls, Iowa during the COVID-19 pandemic (2020) are compared against corresponding calendar normalize electricity consumption data for prior years (2010-2016). These comparisons support an improved understanding and quantification of how the lockdown during the 2020 COVID-19 pandemic affected the electricity use patterns of residential energy users in the rural Iowa.
This study's findings show that 54% of buildings in our database had a significant change in their non-weather-related consumption in 2020 when compared to previous years. From these, 62% of homes decreased in consumption, and 38% increased consumption. Those with increased consumption increased by a larger amount on average. The magnitude of changes in electricity consumption in this dataset was also found to be impacted by certain housing characteristics such as building size, vintage, and number of bedrooms. Accordingly, larger and newer homes were less impacted by the COVID-19 pandemic in 2020 as compared to the rest of the building stock.

INTRODUCTION

On March 11th, 2020, the World Health Organization (WHO) declared the novel coronavirus (COVID-19) outbreak a global pandemic (Cucinotta & Vanelli, 2020). Accordingly, governments across the world established lockdown measures to slow the spread of this virus and protect their citizens. In the U.S., at least 316 million people in at least 42 states, three counties, 10 cities, the District of Columbia and Puerto Rico were urged to stay home (Mervosh et al., 2020). These lockdown orders were accompanied by prolonged school and business closures as well as imposed travel restrictions (Gostin & Wiley, 2020). These measures had a profound impact on daily life routines. Conventional in-person learning environments were replaced by online learning, and non-essential workers had to adapt to a new work from home model. The imposed measures also resulted in a dramatic reduction in transportation, as more people spent the majority of their time at home instead of traveling to and from school, work, or other activities (Conway et al., 2020). These substantial changes in lifestyle cause by the COVID-19 pandemic and lockdown significantly impacted when and how electricity was consumed.

In residential buildings, both HVAC and non-HVAC related loads can be impacted by occupant presence. HVAC use may be impacted since, in many homes, occupants adjust temperature setpoints and/or schedules of their HVAC systems based on whether or not there are occupants present in their home (Kawka & Cetin, 2021). For non-HVAC loads, the added loads may include those associated with the use of homes as substitutes for the office, classrooms, restaurants, and entertainment (Kawka & Cetin, 2021). Accordingly, a number of recent studies have focused on changes in energy and electricity consumption due to the COVID-19 pandemic and lockdown (e.g. Chen et al., 2020; Elavarasan et al., 2020; Kawka & Cetin, 2021; Rouleau & Gosselin, 2021). However, the majority of these research activities have attempted to quantify the impacts of COVID-19 at the grid level (e.g. Abu-Rayash & Dincer, 2020; Prol & Sungmin, 2020). There have been limited efforts to study the impact of the pandemic on electricity consumption at the building level (e.g. Kawka & Cetin, 2021). Even fewer studies have focused on analyzing changes in electricity consumption patterns in rural residential buildings.

Accordingly, in this study, several years of metered residential electricity consumption data from rural households located in Cedar Falls, IA (ASHRAE Climate Zone 6A (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), 2020)) is used to study the comparative electricity consumption of single family homes, including pre-pandemic (2010-2016) and during the COVID-19 pandemic, in 2020. First the data is quality controlled to calendar normalize meter readings and eliminate substantial missing or outlier data. Then, assessors' data is matched with electricity consumption data according to the unique parcel IDs to enable analysis with respect to housing characteristics.

METHODOLOGY

Multiple years of metered electricity consumption data (monthly billing data) for nearly 12,000 residentials customers were obtained for Cedar Falls, Iowa. This data included two datasets, one representing the period between 2010 and 2016, and the other for 2020. The electricity consumption data obtained from Cedar Falls Municipal Utilities included meter readings at irregular time periods (billing cycles), lasting between 8 to 46 days, which is typical of most utility billing data. To normalize this data to a common data frequency for analysis, a customized R script was developed and utilized.

This code assigned the daily average of a billing period to each one of the days that fell into that period. Then these daily averages were summed to form monthly and annual consumption values for each property in the database. All months with zero consumption were removed, since meter readings are subject to errors and vacant homes were not of interest in this study.

