COVID-19's Effect on Energy Usage in a Residential Complex in Hyderabad, India

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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled **" COVID-19's Effect on Energy Usage in a Residential Complex in Hyderabad, India**" by Kuntal Chattopadhyay, has been carried out under my supervision and is not submitted elsewhere for a degree.

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Dedicated to my parents, Uttam Chattopadhyay and Jhuma Chattopadhyay

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Abstract

When the Indian government declared the first lockdown on 25 March 2020 to control the increasing number of COVID-19 cases, people were forced to stay and work from home. The aim of this study is to quantify the impact of stay-at-home orders on residential Air Conditioning (AC) energy and household electricity consumption (excluding AC energy).

This was done using monitored data from 380 homes in a group of five buildings in Hyderabad, India. We gathered AC energy and household electricity consumption data at a 30-minute interval for each home individually in April 2019 and April 2020. Descriptive and inferential statistical analysis was done on this data. To compensate the difference in temperatures for the month of April in 2019 and 2020, only those weekdays were selected where the average temperature in 2019 was same as the average temperature in 2020.

The study establishes that the average number of hours the AC was used per day in each home increased in the range 4.90 – 7.45% depending on the temperature for the year 2020. This can be expected as occupants stayed at home and they have used AC more frequently during lockdown period. Correspondingly, the overall AC consumption increased in the range 3.60 – 4.5%, however the daytime (8:00 AM to 8:00 PM) AC energy consumption increased in the range 22 – 26% and nighttime (8:00 PM to 8:00 AM) AC energy consumption decreased by 5-7% in the year 2020. As the AC was used throughout the day during lockdown period, due to pre-cooling effect the AC consumption during the night time got reduced.

The study showed a rise in household daily electricity consumption of about 15% for the year 2020. The household electricity consumption increased during daytime by 22- 27.50% and 1.90- 6.6% during the nighttime. It can be explained as occupants worked from home, and used monitors, laptops, T.V, internet, lighting which in turn increased the household electricity consumption. It was observed that the morning household electricity peak demand shifted from 7:00 AM in 2019 to 9:00 AM in 2020. Conversely, the evening peak demand shifted from 9:00 PM in 2019 to 7:00 PM in 2020. An additional peak was observed during afternoon hours in the lockdown. This indicates the occupants started waking up late, as they didn't have to commute to their workplaces. Also, there is an earlier evening peak for 2020 than 2019, as occupants in 2019 used to come home after 6:00 PM from their workplaces.

Further, study was conducted for two sets of temperatures (Set_lo and Set_hi) to study the impact of temperature within the years 2019 and 2020. The study establishes that the AC was used more (4.80-5.60%) for the higher temperature days when compared within the year. As expected the AC consumption is more for the higher temperature range. Furthermore, the consumption pattern

throughout the day is similar for both the sets each year. Similarly, the average number of hours the AC was used per day in each home increased by 3.40 – 6.00% for the higher temperature range within the year. The study showed that household electricity consumption was more by 3.00% for the lower temperature range when compared higher temperature range. However, the household electricity consumption pattern is similar for both sets of temperatures.

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Chapter -1

Introduction

1.1 Motivation and background

Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) is the primary cause of the pandemic that started in 2019. COVID-19 has significantly influenced life all over the world. It spread rapidly, infected around half a million people, and killed more than 20 thousand over the globe until 27 March 2020 [1]. The impact of COVID-19 was devastating worldwide, in terms of the economy, health, social and emotional aspects. An unprecedented nation-wide lockdown brought a grinding halt to economic activities, adversely affecting the lives and livelihoods of thousands of daily wage workers. The economic impact was drastic, which led researchers to study transformation in every sector.

The first positive case of COVID-19 was reported in India on 27 January 2020 [2]. By mid-April 2020, India recorded around 12,370 COVID-19 cases and 423 deaths [3]. Initially, many steps were taken to control the spread. The prime minister of India called for 'Janata curfew' on 22 March from 7 AM-9 PM, urging people to stay home except those working in essential services and enforcing public led social distancing interventions [4]. However, the nation was still not able to completely control the situation. Finally, on 25 March 2020 the first lockdown for the entire nation was imposed to tackle the spread of the pandemic [5]. The focus was on the closure of all activities except essential services such as hospitals, telecom, pharmaceuticals, and provisional stores [6]. People saw technology and internet-based services as a major source to communicate, interact, and perform their work from home [7].

The objective of our study is to evaluate the impact of COVID-19 on the AC energy and household electricity (excluding AC energy) consumption independently. AC energy indicates the amount of energy consumed by AC and household electricity indicates the total energy consumed by remaining electrical appliances excluding AC. Further, the following hypotheses were made, and tested:

A. Working from home during weekdays would lead to an increase in energy consumption since occupants may cook lunch, use AC and other electrical devices during the day.
B. The energy consumption during night-time is expected to reduce due to the pre-cooling effect when ACs are operated during daytime.
C. There may be a delay in the morning peak since people may wake up late as they don't need to commute due to the work from home.

The results were also checked to confirm whether these points are statistically significant or not.

1.2 Problem statement

The primary objective of our study is to evaluate the impact of COVID-19 on the AC energy consumption and household electricity consumption of residential buildings in Hyderabad. The AC energy and household electricity data from 387 homes of a group of buildings from a complex located at Hyderabad was gathered for this study.

1.3 Contribution of the thesis

The key findings of this study are summarised as follows:

A. To evaluate the change in AC energy consumption during pre-lockdown and lockdown time.
B. To estimate the number of hours the AC was operated during pre-lockdown and lockdown time.
C. To estimate the change in household electricity consumption during pre-lockdown and lockdown time.
D. To observe the change in pattern of AC energy and household electricity consumption for both the time-periods.

1.4 Outline of the thesis

This thesis is organised into five chapters, following are the description of the chapters:

Chapter 1 gives an overview of the research. The problem statement is defined, and contributions are listed.

Chapter 2 provides a literature review on the change/shift of electricity demand worldwide, during the lockdown. Followed by the studies conducted on the residential electricity consumption for different places during lockdown.

Chapter 3 provides the information about the study area, duration, buildings considered, sensors used, data sampling and data pre-processing.

Chapter 4 presents the results obtained from the analysis done for different sets data sampling and additional discussions.

Chapter 5 consists of a summary, conclusion of this present work and scope for future work.

Chapter 2

Literature review

This chapter is divided in 4 sections. The impact of COVID-19 on the overall electricity consumption of the world is discussed in Section 1. Section 2 gives the information related to the experimental and simulation studies conducted for the energy consumption for residential buildings. Section 3 provides the information about the studies conducted for India so far. The last section will provide the brief overview about the research gaps bridged through this study.

2.1 Overall energy consumption across the Globe

Above all, these restrictions affected production activities and individual ways of living, leading to noticeable changes in energy consumption. According to the reports, more than 80% of the workspaces were closed completely or partially worldwide [8]. Globally, the energy demand reduced by 3.8% within the first three months of lockdown [9], although there was an increase in the energy demand for residential buildings [10]. UK, Spain, France, and India saw their consumption decreased by almost 15% during lockdown periods. The electricity demand of Italy also decreased by 35%. In China, energy utilization dropped by 6.5% in the first quarter and [11] . Studies [11–13] have shown that overall country level consumption decreased during the pandemic. A case study done on Turkey by Yukesltan et al., [14], using a modulated Fourier series expansion on overall electricity consumption, forecasted that the demand will decrease by up to 12 % according to the level of restrictions imposed. Furthermore, Wen et al.,[15] predicted a decline of 12% electricity demand for New Zealand using the auto-regressive-moving-average model. Sánchez-Úbeda et al.,[16] analysed electricity demand of Latin America and Caribbean countries (Peru, Bolivia, Costa Rica, Brazil, Guatemala, Mexico, Dominican Republic, Argentina, Chile, and Uruguay), and found a decrease of 30% for Peru and Bolivia. While a decrease of 6% was observed for Chile and Uruguay, remaining countries had a reduction by 11 to 17%. Alavi et al., [17] observed a reduction of electricity consumption for Bangladesh by 50%. In addition, they developed a neural- network based prediction model, which can predict electricity consumption for Bangladesh if a lockdown is announced in future.

Several studies [18, 19] have shown that there was an energy shift from commercial and industrial buildings to residential buildings. Sanchez-lopez et at.,[20] conducted a similar kind of study on the impact of electricity demand in Chile, using data obtained from 230 thousand smart meters. They noticed a rise of 17% in June, when compared to the same month of 2019. Conversely, the industrial electricity demand was reduced by 75%. Krarti and Aldubyan [21], through their review study, observed the post-pandemic effect on energy consumption of the residential sector as a function of normalized weather time series data. A rise of 11-32 % for few countries (Australia, UK, and the USA) during complete lockdown was observed. This massive shift of energy demand from industrial and commercial buildings towards residential buildings provides an idea of the impact of lockdown during the pandemic.

2.2 Residential energy consumption across the Globe

Several researchers have studied the impact of COVID-19 on residential energy demand. A case study done by Aldubayan and Krarti [22] on residential buildings of Saudi Arabia evaluates the short-term impact of the lockdown. Their study finds a surge of 25.2% in electricity consumption during the lockdown period. Later, when residential building stock models were used, using normalised weather conditions, they found an increase of 16% in housing energy compared to the year 2019. Most of the increase was due to a significantly higher usage of lighting, appliances, and air-conditioning associated with increased occupancy levels during daytime hours. Further, using the same validated residential building model they forecasted that the overall energy consumption can increase upto 13.5% if stay-home living continues compared to the year 2019. Utilizing the information gathered from a study in Ireland, the general increase in energy utilization for houses has been assessed to range between 11 % and 20 % during the lockdown time frame, with even higher increments happening during 9 AM to 5 PM on working days [23].

Meanwhile, Abdeen et al., [24] explored the household hourly electricity consumption in Canada. Using measured electricity consumption data from 500 homes in Ottawa, they observed that daily electricity consumption increased by 12% relative to the non-COVID year. A similar kind of study done by Qarnain et al.,[25] found 34 factors responsible for driving more energy consumption in the residential sector of India, finally concluding that energy was consumed more intensely in pandemic times than in pre-pandemic times. An increase of 12% residential energy consumption after a few weeks of lockdown was reported by Austin Energy [26]. Besides, evaluating the high- frequency electricity data from 491 houses and interviews on household energy consumption with 17 families in Queensland, Snow et al., [27] compared energy use before and during COVID-19 lockdown. They estimated the key factors responsible for household electricity consumption, and cooking and digital devices were the major contributors. Rouleau and Gosselin [28] recently studied a 40-dwelling social housing building located in Canada and noticed occupants were using more electricity from 9:00 AM to 5:00 PM. An increase of 46% was seen relative to the same month in pre-COVID time. A study done by Bielecki [35] on data obtained from 7,000 flats, observed that while energy consumption has increased, there was no change in the average daily peak of these houses. Simulation studies were conducted by few researchers [29–31] to estimate the long-term impact of the lockdown on residential electrical demand. They estimated an increase in the electricity consumption range of 13-27%.

There were also few studies conducted on the variation in energy patterns and the increase of peak demand for residential buildings. The studies also tried to find which devices contributed to the increase in energy consumption. Aldubyan and Krarti [22] further demonstrated the hike of peak demand by 15 to 20% in post-COVID as compared to pre-COVID. Li et al., [29] through their simulation results also predicted a hike of 35-53% in residential hourly peak demand between 12 PM and 5PM. An energy use survey was conducted by Huebner et al.,[32] in the UK for 1016 participants during the first lockdown in March 2020. The survey data concluded that the electricity demand was more during the day and Italy showed an increased usage of cooking appliances, television and computers. Surahman et al. [33] investigated household energy consumption of urban residential buildings in major cities of Indonesia during COVID-19 pandemic. Statistical analysis performed on the survey results received from 311 residents concluded that the average annual energy consumption of samples taken was larger by 3 GJ during pandemic. The increase was majorly due to excessive use of AC and cooking appliances. A study done by Chinthavali et al.,[34] noticed a significant change in the pattern of electricity load in residential buildings during weekdays in lockdown. They also confirmed that HVAC and water heaters are the largest consumers of electricity in residential homes. Further, Kranti and Aldubyan [21] added that most of the energy was consumed by HVAC. Kawka and Cetin [35]compared the HVAC loads, non-HVAC loads and overall loads of 225 housing units located in Texas, for the duration 2018-2020 and concluded that maximum energy consumption in non-HVAC residential buildings occurred between 10 AM-5 PM while HVAC loads also increased for the lockdown period.

2.3 Residential energy consumption of India

According to data published by Times of India (TOI), India also witnessed a decline in energy consumption of 25% in the last week of March 2020, which was more than the decline that occurred in the US and Europe [36]. A study done by the Prayas (energy group) [37] on minute-wise load and voltage data of 81 households located in Uttar Pradesh and Maharashtra from 4 March to 5 May 2020, observed that the daily average household energy consumption increased by 26% in the lockdown period as compared to the pre-lockdown period. The finding was that among all household equipment, Heating, Ventilation, and Air Conditioning (HVAC) and water heaters consumed the most energy.

They analysed houses with and without AC and concluded that AC-homes consumption increased by 45-60% while non-AC homes energy consumption increased by 22% as compared to pre-COVID times. In their study, they showed that residential energy demand depends upon the size of the home, occupancy, climate of the place, and the location. Apart from this small-scale analysis there is a lack of similar studies in the Indian context.

2.4 Research gaps bridged

Based on the detailed literature review of the effect of lockdown on the residential energy consumption, we noticed these research gaps:

1. None of the studies were exclusively conducted on HVAC systems, change in the pattern or magnitude of consumption during lockdown period.
2. The studies were conducted for all the days of a particular period. While the impact of lockdown can be seen better during the weekdays. Moreover, the number of days taken form each period was not reported clearly in any of the studies.
3. The studies done till date are either for a particular building or an area, data from individual homes are not taken.
4. The occupancy before the lockdown and during the lockdown was not checked for the homes.
5. The data used for the studies are either simulated or temperature adjusted. The weather data was not considered for most of the studies.

Chapter 3

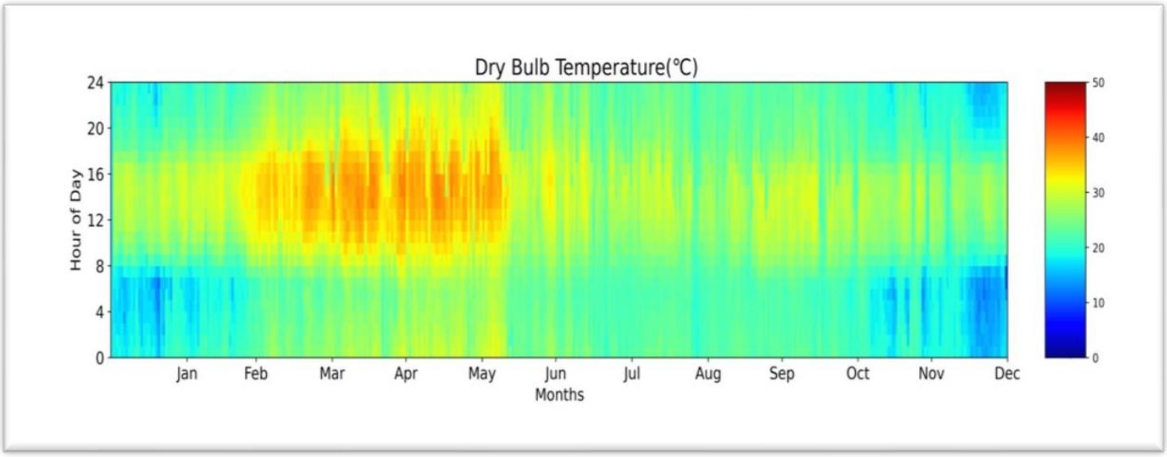
Methodology

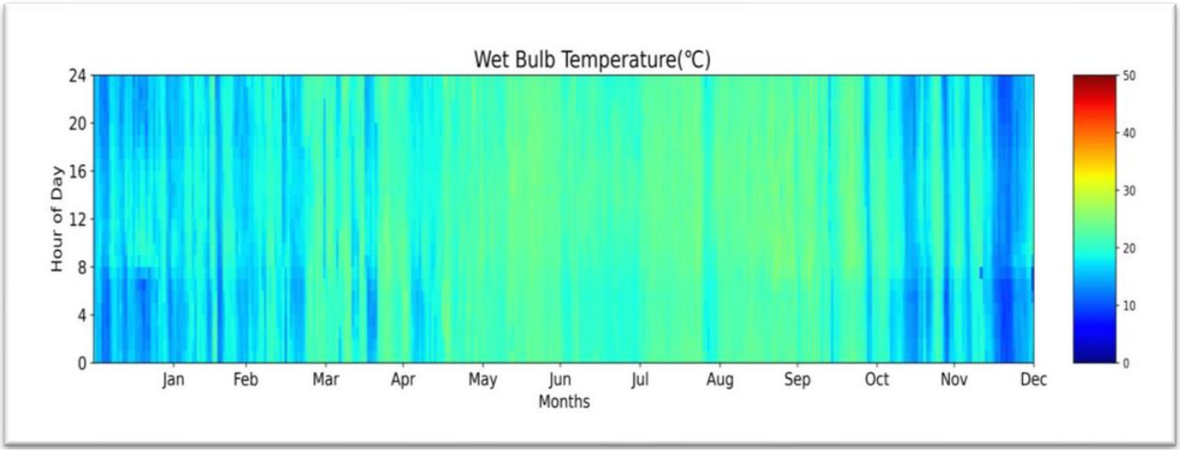
In this chapter we are presenting our proposed methodology and data sets prepared for various analysis. It provides the information about the buildings, its location, sensors used and the duration for the study. Various steps taken for the filtration of the complete data to get the desired data set are also discussed.

3.1 Study area and duration

With a population of over 1.4 billion, India is the second most populated country and the seventh-largest country by area. Located in the south of Asia [38], India's climate can be classified as hot tropical [39]. The temperature ranges from 45 °C in summer to 5 °C during winter in various parts of the country. Summer in India begins from March and continues till June [40].

The data utilized for this study was gathered from a residential complex in Hyderabad. It is a city in the Telangana region located in southern India. Hyderabad features an arid climate, where days are mostly dry and hot. The maximum average temperature can reach up to 40 °C [41]. It can be seen in figure 1 (a, b) that the peak temperature in summer is during the months of April and May, which compels individuals to use AC. The year 2019 represents non-COVID year and 2020 represents COVID year. The lockdown in India was imposed on 25 March 2020. For our study, the months of April and May were found suitable. Since most people use AC during the summer season. To study only the effect of lockdown on the AC energy and household electricity consumption and keeping in mind the school summer vacation in May for children, the month of April was finally selected.





(b)

Figure 1(a): Dry Bulb Temperature (°C) for Hyderabad (b) Wet Bulb Temperature (°C) for Hyderabad [41].

(a)

3.2 Building and Monitoring

The pandemic COVID-19 was unforeseen and unpredicted, and luckily, we were able to collect the AC energy and electricity consumption data for the normal and COVID period. This type of data is rare, but we were able to collect the data from a residential complex consists of 380 homes in 5 buildings, 18 floors each, spread across 5 acres. The area of each home ranges from 180 to 450 sq.m, comprising 3 to 5 bedrooms, a living and drawing room, kitchen, and washrooms. All the rooms are facilitated by a central cooling system. For each home, household electricity was measured for the entire home except AC energy. Since chilled water system was used to provide cooling to the building, it was not part of the household electricity consumption. Only the power supplied to the fan of AC indoor unit was a part of household electricity consumption. The AC energy was measured separately in kWh thermal, and the household electricity was measured in kWh units. AC energy was measured using a metering system that records the cooling energy consumption by individual homes. There is an entity in the complex, which records electrical and cooling readings in 30 mins interval separately. The electricity data of these homes were collected using smart meters, stored dynamically at the local database, and automatically retrieved every month and we received permission to use it for our study. These are commercial grid meters, and the readings were used for the billing purposes. Figure 2 consists of photographs of the residential complex, typical floor plan of the buildings, Energy meter and BTU meter along with its specifications.

(a) (b)

(c) (d)

Figure 2(a): Residential complex (b): Typical floor plan of the buildings (c): Energy meter (d): BTU meter

3.3 Data pre-processing

30 minutes interval data (AC energy and household electricity consumption) for 380 homes was acquired for the month of April 2019 and 2020. In total 2,188,800 data points were obtained for this study. For this analysis weekdays were considered for each month from both the years, as the impact of lockdown can be better seen on working days. Using this criterion, we found 22 working days in April from each year.

The outdoor temperature for the Hyderabad region was collected from the website Visual crossing [42]. It was observed that the average outdoor temperature for the year 2019 was more than that of

2020, as a result the energy consumption for 2020 was expected to be less [42]. To overcome this, days with a similar average temperature range were selected out of the previously selected 22 days from both the years. We segregated the daily average temperatures in two sets, Set_lo for medium temperature range (31-33 °C) and Set_hi for high temperature range (33-35 °C). From the 22 selected days of each year, 7 days from 2019 and 6 days from 2020 were having average temperature ranging between 31-33 °C (Set_lo). For the temperature range of 33-35 °C there were 8 days from 2019 and 12 days from 2020 (Set_hi).

It was observed that for each set the average temperature in the days selected for 2019 and the days selected for 2020 were not similar. Further we wanted to ensure same number of days in both the years. We selected 5 days in each year in Set_lo, such that the average temperature in both the years was close to 32.05 °C. Similarly, 8 days were selected in each year in Set_hi, such that the average temperature in both the years was close to 33.92 °C which can be seen in table 1. The analysis was performed on both the sets of temperature.

Table 1: Selection of days

Date (2019)	Average Temperature (°C)	Date (2020)	Average Temperature (°C)
01-04-2023	34.8	01-04-2020	32
02-04-2019	34.4	02-04-2020	33.1
03-04-2019	31.9	03-04-2020	31.1
04-04-2019	31.7	04-04-2020	28.1
05-04-2019	31.5	05-04-2020	30.9
06-04-2019	29.2	06-04-2020	30
07-04-2019	31.6	07-04-2020	32.7
08-04-2019	31.7	08-04-2020	32
09-04-2019	30.7	09-04-2020	29.3
10-04-2019	32	10-04-2020	30
11-04-2019	33.9	11-04-2020	30.8
12-04-2019	32.9	12-04-2020	33
13-04-2019	33.5	13-04-2020	33.1
14-04-2019	34.7	14-04-2020	33.3
15-04-2019	34.4	15-04-2020	33.7
16-04-2019	33	16-04-2020	34.1
17-04-2019	33.8	17-04-2020	34.3
18-04-2019	33.1	18-04-2020	32.6
19-04-2019	30.8	19-04-2020	31.4
20-04-2019	30.6	20-04-2020	32.6
21-04-2019	33	21-04-2020	33.4
22-04-2019	29.8	22-04-2020	33.5
23-04-2019	32	23-04-2020	34.7
24-04-2019	34.1	24-04-2020	33.2
25-04-2019	35.2	25-04-2020	34.4
26-04-2019	36.1	26-04-2020	33.3

27-04-2019	36	27-04-2020	33.2
28-04-2019	35.7	28-04-2020	30.3
29-04-2019	35.6	29-04-2020	32.5
30-04-2019	35.6	30-04-2020	34.4

Weekends	Days selected for Set_lo	Days selected for Set-hi	Days not selected

It was noticed that not all the 380 homes were occupied for the selected days. Further it was seen that some of the homes which were occupied during 2019 were not occupied during 2020 and vice-versa. To overcome this challenge, the common homes which were occupied for both years were taken to get more unbiased results. Two criteria were used to detect if the home was occupied: AC consumption to be greater than 1 kWh thermal and household electricity consumption greater than 1 kWh per day for the selected days. The common homes (between 2019 and 2020) qualifying both the criteria for all the selected days in the set were taken for the analysis. We filtered out 154 homes for Set_lo and 184 homes for Set_hi common in both the years. Table 2 provides the outcomes obtained of each filter.

Table 2: Details of filtration process.

Filter number	Filter criteria	Number of days in 2019	Number of days in 2020	Average-temp 2019	Average-temp 2020	Number of homes 2019	Number of homes 2020
0	Raw data	30	30	33.20 °C	32.40 °C	380	380
1	Working days	22	22	33.14 °C	32.60 °C	380	380
2	Set_lo (medium temperature range)	7	6	31.95 °C	32.15 °C	380	380

	Set_hi (high temperature range)	8	12	33.93 ℃	33.67 ℃	380	380
3	Number of days further selected in Set_lo	5	5	32.06 ℃	32.04 ℃	380	380
	Number of days further selected in Set_hi	8	8	33.93 ℃	33.91 ℃	380	380
4	Common Occupancy in Set_lo	5	5	32.06 ℃	32.04 ℃	154	154
	Common Occupancy in Set_hi	8	8	33.93 ℃	33.91 ℃	184	184

By implementing this filtration process we ensure that each set has same number of working days and same homes in both the years with very close average temperature in both the years. The AC energy consumption, household electricity consumption and operating hours are calculated for the final filtered data that is shown in Table 2. The operating hours were calculated using the AC energy consumption data, if the AC energy consumption is zero for half-hour, we considered the AC to be off and vice-versa.

Figure 3 shows the flow chart of the complete filtration process. Firstly, the raw data was taken and in the second step, the data was divided into two durations, pre-covid (2019) and lockdown (2020). In the third step the equal number of days were selected from the April month of both the years. The last filter was used to obtain the common occupied homes from all the homes, for both Set_lo and Set_hi. These sets of common homes were used for the analysis.

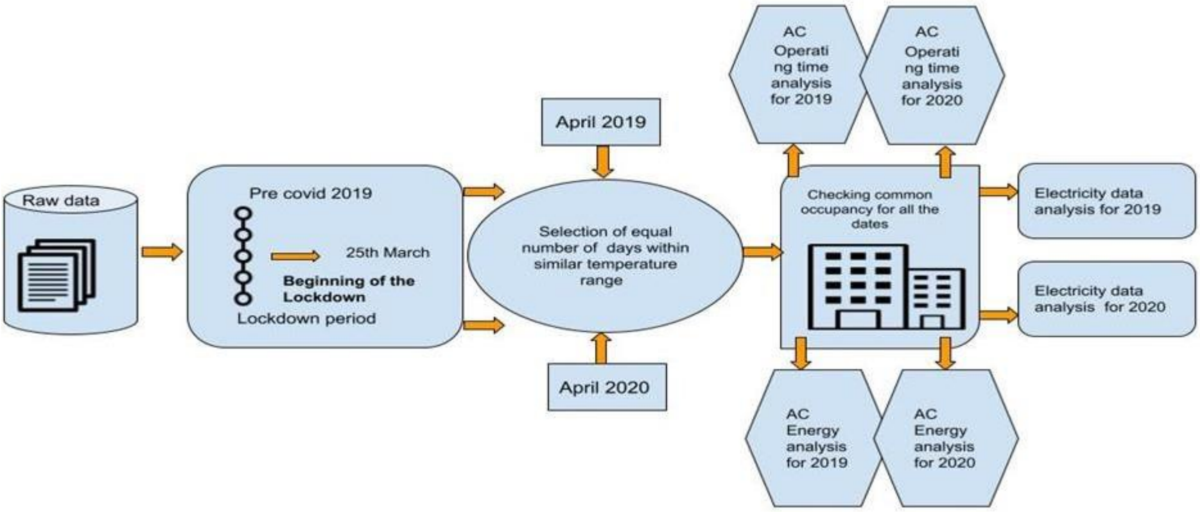


Figure 3: Flowchart of the analysis progression

Chapter 4

Results

The study is broadly divided into two groups:

- Analysis done for similar sets of temperatures for 2019 and 2020.
- Analysis done within the year for different sets of temperature.

The overall AC energy consumption and number of operating hours was calculated for both the years in each set. Furthermore, the day and night time consumption was calculated for the same. Followed by the total household electricity consumption, the day and night time household electricity consumption was also calculated. The results are tabulated along with the graphs for each analysis. The statistical tests for significance and frequency distribution of the data points were done and tabulated along with the graphs. The following analysis was done for both the groups.

4.1 Comparison between pre-covid and lockdown duration

In this section, two sets with similar of temperature ranges were taken. The comparison was made between 2019 and 2020 for both the sets. The AC energy consumption, number of hours the AC was used, and household electricity was analysed.

4.1.1 AC energy consumption

The AC consumption for both the sets in 2019 and 2020 is analysed in this section. The net change and percentage change along tabulated along with the relevant graphs.

- *Overall energy consumption*

  The average AC energy consumption per day per home for both the sets was calculated and analysed to find the energy consumed by the homes. It can be seen from table 3 that the energy consumption for the year 2020 was 3.68% more for Set_lo and 4.49% for Set_hi.
- *Day time energy consumption*

  12-hour AC energy consumption from 8:00 AM to 8:00 PM was taken for the daytime study. During the lockdown, the significant difference in the energy consumption for both years can be seen better during the day time, as people are expected to stay at home.

  Table 3 shows the daytime analysis for both sets. It can be observed that during the lockdown period, the daytime consumption was extensively high for both sets. We can see a hike of 22.14% for Set_lo and 26.01 for Set_hi for the year 2020.

- *Night time energy consumption*

  AC energy consumption data from 8:00 PM to 8:00 AM was taken to determine the consumption during night time. Similar process as of the day time analysis was followed for the night time analysis.

  The obtained results are given in table 3. The energy utilization was more during night time compared to day time. For the year 2019, during daytime, 11.84 kWh thermal units were consumed, but it was 28.77 kWh thermal units during night time, an upsurge of 2.43 times. For the year 2020, the consumption during night time was around 1.84 times the consumption during the daytime.

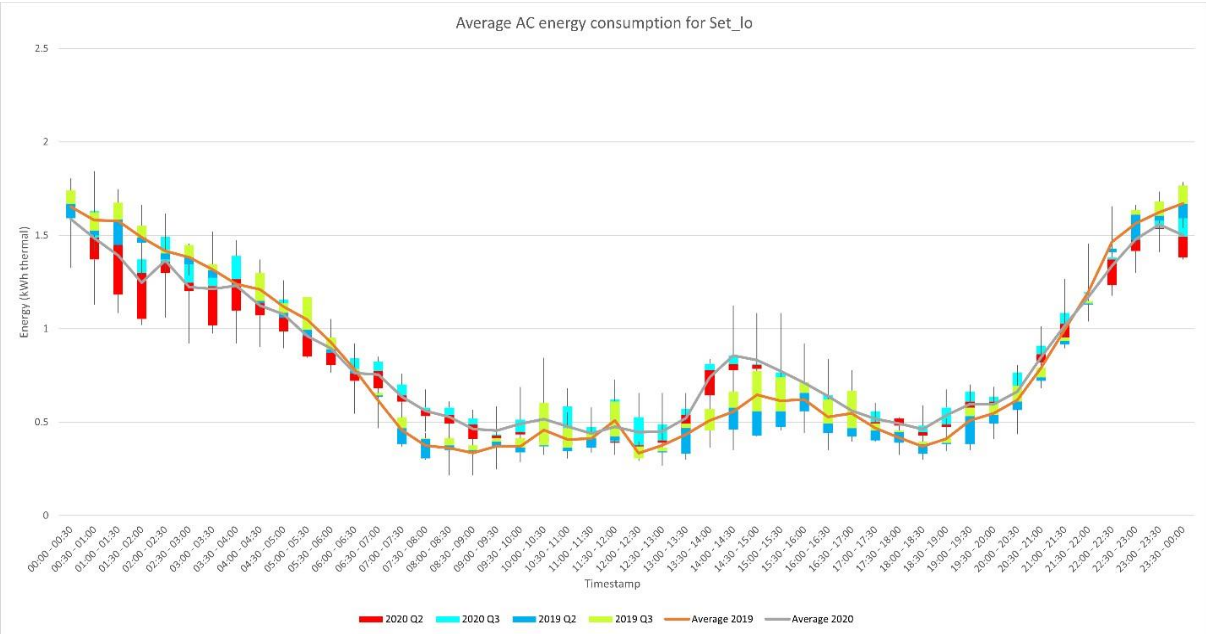
  Overall analysis for night time signifies that the energy consumed during the night was 4.35% more in 2019 compared to 2020. The AC energy consumption in 2020 during the night time is low because of the pre-cooling effect in the homes, as the AC was operated more during the daytime.