Next, the data was filtered to only include single family homes and to remove outliers based on estimated minimum and maximum monthly consumption from the Residential Energy Use Survey (RECS) data (U.S. Energy Information Administration (EIA), 2015a). These outliers were found by dividing the minimum and maximum annual consumption in the RECS dataset by 12 which limits the monthly consumption values to a lower bound of 4.9 kWh and an upper bound of 5,268.1 kWh. Then, the two datasets were combined and parcels that only existed in one dataset were removed as this limited the potential for comparison.

In addition to the datasets discussed above, the assessors' dataset from the selected location was also obtained and used. The assessors' data included information on the buildings' age, size, type, and other variables describing the properties of the residential building stock. Table 1 presents summary statistics for the 9,016 parcels in the resulting data.

Table 1. Overview of the acquired dataset.

Variable	Mean	Min	25th Percentile	50th Percentile	75th Percentile	Max
Home Age (years)	56.03	6	30	59	70	191
Number of Bedrooms	3.1	0	3	3	4	8
Home Area (m^2)	105.2	23.4	80.3	97.5	124.9	456.9
Monthly Consumption (kWh)	881.3	4.93	504.8	764.1	1117.8	5267.9

Removing Non-Weather-Related Electricity Consumption

Electricity consumption data for each meter reading was divided into a weather-related and a non-weather-related component to allow for comparison across different years and seasons. Accordingly, in addition to the data discussed thus far, temperature data for Cedar Falls in intervals from one hour to one day, based on availability, were also collected from the National Solar Radiation Database (NSRDB) (US Energy Information Administration (EIA), 2021). This data was used to distinguish the non-weather-related component of electricity consumption for each home, by removing the variation in consumption due to changes in local weather. To do so, first heating degrees days (HDD) and cooling degrees days (CDD) were calculated from a base temperature of 18.33°C (65°F) for each observation in the NSRDB and summed up for each month. Next, two linear regression analyses between the calculated degree days and consumption were used to determine how much of the electricity consumption is related to changes in local weather conditions. Accordingly, for each home, months May through August were used for the CDD regression analysis, and all other months were used for the HDD analysis. The resulting model coefficients were then used to remove weather-related consumption for each individual observation of monthly consumption. To determine the non-weather-related consumption for each home, Equation (1) was utilized,

$$C_n = C - (D_h * C_h + D_c * C_c) \qquad \textbf{(1)}$$

where C_n is the non-weather-related consumption, C is consumption, D_h and D_c are month's HDD and CDD respectively, and C_h and C_c are heating and cooling degree day coefficients. A consideration made in this analysis was related to the number of observations available for each home. Figure 1 shows the relationship between HDD coefficients and number of observations used in regression analysis. Homes with less than 26 observations (7.4%) generally were not found to have realistic HDD coefficients and were thus removed.

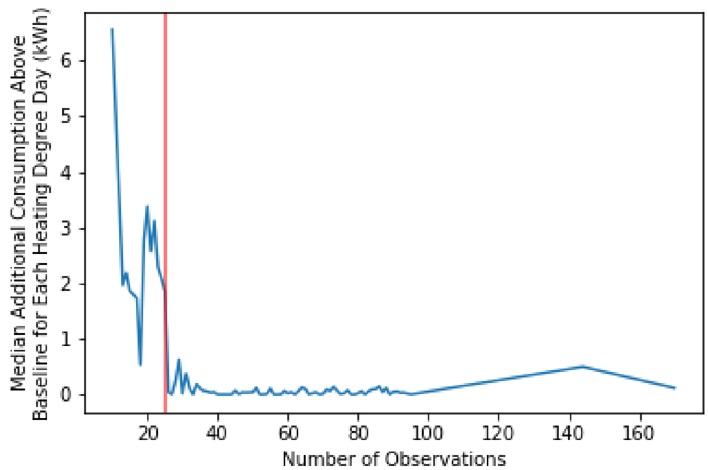


Figure 1. Relationship between the number of observations and heating degree day (HDD) coefficients

Next the 95% mean confidence intervals of non-weather-related electricity consumption were found for each month and year across all parcels and plotted to visually compare the consumption of 2020 to previous years.

RESULTS & DISCUSSION

To compare the electricity consumption during the COVID-19 lockdown in 2020 against previous year, the 95% confidence interval for monthly non-weather-related electricity consumption was identified for all studied years across all homes (2010 to 2016 and 2020). As seen in Figure 2, all months are used in this analysis except for the month of December which had missing data in the year 2020 and was thus not suitable for analysis.