Table 3: Analysis of the AC energy consumption

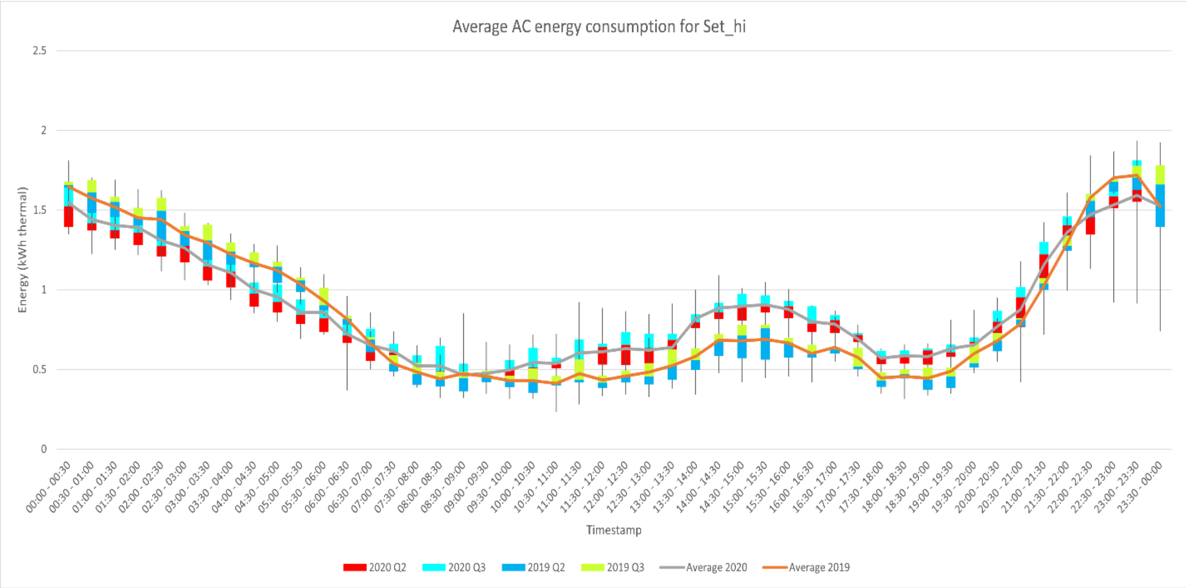
Set_lo	**2019** (kWh thermal)	**2020** (kWh thermal)	**Net Change**	**Percentage change**
Average AC consumption per day per home (Total energy/ number of homes selected)	39.21	40.65	1.44	3.68
Average AC consumption during daytime. (8:00 am-8:00pm)	11.11	13.58	2.47	22.14
Average AC consumption during night time. (8:00 pm- 8:00 am)	28.11	27.08	-1.03	-3.62
Set_hi	**2019** (kWh thermal)	**2020** (kWh thermal)	**Net Change**	**Percentage change**

Average AC consumption per day per home (Total energy/ number of homes selected) (kWh thermal)	41.12	42.93	1.81	4.49
Average AC consumption during daytime. (8:00 am- 8:00 pm)	12.57	15.84	3.27	26.01
Average AC consumption during night time. (8:00 pm- 8:00 am)	28.55	27.09	-1.46	-5.11

The average per day per home AC energy consumed by the residential buildings throughout the day for both years are illustrated in figure 4 (a, b). The x-axis represents the time stamp and the y- axis represents the consumption in kWh thermal units.



(a)



(b)

Figure 4(a): AC energy consumption throughout the day for Set_lo (b) AC energy consumption throughout the day for Set_hi

4.1.2 AC operating hours

The number of hours the AC was operated for both the sets in 2019 and 2020 is analysed in this section. The net change and percentage change along tabulated along with the relevant graphs.

- *Overall*

  Out of 48 half-hours, the average number of hours the AC was used per day per home for the two sets was determined for this analysis. From table 4, we can conclude that the AC was used more in 2020 as compared to 2019. On an average, an individual operated the AC for 10 hours daily in 2019, whereas for 11 hours in 2020. It resulted in a hike of 7.45% for Set_lo and 4.93% for Set_hi. The outcome from this study supports the energy analysis.

- *Day time operating hours*

  To comprehend the energy analysis further, it was important to see if the results obtained from half-hour analysis justifies the AC energy consumption. This study follows the same procedure that we followed for AC energy analysis, 12-hour AC energy data from 8:00 am to 8:00 pm was taken for this analysis. Table 4 provides information regarding the half-hour usage for both the years. Number of AC operational hours was more in 2020 for both the sets. The AC usage was increased by 1 hour (per home per day) during the daytime, an increase by 33.33% in the year 2020.

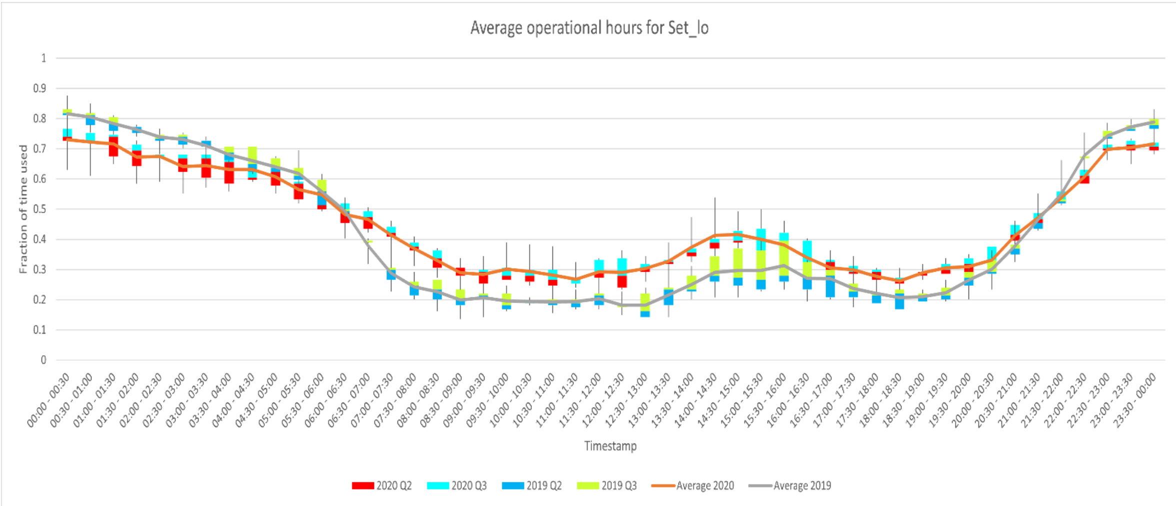
- *Night time operating hours*

  The number of operational hours for the night-time was computed by taking the data from 8:00 pm to 8:00 am. The same steps as for day-time analysis were followed during this study. Table 4 indicates that AC was mostly functional during night time. The AC was operated for around 7.5 hours during the night-time for both years. The average operating hours was more for 2019 by 4.75%. This is expected to happen because of pre-cooling of the homes.

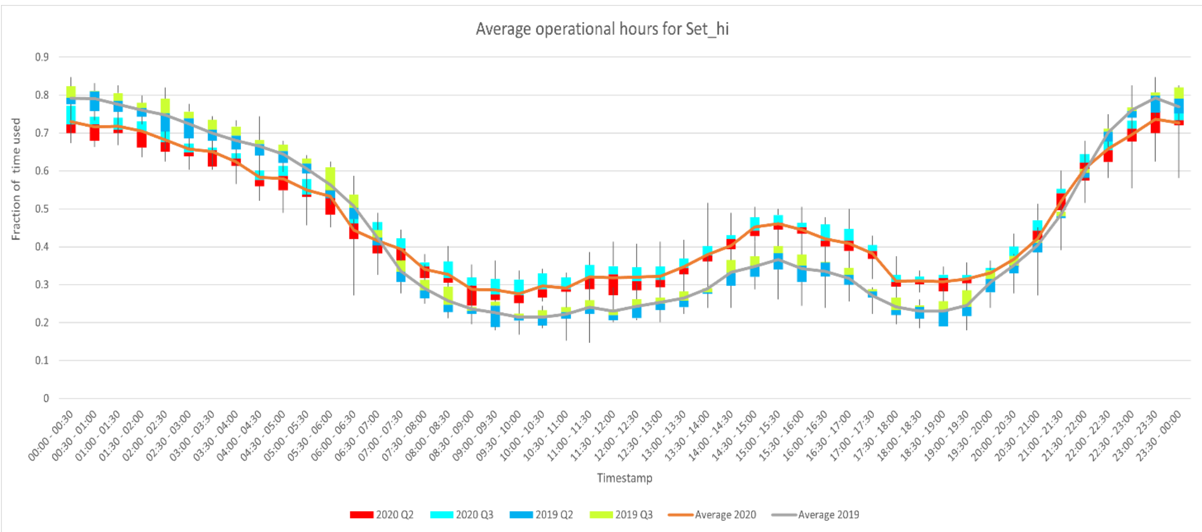
Table 4 :Analysis of the number of hours AC was operated.

Set_lo	**2019**	**2020**	**Net Change**	**Percentage change**
Average operating time per day per home (Total half hours/number of homes)	10.06	10.82	0.76	7.50
Average AC operating time during daytime. (8:00 am- 8:00pm)	2.77	3.82	1.05	37.72
Average AC operating time during night. (8:00 pm- 8:00 am)	7.29	7.00	-0.29	-4.04
Set_hi	**2019**	**2020**	**Net Change**	**Percentage change**
Average operating time per day per home (Total half hours/number of homes)	11.96	12.56	0.6	4.94
Average AC operating time during daytime. (8:00 am- 8:00pm)	3.23	4.16	0.93	28.80
Average AC operating time during night. (8:00 pm- 8:00 am)	7.45	7.05	-0.40	-5.40

The average proportion of AC operating hours for both the years are given in figure 5 (a, b). The x-axis represents the timestep, and the y-axis represents the portion of the time the AC was functional on an average scale.



(a)



(b)

Figure 5(a): Half-hour the AC was operated throughout the day for Set_lo (b) Half-hour the AC was operated throughout the day for Set_hi.

From table (3, 4), the amount of AC energy utilised, and operational hours of the AC is more for Set_hi when compared with Set_lo for the same year. It can be concluded that, because of the higher temperature range for Set_hi the consumption is more. But the increase in AC energy consumed for Set_lo is not proportional to the number of operational hours, whereas for Set_hi we can see a proportional increment for the AC energy as well as operational hour utilised. From table (3, 4), it is observed that the AC energy consumption for Set_lo has increased by 3.67% whereas the number of operational hours increased by 7.50%. Likewise, the amount of AC energy increases, and the hike in operational hours for Set_hi is similar. This can be explained from the graphs in figure 4. The AC energy consumed for the Set_hi is significantly more after 9:00 am, whereas AC energy consumption for Set_lo is more around 8:00 AM after which the energy consumption decreases till 12:00 PM. If we look at the operating hours graphs in figure 5, the AC was equally functional for both the sets. The temperature range for Set_lo is medium and due to the pre-cooling effect on the homes, the cooling load on the AC is less. However, for Set_hi, due to higher temperature the cooling load is higher, and the AC must consume more energy to reach the desired set point temperature provided by the occupants.

The AC energy consumed increased by 1.44 kWh thermal units for Set_lo and 1.81 kWh thermal units for Set_hi in 2020 as compared to 2019. The number of hours the AC operated increased by 0.76 hours for Set_lo and 0.6 for Set_hi in 2020. The net increase is almost equal for both the parameters.

4.1.3 Household electricity consumption

- *Overall*

  The average per day per home household electricity consumption was considered to find the overall electricity used by the homes. From table 5, it can be observed that the average daily household electricity consumption for the year 2019 was around 12.37 kWh as compared to 14.22 kWh for 2020. The electricity utility was increased by 15.03% for Set_lo and 14.87 % for Set_hi in the year 2020. The increment in household electricity consumption is similar for both the sets, as there is no direct impact of temperature on the household electricity consumption.

- *Day time*

  To observe the change in electricity consumption during daytime, analysis was done on the same data. The 12 hours data from 8:00 am to 8:00 pm was used. From the results tabulated in table 5, it can be seen that the change in consumption is slightly higher during the daytime. The average electricity consumption for both the sets in 2019 was 6.42kWh, and 8.02 kWh for 2020. An increase of electricity demand by 24.84% was seen during the lockdown period. These results indicate that people were using more electrical appliances such as monitors, laptops, cooking inductions during the lockdown as people were staying at home.

- *Night time*

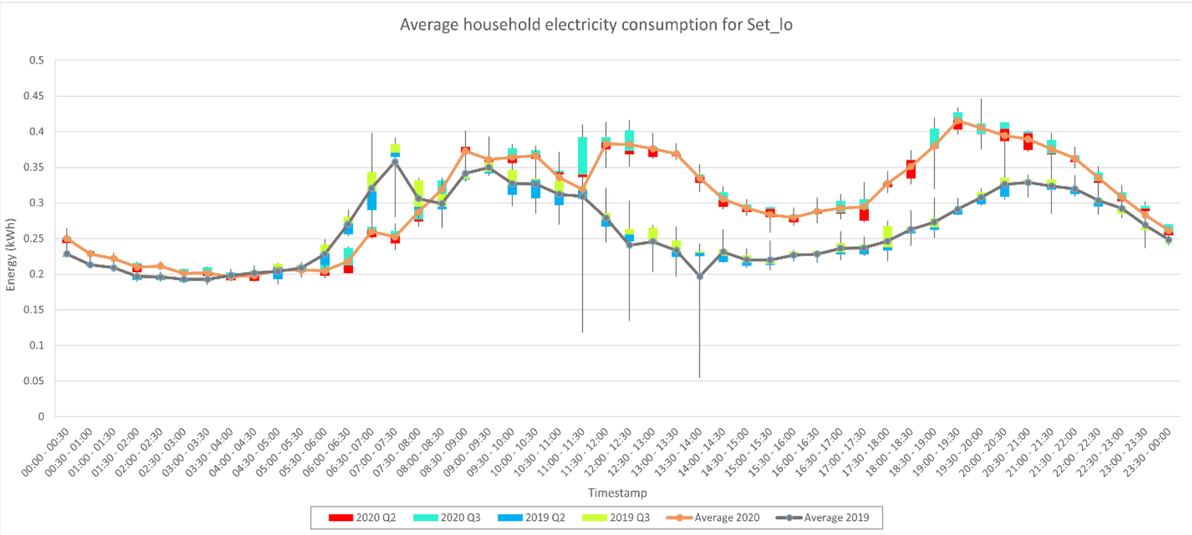
  Night-time analysis was done by taking the remaining data of the same days from 8:00 pm to 8:00 am. The results for the night time are summarized in table 5. We can see that the electricity consumption increased by 4.30% in the year 2020. It is expected that people would have stayed at home during the night time for both the years, as a result the household electricity consumption was similar for both the years, and a small hike for 2020 is seen. When both the years were compared, it was seen that the percentage increase for day time consumption is more significant than night time consumption. These hikes conclude that the electricity consumption has majorly increased due to the day time usage of electricity during the lockdown period.

Table 5: Analysis of the household electricity consumption

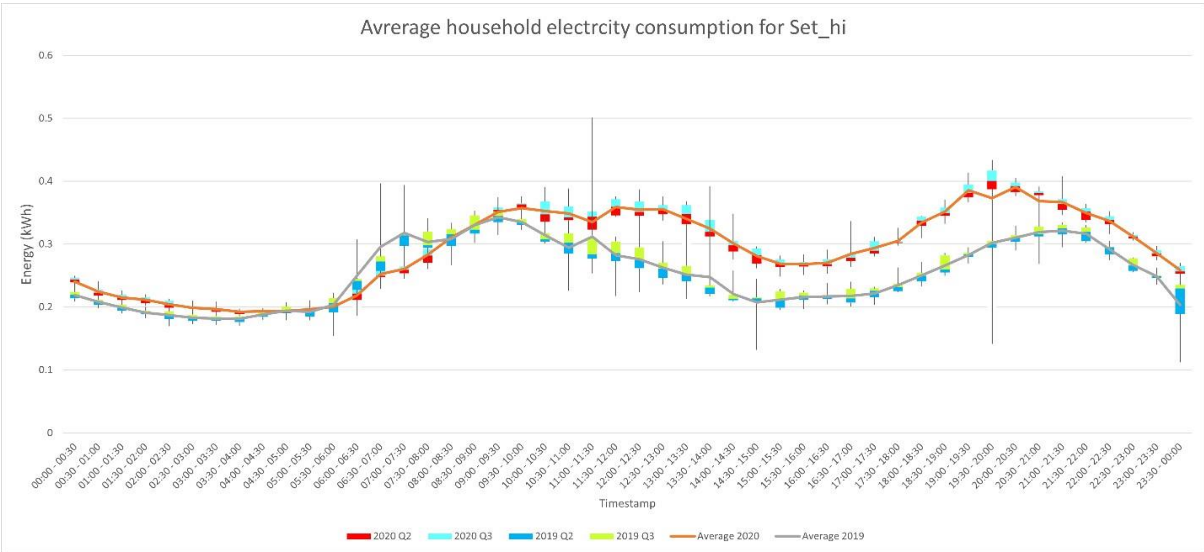
Set_lo	**2019** (kWh)	**2020** (kWh)	**Net Change**	**Percentage change**
Average household electricity consumption per day per home (Total energy/ number of homes selected) (kWh)	12.57	14.46	1.89	15.03
Average electricity consumption during daytime. (8:00 am- 8:00pm)	6.44	8.20	1.76	27.33
Average electricity consumption during night time (8:00 pm- 8:00 am)	6.14	6.26	0.12	1.95
Set_hi	**2019** (kWh)	**2020** (kWh)	**Net Change**	**Percentage change**
Average household electricity consumption per day per home (Total energy/ number of homes selected)	12.17	13.98	1.81	14.87
Average electricity consumption during daytime. (8:00 am- 8:00pm)	6.40	7.84	1.44	22.50

Average electricity consumption during night time (8:00 pm- 8:00 am)	5.77	6.15	0.38	6.59

The increment in household electricity consumption is similar for both the sets, as there is no direct impact of temperature on the household electricity consumption. The average net electricity consumption across the day of both the years are given in figure 6 (a, b). The x-axis represents the timestep, and the y-axis represents the household electricity consumption in kWh units.



(a)



(b)

Figure 6(a): Electricity consumption throughout the day for set_lo (b) Electricity consumption throughout the day for Set_hi.

4.1.4 Clustering of data

- *Household electricity consumption*

For this study, the five clusters were made for both the sets (Set-lo and Set_hi) and compared. To generate the clusters, the number of occupied homes for each set were arranged in decreasing order of their household electricity consumption for the year 2019, and then were divided equally into five clusters for the year 2019 and 2020, the decision tree is provided in figure 7. The average consumption of household electricity units for both the sets were tabulated along with the graphs in table 6 and figure 8. We can observe a similar pattern for both the sets. The household electricity consumption for the year 2020 is more for all the clusters in both the sets.

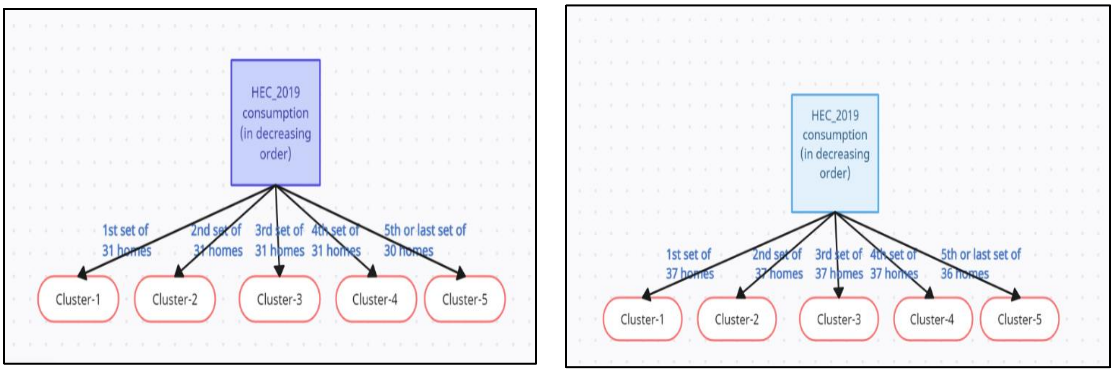
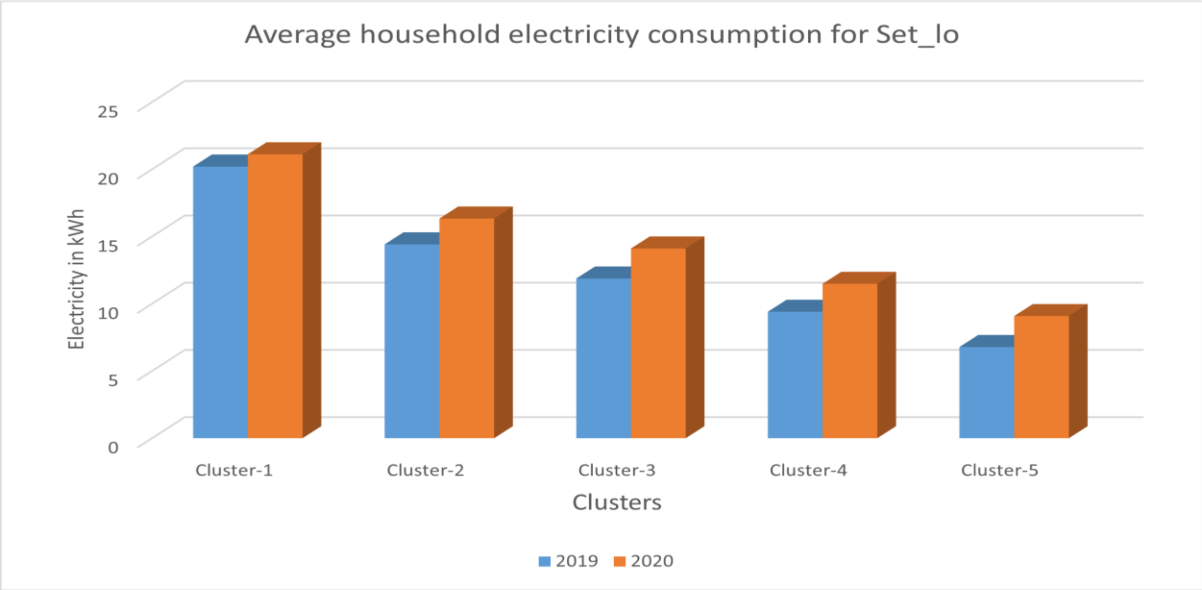


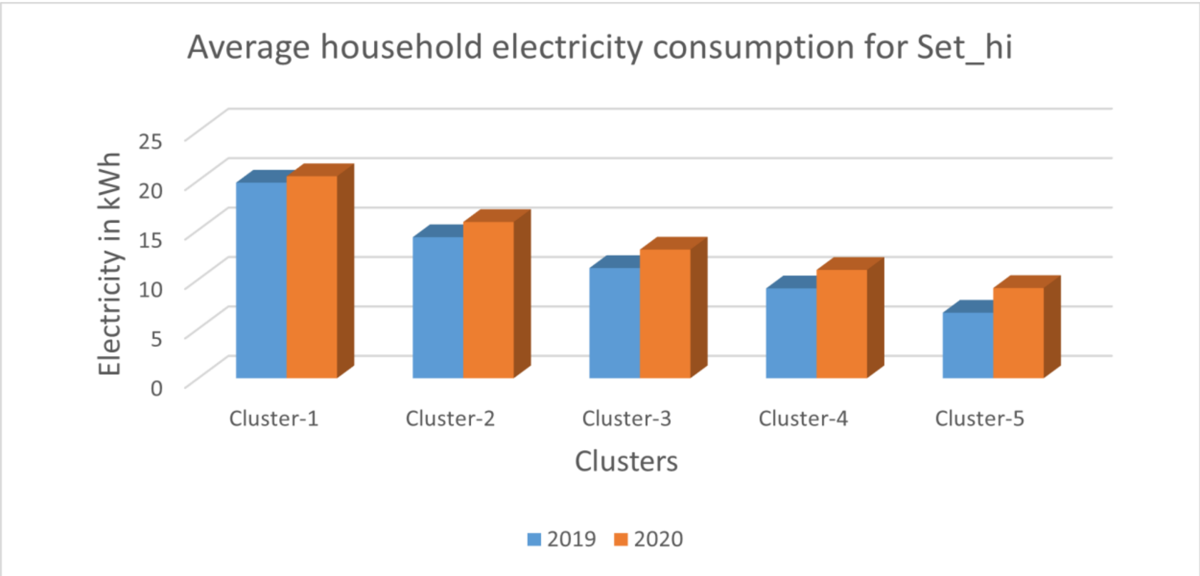
Figure 7: Decision tree for forming clusters (Set_hi and Set_lo)

Table 6: Average household electricity consumption in each cluster

Set_lo	**2019 (kWh units)**	***2020* (kWh units)**
Cluster-1	20.20	21.12
Cluster-2	14.42	16.34
Cluster-3	11.88	14.11
Cluster-4	9.40	11.48
Cluster-5	6.78	9.08
Set_hi	**2019 (kWh units)**	***2020* (kWh units)**
Cluster-1	19.78	20.43
Cluster-2	14.7	15.80
Cluster-3	11.15	13.01
Cluster-4	9.09	10.96
Cluster-5	6.63	9.13



(a)



(b)

Figure 8(a): Household electricity consumption clustering for Set_lo (b) Household electricity consumption clustering for Set_hi

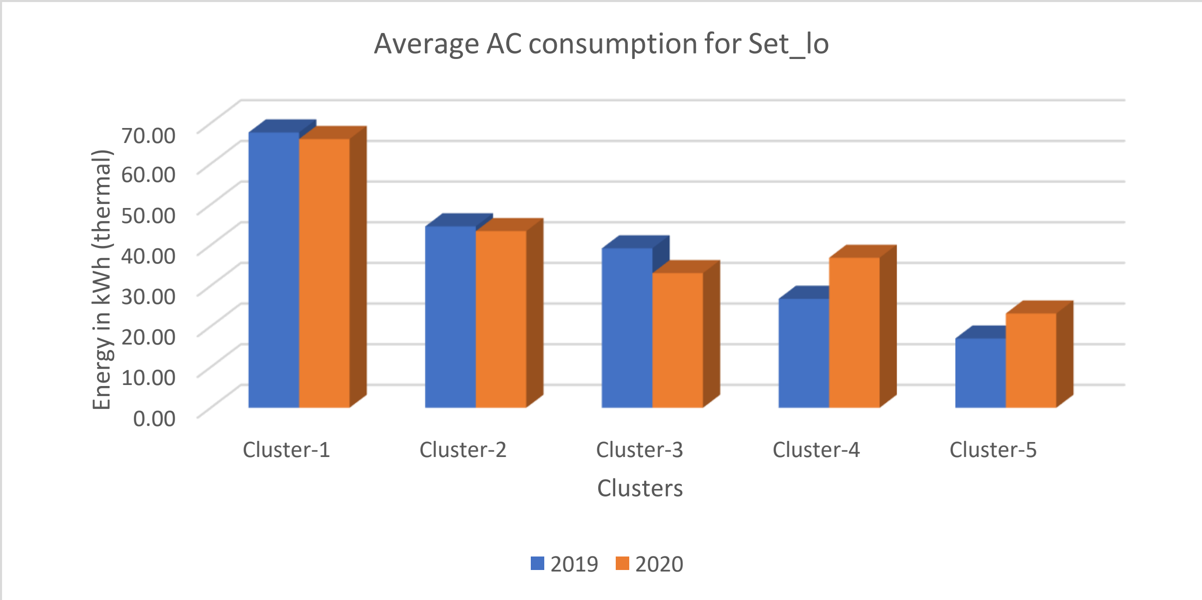
- *AC energy consumption*

Similar to the previous experiment, the AC consumption of the occupied homes for each set were arranged in decreasing order of their household electricity consumption for the year 2019 to maintain the consistency, and then were divided equally in clusters for the year 2019 and 2020. The average consumptions of AC units for both sets were tabulated along with the graphs in table

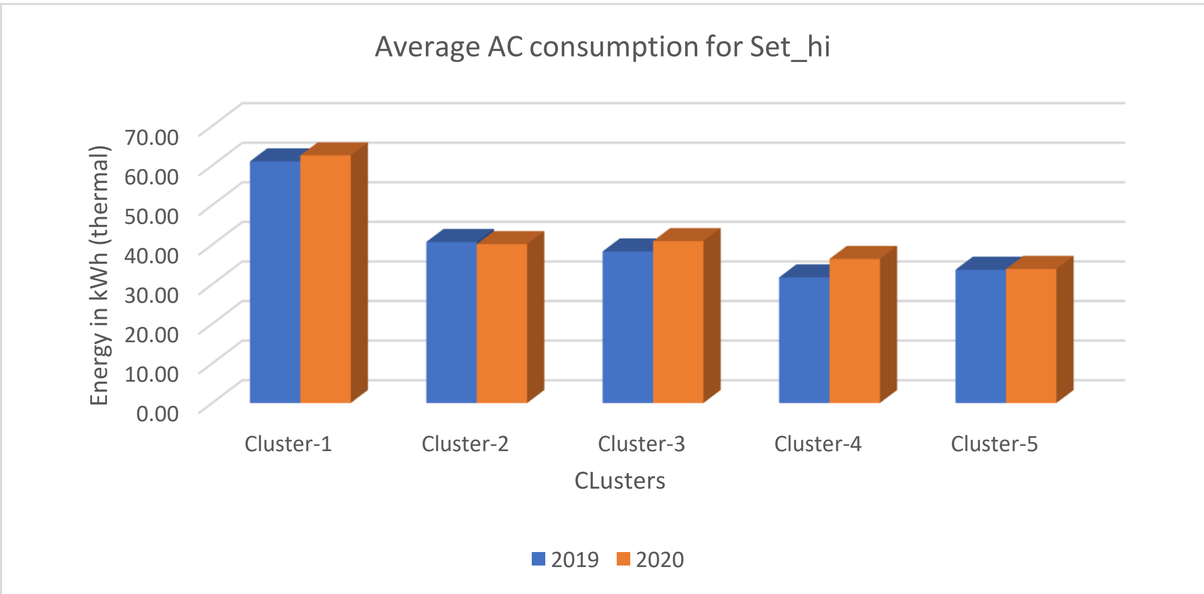
7 and figure 9. We can observe a similar pattern for both the sets in figure 9. The AC energy consumption for the year 2019 is more for few clusters with average reduction of 5%, whereas for the remaining clusters the AC consumption is more by 15% in average for the year 2020.