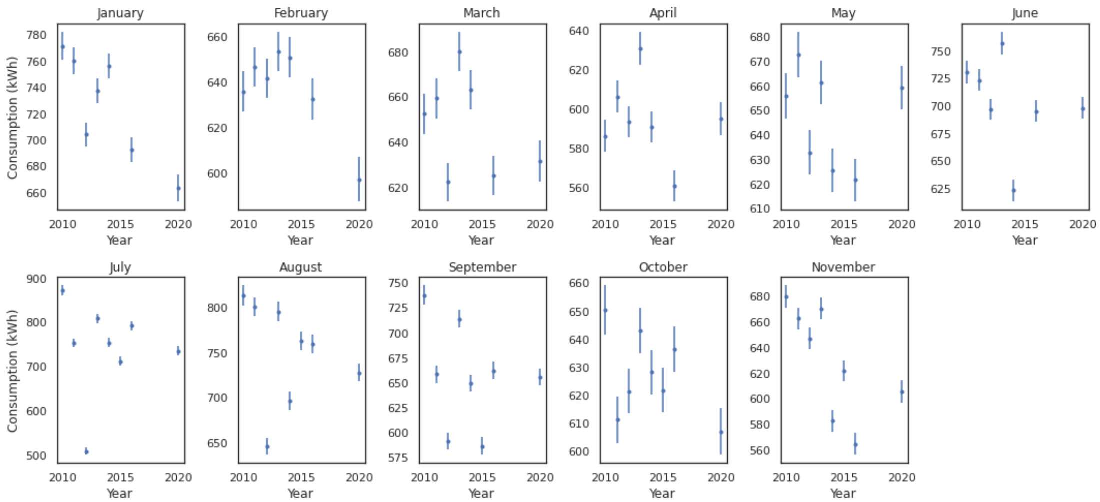


Figure 2. 95% mean confidence intervals for non-weather-related electricity consumption by month and year for all residential parcels in Cedar Falls, IA.

From these data, confidence intervals for percent change in non-weather-related electricity consumption were derived (Figure 3). Here, the months January and February in 2020 appeared to have had significantly lower consumption levels compared to previous years. Similar trends can be seen in the Monthly Energy Review reports published by the EIA, which shows that electricity consumption by the U.S. residential sector in the first three months of 2020 were lower than the comparative period in previous years (U.S. Energy Information Administration (EIA), 2021b).

During these three months, the weather was relatively warmer than average in the U.S. and HDDs on average were 15% fewer (U.S. Energy Information Administration (EIA), 2021a). It has been suggested that because of this warmer weather, residential energy consumption of several heating fuels, including electricity, in the first three months of 2020 was lower than previous years (U.S. Energy Information Administration (EIA), 2021a). However, since this analysis considers non-weather-related electricity consumption, and the majority of residential space heating in the State of Iowa is not powered by electricity (76.3%), it is suggested that further investigation is needed to understand the root cause of the relatively lower consumption witnessed in January and February of 2020 (U.S. Energy Information Administration (EIA), 2015b; US Energy Information Administration (EIA), 2021).

Regardless, assuming that percent change for each parcel is considered significant when zero does not fall within the interval, non-weather-related electricity consumption for most other months in 2020 appears to be within the range of previous years. This suggests that changes in monthly non-weather-related electricity consumption between the lockdown period and previous years were not significant for most months in this dataset. Similar trends were found when studying the nationwide residential electricity consumption, according to which most months' consumption values were within a 10% range difference from the mean of previous year (2010-2016). The annual electricity consumption in this sector was only 3.8% more than the mean of the control period (U.S. Energy Information Administration (EIA), 2021b).

The higher annual electricity use for residential buildings is mainly believed to be driven by HVAC and appliance use during daytime hours, and thus relates to both weather and non-weather related electricity loads (Krarti & Aldubyan, 2021).

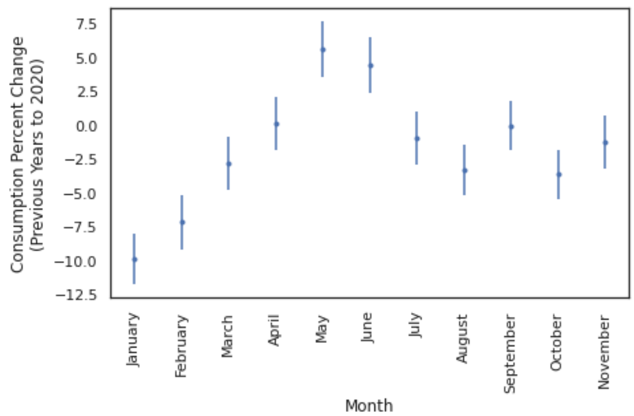


Figure 3. The change in 95% mean confidence intervals for non-weather-related electricity consumption between 2020 and previous years for all residential parcels in Cedar Falls, IA.