Table 7: Average AC energy consumption in each cluster

Set-lo	**2019 (kWh thermal units)**	***2020* (kWh thermal units)**
Cluster-1	67.72	66.10
Cluster-2	43.61	43.61
Cluster-3	39.21	33.11
Cluster-4	26.79	36.89
Cluster-5	17.03	23.19
Set-hi	**2019 (kWh thermal units)**	***2020* (kWh thermal units)**
Cluster-1	61.04	62.55
Cluster-2	40.68	40.13
Cluster-3	38.29	40.19
Cluster-4	31.73	36.40
Cluster-5	33.67	33.87



(a)



(b)

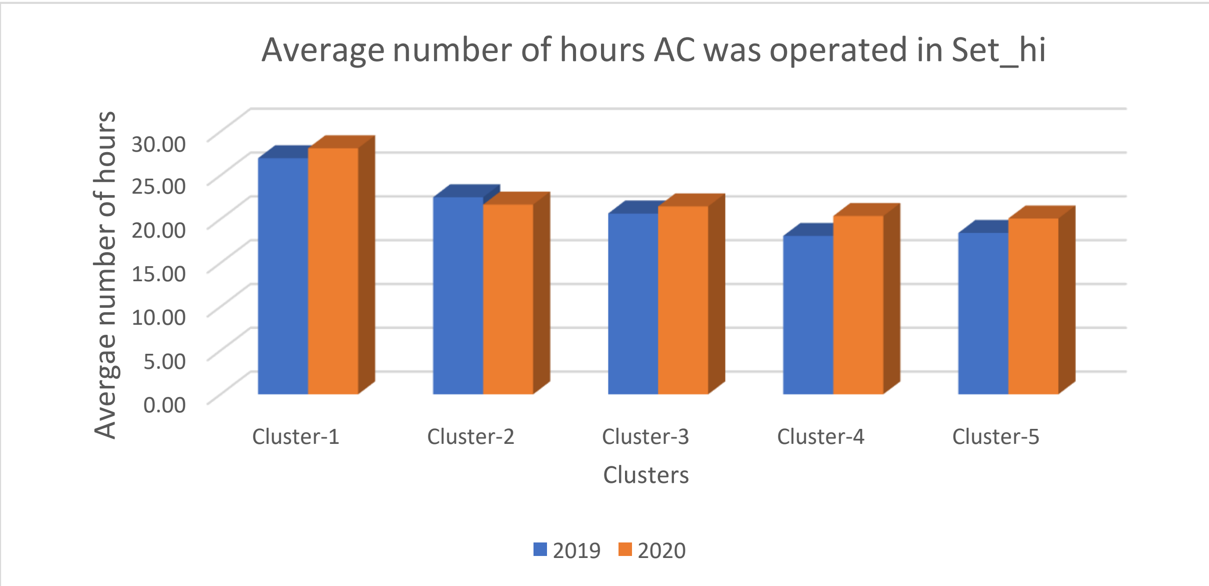
Figure 9(a): AC energy clustering for Set_lo (b) AC energy clustering for Set_hi.

- *AC operational hours*

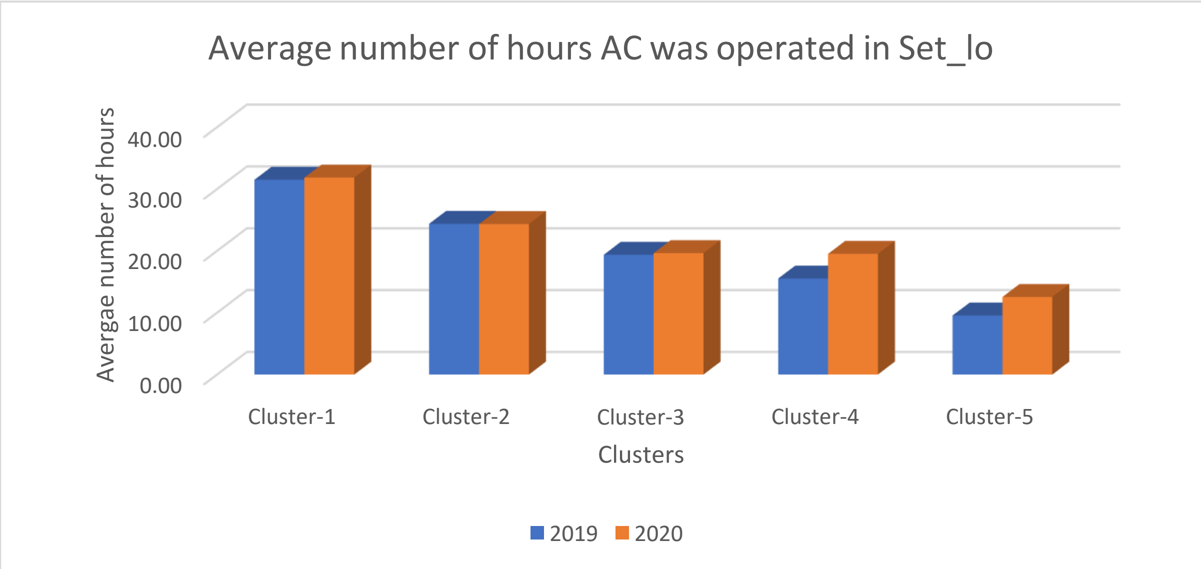
Similar to the previous experiment, five clusters were made for both the sets and compared for the AC operational hours. The AC operating hour consumption for the occupied homes for each set were arranged in decreasing order of their household electricity consumption for the year 2019, and then were divided equally in 5 clusters for the year 2019 and 2020. The average AC operational hours units for both the sets were tabulated along with the graphs in table 8 and figure 10. We can observe a similar pattern for both the sets in figure 10. The AC operational hours consumption for the year 2020 is more for all the clusters in both the sets.

Table 8: Average AC operational hours in each cluster

Set_lo	**2019 (half hours)**		***2020* (half hours)**
Cluster-1	31.51		31.85
Cluster-2	24.37		24.34
Cluster-3	19.37		19.64
Cluster-4	15.53		19.52
Cluster-5	9.55		12.54
Set_hi	**2019 (half hours)**		***2020* (half hours)**
Cluster-1	26.95		28.08
Cluster-2	22.49		21.66
Cluster-3	20.63		21.45
Cluster-4	18.07		20.35
Cluster-5	18.42		20.06



(a)



(b)

Figure 10(a): AC operational hours for Set_lo (b) AC Operational hours for Set_hi.

4.1.5 Statistical test on the data

The significance test is performed to check whether the observed differences between assessment results occur because of sampling error or chance. If the test turns out to be insignificant, then the results should not be considered because they do not reflect real differences [43]. There are multiple significance tests in literature [44] among which, the t-test [45] was more suitable for our purposes. T-Tests are tests for statistical significance that are used with interval and ratio level data. It can be used for several different types of statistical tests, such as, to test whether there are differences between two groups on the same variable, based on the mean (average) value of that variable for each group, to test whether a group's mean (average) value is greater or less than some standard or to test whether the same group has different mean (average) scores on different variables [44]. For our study paired t-tests were used, as the samples were from a single population [45]. The test was conducted on the AC energy, number of hours AC was operated and electricity data as the data obtained is from the same source i.e., homes. The test was performed using a 95% confidence interval. Table 9 presents results obtained for the statistical test comparison of 2019 and 2020 for three sets of samples: AC energy, operating hours, and household electricity data. If the magnitude of t-stat value is less than t-critical two-tail, then we assume the null hypothesis is true. From table 9 it can be seen that the t-stat values for all the 3 samples are greater than t-critical two-tail, hence the results provide strong evidence against the null hypothesis that μ2019 is equal to μ2020, hence concluding that "means of these two data sets for the same set of objects when compared pre-COVID and COVID years are statistically different for energy and number of operating hours."

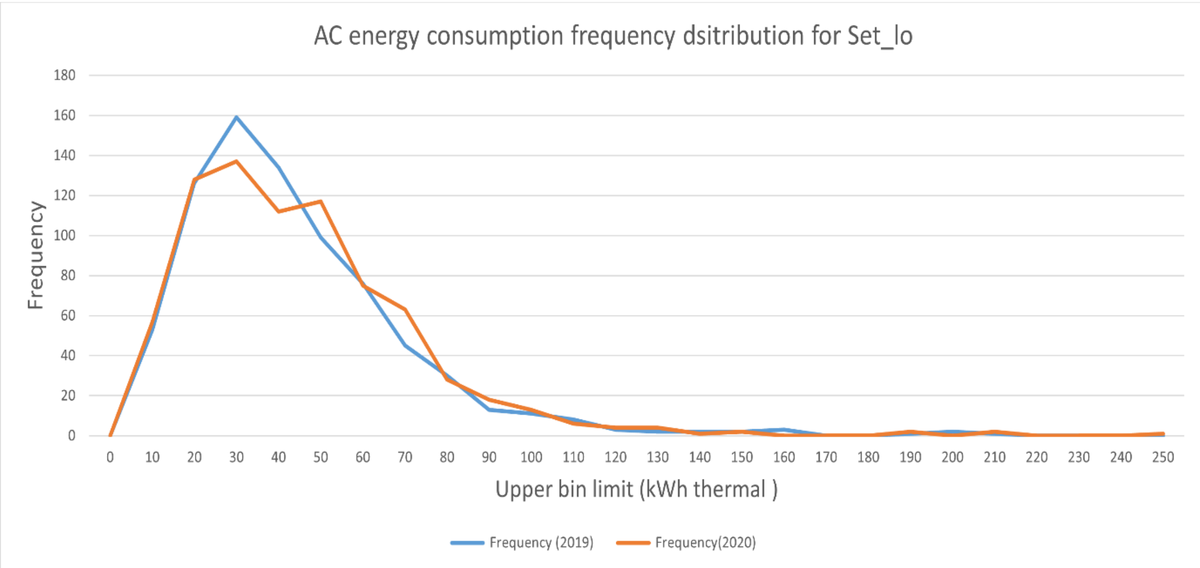
Table 9: Paired t-test analysis

Parameters	**AC energy 2019**	**AC energy 2020**	**Operating hour 2019**	**Operating hour 2020**	**Household electricity 2019**	**Household electricity 2020**
Mean	40.47	42.10	20.92	22.09	12.31	14.05
Variance	720.26	769.78	90.76	121.72	28.20	34.46
Number of Observations	2242.00	2242.00	2242.00	2242.00	2242.00	2242.00
Degree of freedom	2241.00		2241.00		2241.00	
T stat	-3.04		-5.31		-20.81	
P(T<=) two tail	0.002		12.4E-8		4.66E-88	
T critical two-tail	1.961		1.961		1.961	

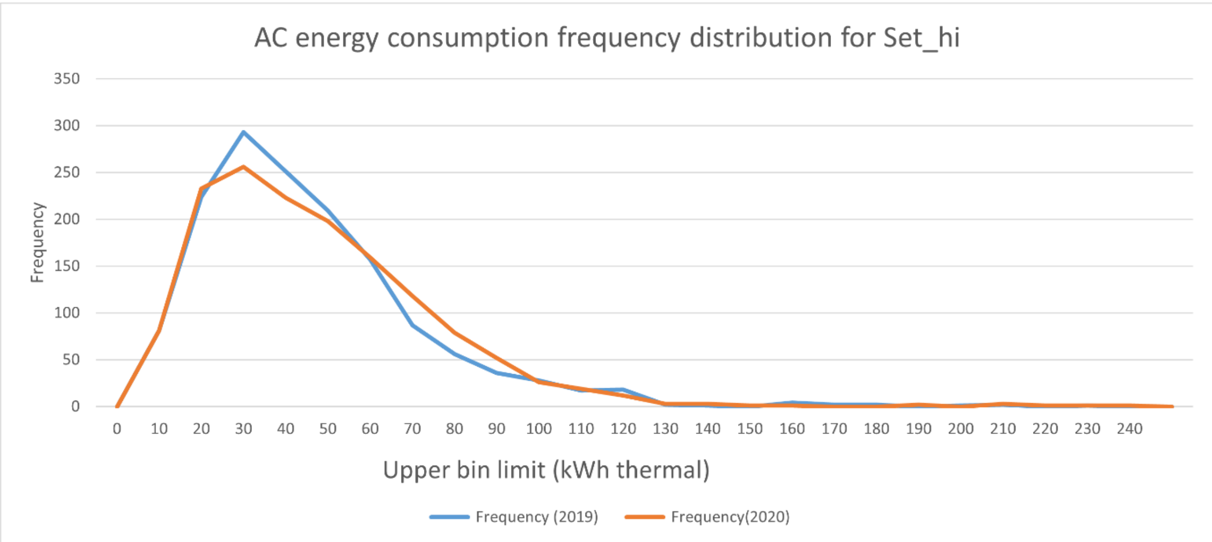
4.1.6 Frequency distribution

- *Frequency distribution for AC energy consumption*

  For this analysis, the everyday AC consumption data for all the occupied homes for the selected days from April month for both years was taken. For Set_lo we had 5 days and 154 homes and for Set_hi we had 8 days and 184 homes, a total of 770 data points for Set_lo (31-33 ℃) and 1472 data points for Set_hi (33-35 ℃). The frequency graph for each set was prepared separately. Figure 11 (a, b) provides information about the AC energy consumed by all the homes for the selected days. The higher frequencies for 2019 and 2020 are at 30-40 kWh thermal, but for the year 2020 the peak has covered a greater range, which indicates that the homes have started using more AC in 2020 as compared to 2019. The x-axis in figure 10 (a,b) represents AC energy consumption in kWh thermal units, the bin size is kept as 10 units. The Y-axis represents the frequency of the homes falling in the particular bin size.



(a)

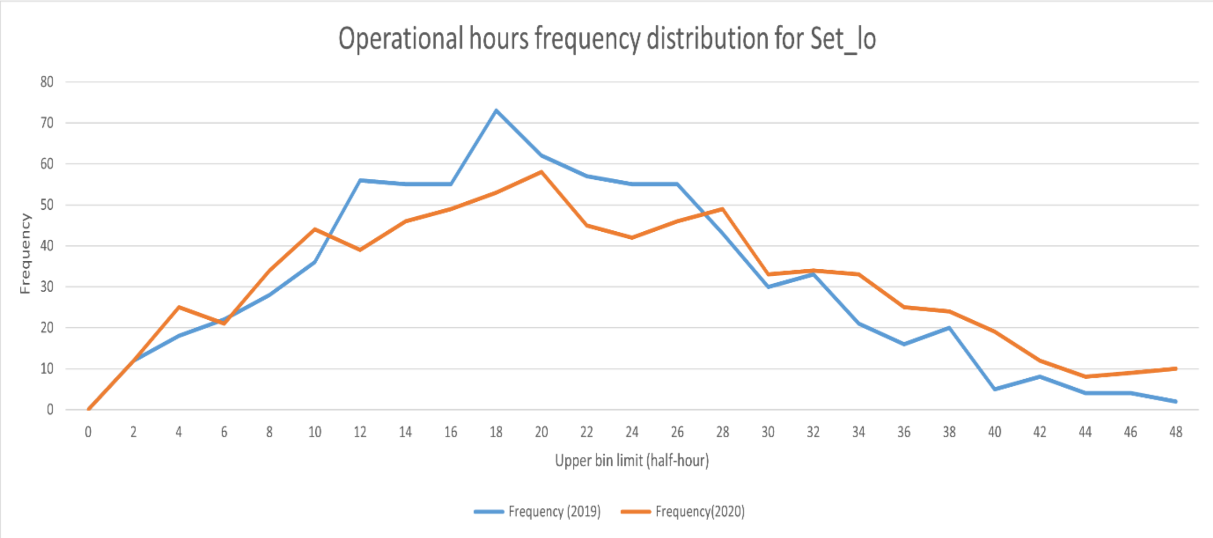


(b)

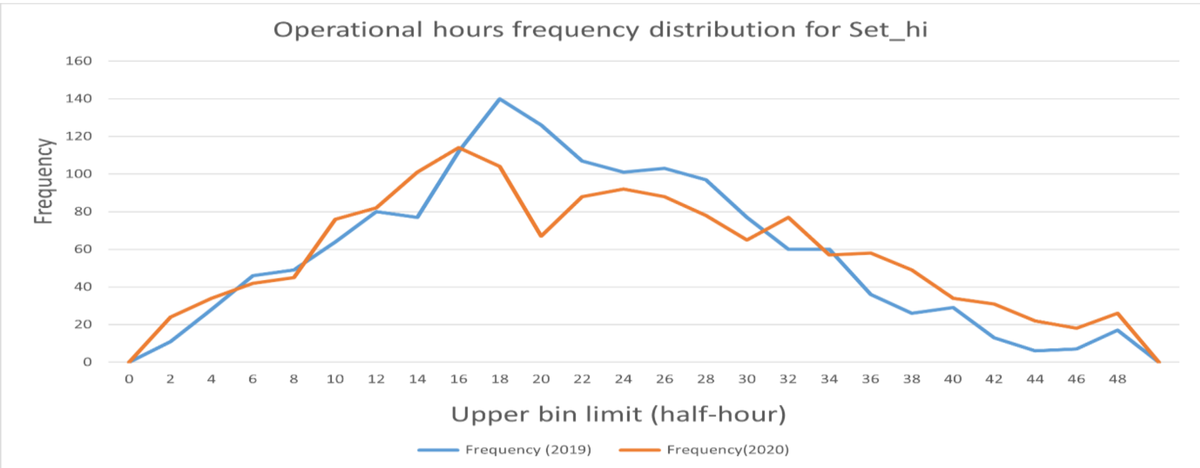
Figure 11(a): Frequency graph for AC consumption, Set_lo (b) Frequency graph for AC consumption, Set_hi

- *Frequency distribution for operating hours of AC*

  For this analysis, the number of hours the AC was operated for the occupied homes for the selected days from April month for both years was taken. We obtained the same number of data points as of previous analysis, a total of 770 data points for Set_lo and 1472 data points for Set_hi. The analysis for Set_lo and Set_hi was done separately figure 12 (a, b) provides details about the AC operating hours for all the homes for the selected days. We can observe that the curve for the year 2020 is slightly flat when compared to 2019. The number of hours the AC was operated for the year 2020 has surpassed 2019 at higher bin limits. The x-axis in figure 12 (a,b) represents the number of half- hours in each day, each bin size is 2 units (1 hour) and the y -axis represents the frequency of the homes falling in a particular bin size.



(a)

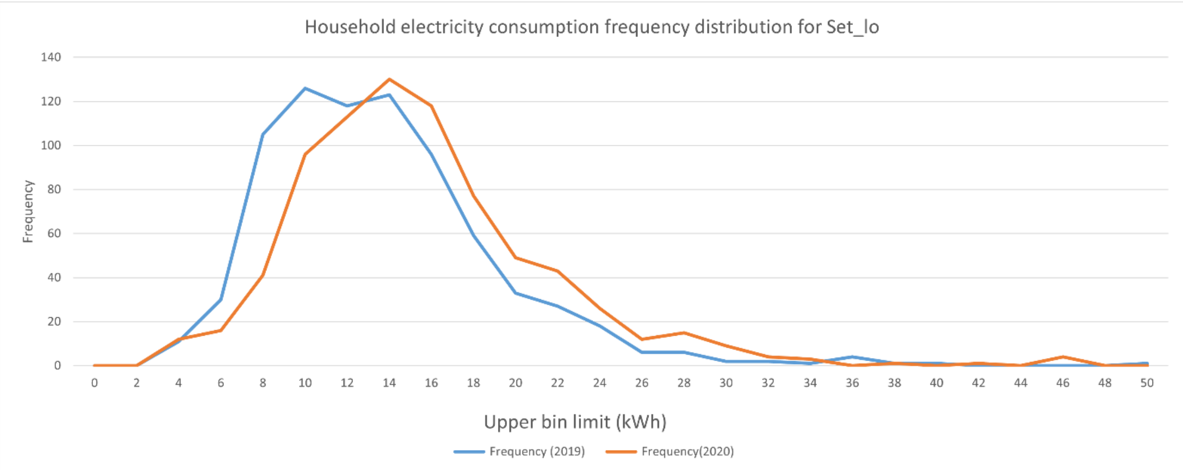


(b)

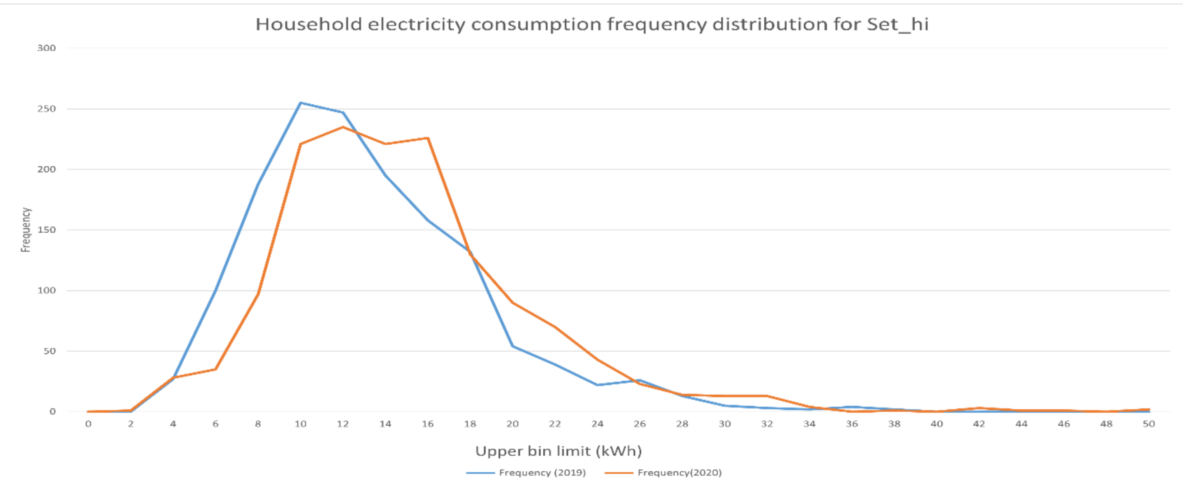
Figure 12(a): Frequency graph for operational hours for Set_lo (b) Frequency graph for operational hours for Set_hi.

- *Frequency distribution for household electricity consumption*

  The household electricity data was taken for all the occupied homes for the selected days in April month for both the years. These electricity data include the electricity demand for all the household appliances except the AC consumption data. For this analysis, we obtained a total of 770 data points for Set_lo (31-33 ℃) and 1472 data points for Set_hi (33-35 ℃). The figure 13 (a, b) provides information about the electricity consumed by all the homes for the selected days. We can see that the peak frequency has hiked from 10 kWh in 2019 to 15 kWh in 2020 for both the sets, further it can be seen that the curve for 2020 has slightly shifted towards the higher electricity consumption at x-axis. The x-axis in figure 13 (a,b) represents household electricity consumption in kWh units, the bin size is kept as 2 units. The y-axis represents the frequency of the homes falling in the bin size.



(a)



(b)

Figure 13(a): Frequency graph for electricity consumption Set_lo (b) Frequency graph for electricity consumption for Set_hi.

4.2 Impact of temperature on the Sets

In this section, the data was taken for same year from different sets. AC consumption data from Set_lo and Set_hi for the year 2019 was taken to evaluate the impact of temperature. Similar kind of study was done for 2020. The AC energy consumption, number of hours the AC was used, and household electricity for different sets of temperature for same year was analysed.

4.2.1 AC energy consumption

The AC consumption for the year 2019 and 2020 form both the sets are analysed. The net change and percentage change along tabulated along with the relevant graphs.

- *Overall energy consumption*

  The average AC energy consumption per day per home for both the sets was calculated and analysed to find the energy consumed by the homes. It can be seen from table 10 that the energy consumption for Set_hi was 4.85% more for 2019 and 5.57% more for the year 2020 than Set_lo.

- *Day time energy consumption*

  12-hour AC energy consumption from 8:00 AM to 8:00 PM was taken for the daytime study. During the lockdown, the significant difference in the energy consumption for both years can be seen better during the day time, as people are expected to stay at home.

  Table 10 shows the daytime analysis for both the years. It can be observed that the daytime consumption for Set_hi was extensively high for both years. We can see a hike of 13.14% for the year 2019 and 16.63% for the year 2020.

- *Night time energy consumption*

  AC energy consumption data from 8:00 PM to 8:00 AM was taken to determine the consumption during night time. Similar process as of the day time analysis was followed for the night time analysis.

  The obtained results are given in table 10. The energy consumption was more during nighttime compared to day time. For Set_lo, during daytime, 12.34 kWh thermal units were consumed, but it was 27.60 kWh thermal units during night time, an upsurge of 2.23 times. Similarly for Set_hi, the consumption during night time was around 1.96 times the consumption during the daytime.

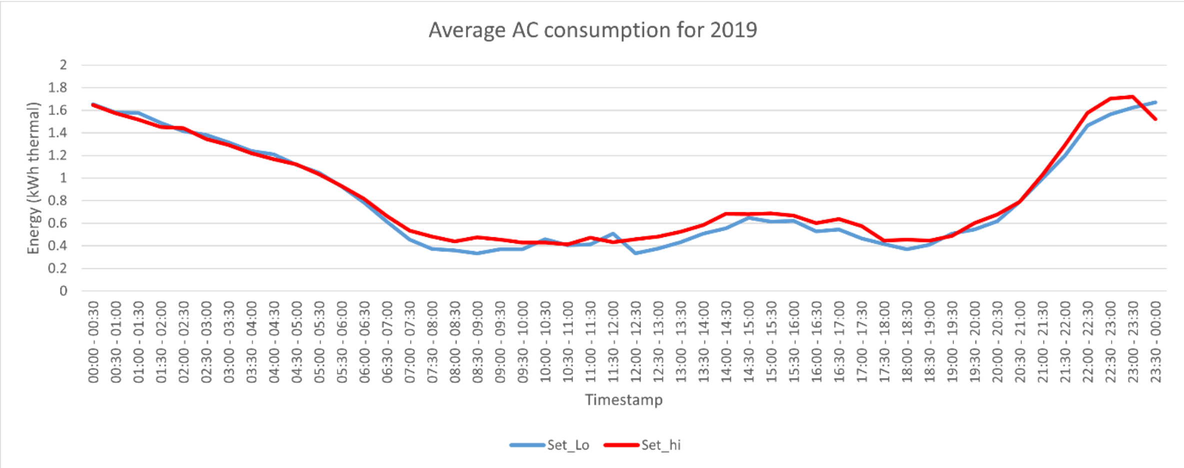
Overall analysis for night time signifies that the energy consumed during the night was 4.18% more for Set_hi when compared to Set_lo. Further, the AC energy consumption during the night time is similar for both the sets for the year 2019 and 2020.

Table 10: Analysis of the AC energy consumption

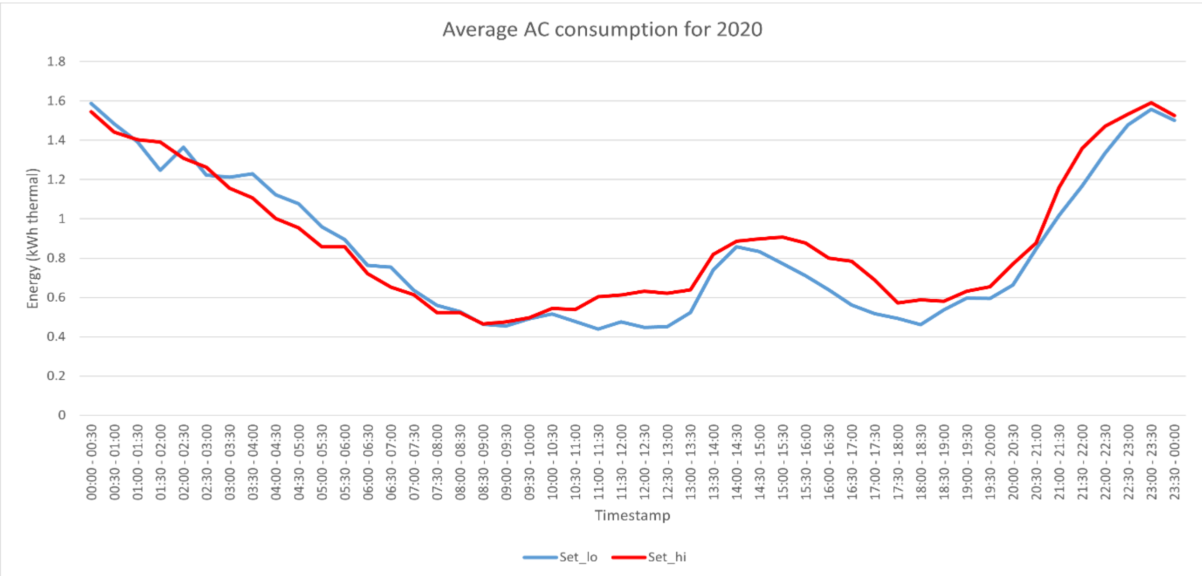
2019	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average AC consumption per day per home (Total energy/ number of homes selected)	39.21	41.12	1.91	4.85
Average AC consumption during daytime. (8:00 am- 8:00pm)	11.11	12.57	1.46	13.14
Average AC consumption during night time. (8:00 pm- 8:00 am)	28.11	28.55	0.44	1.58
2020	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average AC consumption per day per home (Total energy/ number of homes selected) (kWh thermal)	40.65	42.93	2.28	5.57
Average AC consumption during daytime. (8:00 am- 8:00 pm)	13.58	15.84	2.26	16.63
Average AC consumption	27.08	27.09	0.02	0.031

during night time. (8:00 pm- 8:00 am)				

The average per day per home AC energy consumed by the residential buildings throughout the day for both years are illustrated in figure 14 (a, b). The x-axis represents the time stamp and the y- axis represents the consumption in kWh thermal units.



(a)



(b)

Figure 14(a): AC energy consumption throughout the day in 2019 (b) AC energy consumption throughout the day in 2020

4.2.2 AC operating hours

The number of hours the AC was operated for both the sets in 2019 and 2020 is analysed in this section. The net change and percentage change along tabulated along with the relevant graphs.