The homes with a significant change in annual non-weather-related electricity consumption between 2020 and previous years of data (54%) were then analyzed more closely to determine the drivers of this witnessed change in consumption. Figure 5 shows the distribution of these parcels based on the change in their 95% mean confidence intervals for non-weather-related electricity consumption between the year 2020 and the 2010-2016 period. It can be seen that of the 54% of homes with a significant change in consumption during the COVID-19 lockdown, 62% witnessed a decrease in consumption. However, the average change of significance decreasing homes was calculated to be 42.3%, whereas the average change of significance increasing homes was calculated to be 87.8%. This means that although more parcels had witnessed a decrease in consumption, those with increased consumption had a larger amount of change on average.

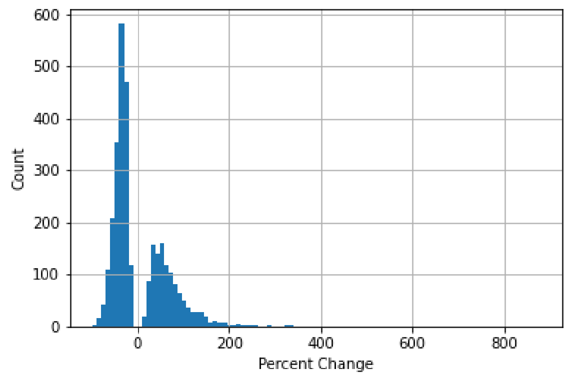
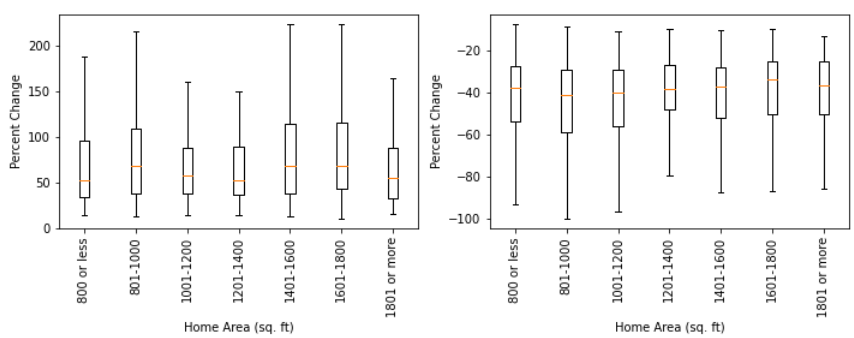
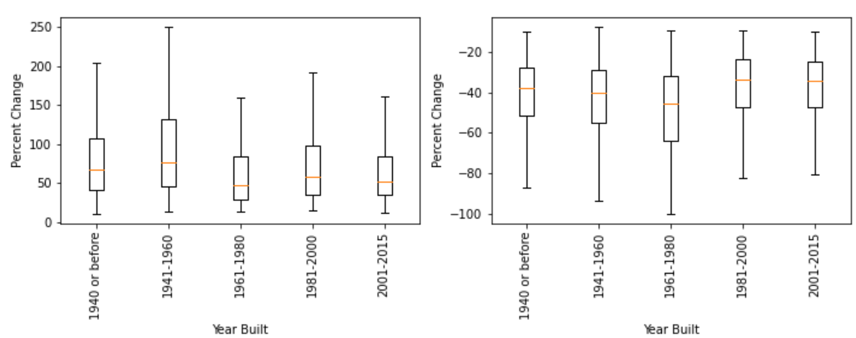


Figure 4. Distribution of homes by percent change in non-weather-related consumption (*Note: Only parcels IDs with statistically significant percent change in 95% mean confidence interval 95% mean confidence intervals are shown).*