- *Overall*

  Out of 48 half-hours, the average number of hours the AC was used per day per home for the two sets was determined for this analysis. From table 11, we can conclude that the AC was used more in Set_hi when compared to Set_lo. On an average, an individual operated the AC for 10.45 hours daily in Set_lo, whereas for 11 hours in Set_hi. It resulted in an increase by 5.93% for the year 2019 and 3.45% for the year 2020. The outcome from this study supports the energy analysis.
- *Day time operating hours*

  To comprehend the energy analysis further, it was important to see if the results obtained from half-hour analysis justifies the AC energy consumption. This study follows the same procedure that we followed for AC energy analysis, 12-hour AC energy data from 8:00 am to 8:00 pm was taken for this analysis. Table 11 provides information regarding the half-hour usage for both the years. Number of AC operational hours was more for Set_hi for both the years. The AC usage was increased by half hour (per home per day) during the daytime, an average increase by 12.75% for Set_hi in both the years.
- *Night time operating hours*

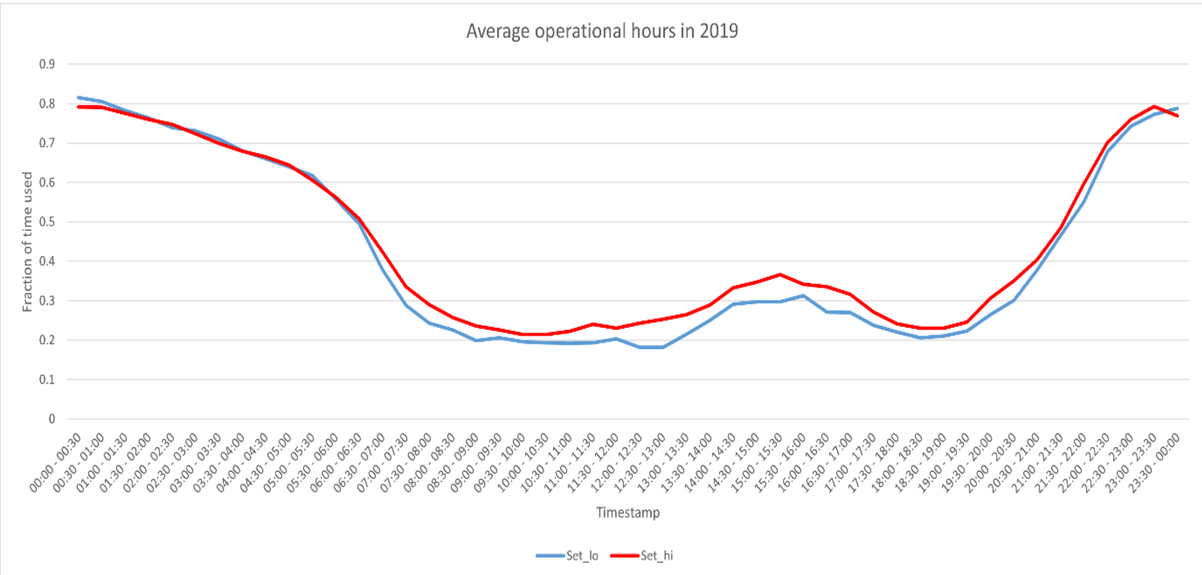
  The number of operational hours for the night-time was computed by taking the data from 8:00 pm to 8:00 am. The same steps as for day-time analysis were followed during this study. Table 11 indicates that AC was mostly functional during night time. The AC was operated for around 7.2 hours during the night-time for both the sets. The average operating hours was more for Set_hi by 1.91% for the year 2019 and 0.42% for the year 2020

Table 11: Analysis of the number of hours AC was operated.

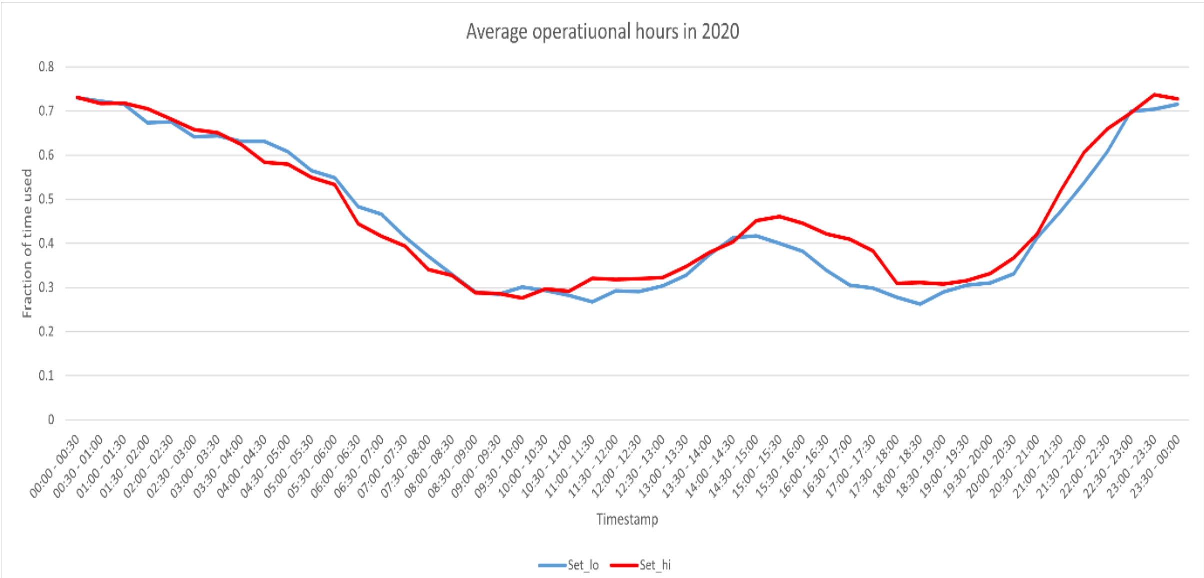
2019	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average operating time per day per home (Total half hours/number of homes)	10.06	10.82	0.76	5.93
Average AC operating time during	2.77	3.23	0.46	16.50

daytime. (8:00 am- 8:00pm)				
Average AC operating time during night. (8:00 pm- 8:00 am)	7.29	7.45	0.16	1.91
2020	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average operating time per day per home (Total half hours/number of homes)	10.82	11.19	0.37	3.45
Average AC operating time during daytime. (8:00 am- 8:00pm)	3.82	4.16	0.34	9.00
Average AC operating time during night. (8:00 pm- 8:00 am)	7.00	7.05	0.05	0.42

The average proportion of AC operating hours for both the years are given in figure 15 (a, b). The x-axis represents the timestep, and the y-axis represents the portion of the time the AC was functional on an average scale.



(a)



(b)

Figure 15(a): Half-hour the AC was operated throughout the day in 2019 (b) Half-hour the AC was operated throughout the day in 2020.

4.2.3 Household electricity consumption

- *Overall*

  The average per day per home household electricity consumption was considered to find the overall electricity used by the homes. From table 12, it can be observed that the average daily household electricity consumption for the Set_lo was around 13.51 kWh as and 13.07 kWh for Set_hi. The electricity utility was more by 3.18% for the year 2019 and 3.32 % for the year 2020 in Set_lo. The increment in household electricity consumption is similar for both the years, as there is no direct impact of temperature on the household electricity consumption. As the temperature is low for Set_lo, it is assumed that the occupants might have used geysers, or air cooler as per their comfort. Please note that the AC energy consumption is more for Set_hi for both the sets.

- *Day time*

  To observe the change in electricity consumption during daytime, analysis was done on the same data. The 12 hours data from 8:00 am to 8:00 pm was used. From the results tabulated in table 12. The average electricity consumption for both the years in Set_lo was 7.32kWh, and 7.12 kWh for Set_hi. An increase of electricity consumption by 2.5% was seen for Set_lo.

These results indicate that consumption of electricity by the occupants is similar for both the years, as the day to day routine was same in a given year.

- *Night time*

  Night-time analysis was done by taking the remaining data of the same days from 8:00 pm to 8:00 am. The results for the night time are summarized in table 12. It can be can see that the electricity consumption is more for Set_lo by 3.88%, similar trends of results were obtained for the daytime analysis. It is expected that people would have stayed at home during the night time for both the years, as a result the household electricity consumption was similar for both the years, and a small increase for Set_lo is seen.

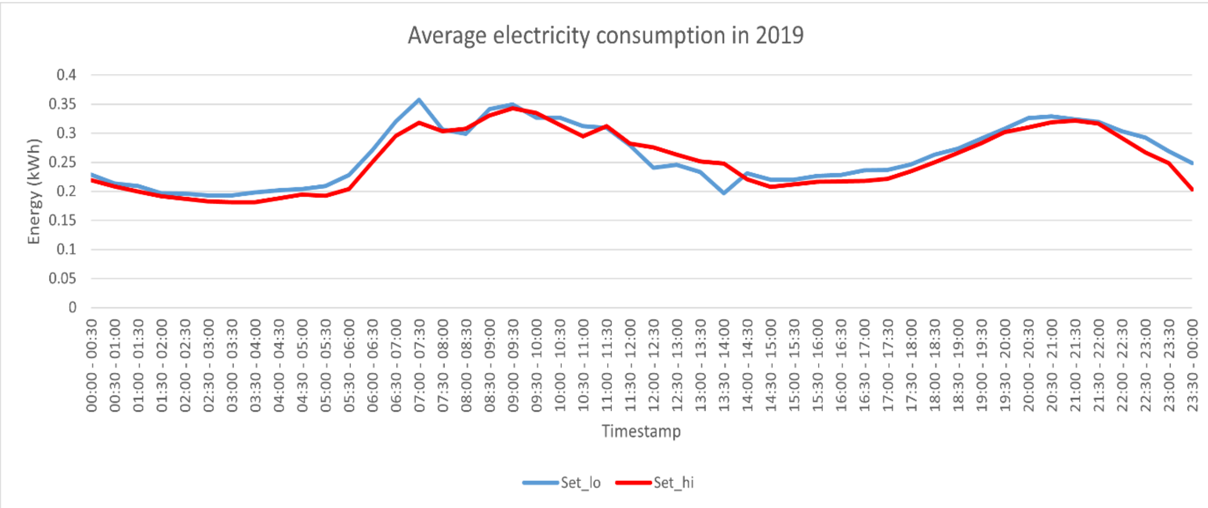
Table 12: Analysis of the household electricity consumption

2019	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average household electricity consumption per day per home (Total energy/ number of homes selected) (kWh)	12.57	12.17	-0.4	-3.18
Average electricity consumption during daytime. (8:00 am- 8:00pm)	6.44	6.40	-0.04	-0.62
Average electricity consumption during night time (8:00 pm- 8:00 am)	6.14	5.77	-0.37	-6.02
2020	**Set_lo** (kWh thermal)	**Set_hi** (kWh thermal)	**Net Change**	**Percentage change**
Average household electricity consumption per day per home (Total energy/ number of homes selected)	14.46	13.98	-0.48	-3.32
Average electricity consumption during daytime. (8:00 am- 8:00pm)	8.20	7.84	-0.36	-4.4
Average electricity consumption	6.26	6.15	-0.11	-1.75

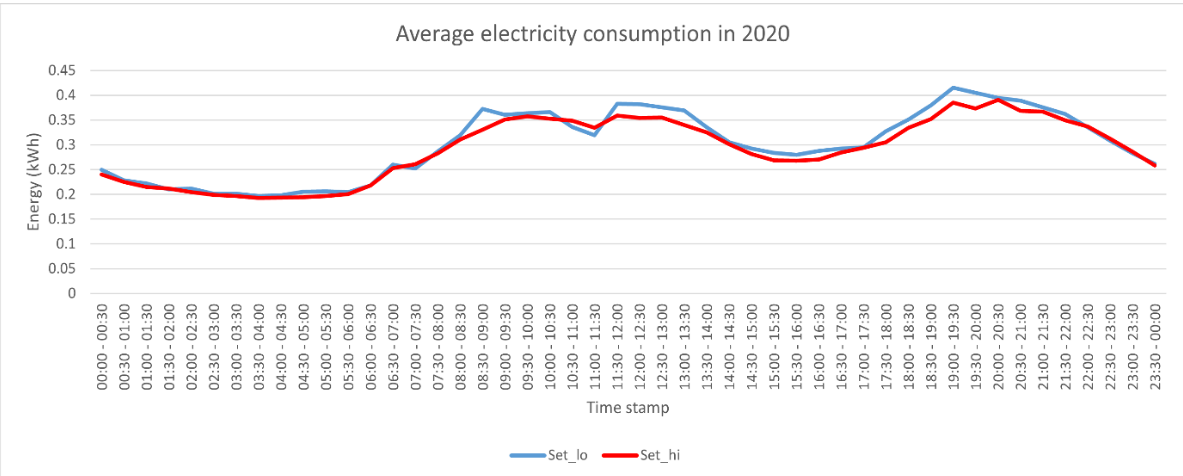
during night time (8:00 pm- 8:00 am)				

The increment in household electricity consumption is similar for both the sets, as there is no direct impact of temperature on the household electricity consumption.

The average net electricity consumption across the day of both the years are given in figure 16 (a, b). The x-axis represents the timestep, and the y-axis represents the household electricity consumption in kWh units.



(a)



(b)

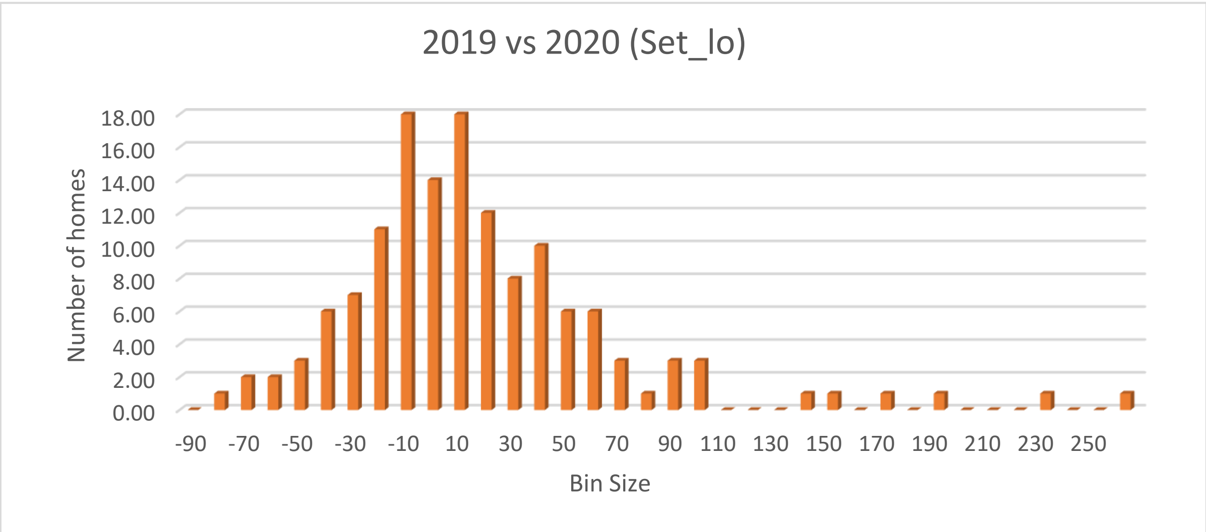
Figure 16(a): Electricity consumption throughout the day in 2019 (b) Electricity consumption throughout the day in 2020

4.3 Comparison among common homes

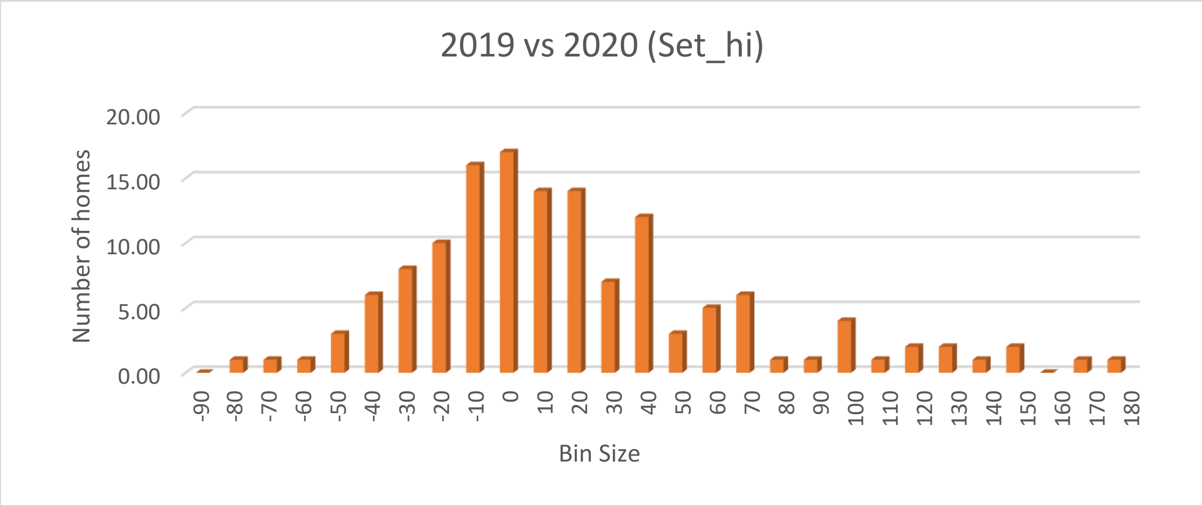
In this study, homes which were common in the two sets i.e., Set_lo and Set_hi from both the years 2019 and 2020 were considered. We obtained 140 homes which were common in Set_lo as well as in Set_hi. This analysis was performed on these homes to study the variation in the AC consumption in different scenarios. The results are plotted for each analysis.