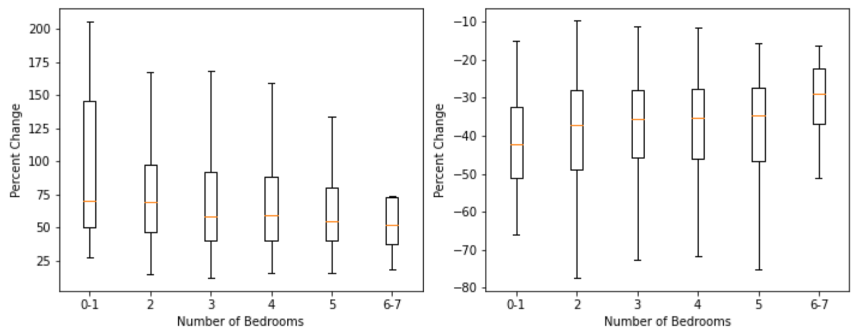
Other studies on the impact of COVID-19 on the electricity consumption in residential sector have concluded that the magnitude of the increase in home energy use depends on the household and housing characteristics (Krarti & Aldubyan, 2021). The parcels with significant change were thus analyzed with respect to select building characteristics based on data obtained from the assessors in Cedar Falls (Figure 5). This figure shows the (left) positive and (right) negative change in 95% mean confidence intervals for non-weather-related electricity consumption between 2020 and previous years based on (a) building size, (b) building age, and (c) number of bedrooms.



(a)



(b)



(c)

Figure 5. The (left) positive and (right) percent change of non-weather-related electricity consumption between 2020 and previous years for homes in Cedar Falls, IA based on (a) building size, (b) building age, and (c) number of bedrooms.

It can be seen that the variance in percent change for all three groups of buildings attributes is substantial. For the analysis involving the number of bedrooms specifically, there appears to be a negative correlation between the percent change in households with relatively higher consumption levels in 2020 with regards to an increase in the number of bedrooms. Similarly, a positive correlation was found between consumption values for homes that had lower consumption in 2020 as compared to previous years. Table 2 summarizes the regression metrics for this set of analysis and shows that home area was the only non-significant factor when analyzing homes with increased consumption in 2020. All other factors were statistically significant in both reduced and increased consumption models. Overall, the data suggests that larger homes with respect to both area and number of bedrooms were less affected by changes in lifestyle experience during the COVID-19 pandemic. Prior research had also suggested that the relative influence of occupants differs for varied building characteristics (van den Brom et al., 2019). However, all R-squared values are low, suggesting that the regression models built using the selected housing characteristics can explain little variance in changes in electricity consumption between the year 2020 and previous years with available data.

Table 2 . Housing characterstics-based regression metrics for changes in electricty consumption.

Variable	Type of change	R squared	p-value	95% CI coef lower	95% CI coef upper	Coef
Bedrooms	+	0.003	0.022*	-11.238	-0.876	-6.057
Bedrooms	-	0.007	0.000***	1.062	2.749	1.906
Home Area	+	0.001	0.216	-0.018	0.004	-0.007
Home Area	-	0.011	0.000***	0.003	0.007	0.005
Year Built	+	0.014	0.000***	-0.478	-0.203	-0.341
Year Built	-	0.040	0.000***	0.105	0.151	0.128

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘·’ 0.1 ‘ ’ 1

CONCLUSIONS

In this study, electricity consumption data from more than 9,000 detached single-family residential meters in Cedar Falls, Iowa during the COVID-19 pandemic (2020) were compared against corresponding calendar normalize meter readings consumption data for prior years (2010-2016). The study's main objective was to understand and quantify how the lockdown during the 2020 pandemic affected the electricity use patterns of residential energy users in the rural Iowa. The findings showed that 54% of buildings in our database had a significant change in their non-weather-related consumption in 2020 when compared to previous years. From these, 62% of the witnessed changes in consumption were classified as a decrease. However, although more parcels had witnessed a decrease in consumption, those with increased consumption had a larger amount of change on average. Assessors' data was also studied to characterize the homes with significant change in electricity consumption between the year 2020 and the 2010-2016 period. We found that overall, larger homes, homes with more bedrooms, and newer homes were less affected by the changes in lifestyle experienced during the pandemic.

The limitations inherent in the sample of this study are related to the unavailability of household size and demographics characteristics. Future studies can benefit from such data to control for socio-economic status. Another set of limitations are related to the unavailability of data for the 2017-2019 period which created a gap in the analysis. It may be possible that renovations or changes in ownership happened over this period for certain homes which might have affected its housing and household characteristics.

ACKNOWLEDGEMENTS

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