- *Impact of Covid*

  In this study the comparison is made between the years 2019 and the Covid year 2020 for each of the sets i.e., Set_lo and Set_hi. The total AC energy consumption was calculated for the selected 140 homes in both the cases. Furthermore, to check whether the homes have started consuming more units, percentage increase/decrease was calculated and plotted in figure 16. As can be seen from figure 16, that number of homes that started using more AC due to lockdown is around 76 and 64 homes reduced their AC usage for Set_lo. Similarly, 77 homes have started using more AC in 2020, whereas 63 homes have reduced their AC usage during lockdown for Set_hi. It can be concluded that the increase in AC energy consumption is not due to one or two homes but due to a mix of increase and decrease across different homes with an overall increase in consumption overall the Covid year. The y-axis of figure 17 represents the number of homes and x-axis represents the bin size. For this study, bin size is kept as 10% i.e., (-10, 0] is bin size 0, (0, 10] is bin size 10 and so on.



(a)

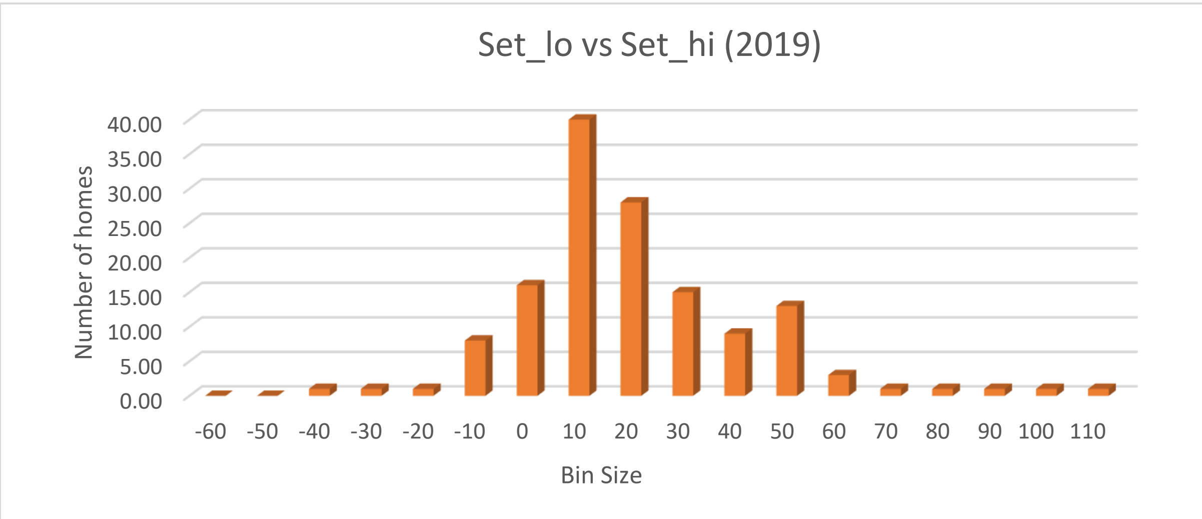


(b)

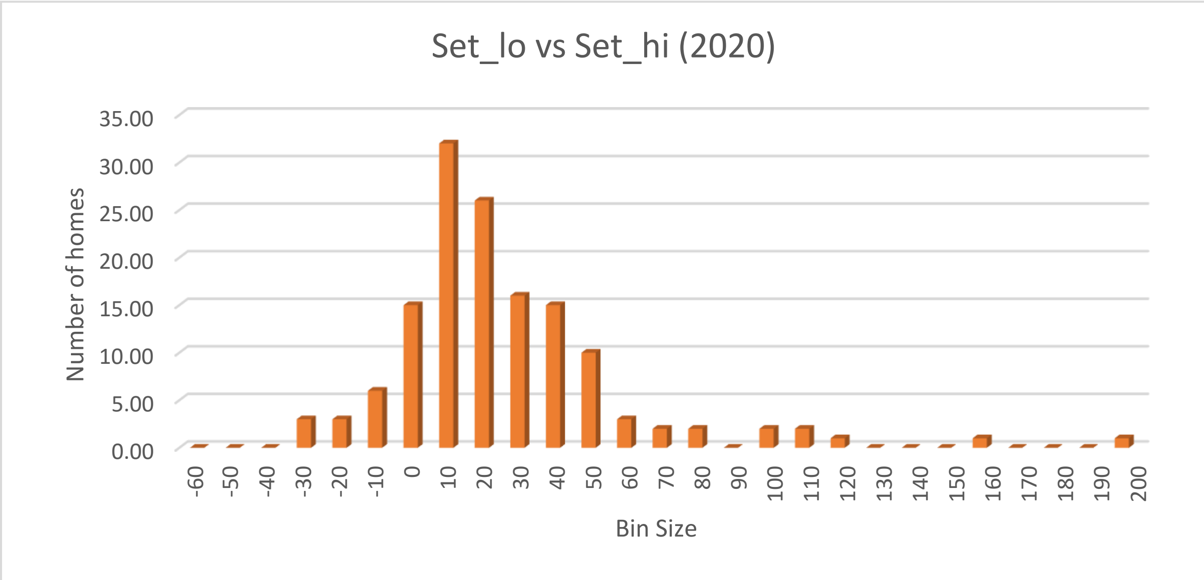
Figure 17(a): Distribution for Set_lo (b) Distribution for Set_hi

- *Impact of temperature*

  In this study, comparison is made for Set_lo and Set_hi within a year. The total AC energy consumption was calculated for the selected 140 homes for each of the years 2019 and 2020. Further to check whether the homes have started consuming more units, percentage increase/decrease was calculated and plotted in figure 18. It can be seen from figure 17, that number of homes started using more AC is around 113 and 27 homes reduced their AC usage in 2019. Similarly, 81 homes have started using more AC in 2020, whereas 59 homes have reduced their AC usage. The effect of the temperature is clearly seen, as it is expected that occupants will use AC more on hotter days.



(a)



(b)

Figure 18(a): Distribution for 2019 (b) Distribution for 2020

- *All data comparison*

  In this study the amount of AC energy consumed for 2019 and 2020 is compared using all the data points obtained from the selected 140 homes. The data from Set_lo and Set_hi was combined using weighted average method to obtain a single data set for each year, as there were 5 days in Set_lo and 8 days in Set_hi. The average consumption for the Set_lo would therefore be multiplied by 5, Set_hi multiplied with 8 and the total divided by 13 to obtain the weighted average result. This comparison is done to study the overall impact of Covid without considering the temperature. The percentage increase or decrease is calculated for the selected homes by keeping the base year as 2019. Figure 19 shows the distribution for the data points. It can be seen that 72 homes are having more AC usage, whereas 68 homes have reduced their AC energy consumption for the year 2020. It can be concluded that the usage of AC was more for the lockdown period.

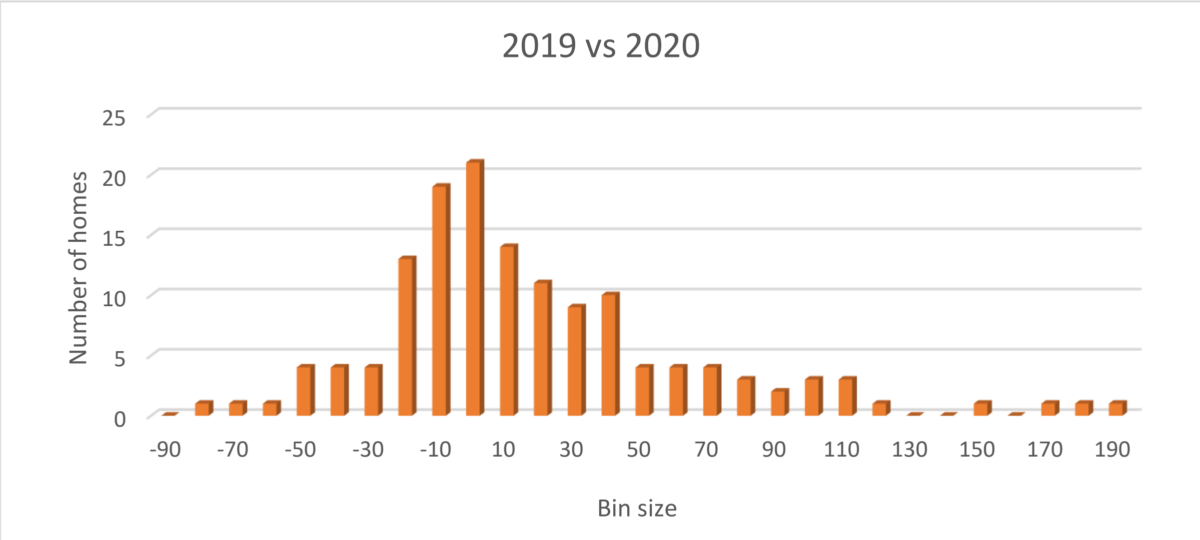


Figure 19: Distribution for common homes

4.4 Discussions

Kawka and Cetin's [35] study on 225 homes for energy consumption during the lockdown period, observed that most of the energy consumption increase was between 10 AM and 1 PM. They also noticed a possibility of evening peak shifting earlier during the lockdown, assuming that home occupants complete their evening routines sooner than pre-pandemic periods without the commute. In our study, we observed that maximum energy consumption occurred during the day between 10 AM and 8 PM because people were working from home and probably woke up later in the morning. We went a step further and collected data for household electricity usage that showed how the evening peak shifted by approximately two hours during the lockdown period.

According to another study by Rouleau and Gosselin [28], the occupants of residential buildings used more energy during lockdown when compared to non-COVID years. They observed that the average daily electricity consumption increased by 17.5% for April and between "9 AM to 5 PM", the consumption increased by 46%. In comparison, as per our study, an increase of 24.5% was seen during a window of "8 AM to 8 PM". According to Bielecki et al., study [35], the peak demand for 7000 apartments on average increased by about 9% during the lockdown compared to the same time of the year before the lockdown. Similarly, M. Aldubyan [22] also observed a increase of 25.2% for residential buildings in Saudi Arabia. Sanchez-Lopez et at.,[20] also had a similar observation, as they found an increase of 17% in energy consumption. As per our analysis, the household electricity consumption increased by 15% for the samples collected from a residential complex in Hyderabad, India. Overall, we can see the residential energy consumption for households increased in several countries.

Given the peak load, Ahmed Abdeen [24] reported an increase of peak load by 15-20% in the COVID year compared to the non-COVID year. Our study shows an increase upto 17-23% in household electricity consumption for April during the lockdown period. The variation in peak load results can be because of several factors like the climate of the place, income group of people from which the data was collected, occupancy, and building type.

The Prayas group [37] obtained the electricity data from State Load Dispatch Centers (SLDCs) for Maharashtra and Uttar Pradesh from 21st March to 26th March 2020. According to them, the overall electricity consumption for Maharashtra decreased by 32%, and a reduction of 17% was seen for Uttar Pradesh when compared to previous year's electricity consumption. According to them, residential electricity consumption contributes about 19% of the total electricity in Maharashtra, whereas it contributes 43% in Uttar Pradesh. According to their hypothesis, because of more contribution from the residential sector in Uttar Pradesh, the total energy consumption dropped less for Uttar Pradesh when compared to Maharashtra.

Furthermore, they analysed the household electricity for a few places in both states. They have analysed the metering data gathered from 81 households from both states. Their analysis period was from 4th March to 5th May 2020; however, the lockdown in India was from 25th March 2020. The daily average for the sample increased by 26% when compared to the lockdown period. According to them, the increase can be because of two factors: an increase in summer temperatures and people spending more time at home during the lockdown. But, according to our observation, the average temperature was more in 2020 than in 2019.

They have observed the households with AC in Pune district, and Pune city in Maharashtra increased by 45-60%. In contrast, there was an increase of 22% for households without AC. Further, they observed an increase of 35% and 45% for Aurangabad and Gonda, respectively.

In our study, there was an increase of 3-4% for AC energy consumption and 15% increase for household electricity consumption of the residential buildings in Hyderabad. We included a significant number of data points to provide more reliable results, such as analyzing with similar temperature and ensuring the analysis was done on homes occupied for both years.

Chapter 5

Conclusion

This thesis explores the effect of lockdown due to COVID-19 on residential buildings. Due to the stay-at-home orders, the energy demands of residential buildings at Hyderabad increased. Based on the hypotheses made and analysis performed, following are the key observations:

- The household electricity consumption increased during the lockdown which supports the hypothesis A. It can be explained as occupants worked from home, and used monitors, laptops, T.V, internet, lighting which in turn increased the household electricity consumption.
- The overall AC energy consumption and operational hours increased in 2020 compared to 2019. During daytime the AC energy consumption was more in 2020, but during the nighttime the consumption is more for 2019, hence the B hypothesis can be claimed to be true. Since the occupants were expected to operate the AC during the night after coming back from work in the year 2019, the nighttime energy consumption is more for 2019 than 2020. As the AC was functional throughout the day in 2020 the pre-cooling effect was observed since the set was already maintained.
- The AC energy consumption is more for Set_hi due to the higher temperature range. The effect of temperature is not seen in the household electricity consumption; both the sets have a similar increase of about 15%. Since there is no impact of temperature on the household electricity consumption.
- The peak in household electricity consumption for the year 2019 was seen in the morning, but for 2020 the peak shifted from morning to noon, supporting the (C) hypothesis. Thisindicates the occupants started waking up late, as they didn't have to commute to their workplaces. Also, there is an earlier evening peak for 2020 than 2019, as occupants in 2019 used to come home after 6:00 PM from their workplaces.
- The AC consumption for the Set_hi is more than that of Set_lo, as Set_hi has higher temperature range. Furthermore, the consumption pattern throughout the day is similar for both the sets each year.

Covid-19 made a significant impact on our lives due to which major adjustments were made. Some of these adjustments were of benefit e.g., office employees saved significant time, stress, and money by working from home, instead of commuting by private or public transport. As the world becomes increasingly technology driven, workplace policies may change and work from home may increase. Based on these inferences, energy consumption of commercial and residential buildings can be analysed to understand the potential effects and steps can be taken accordingly. For example, we observed that the peak electricity consumption during lockdown has increased during the day in residential sectors, moreover there was an occurrence of an additional peak. Insights of this nature can help with planning the development of appropriate infrastructure, such as transformers and power plants. If similar studies conducted on a larger number of samples result in similar observations, energy policies can be designed at national level for a more efficient usage of energy.

Related Publications

1. Kuntal Chattopadhyay, Vishal Garg, Praveen Paruchuri, Jyotirmay Mathur, Srinivas Valluri. **Impact of COVID-19 on Energy Consumption in a Residential Complex in Hyderabad, India**. In proceedings of Energy Informatics Academy Conference 2022 [DOI: 10.1186/s42162-022-00240-5]

Additional Publications

1. Md Anam Raihan, Kuntal Chattopadhyay, Aviruch Bhatia, Vishal Garg, Aftab M Hussain **Energy performance analysis of building integrated photovoltaic window in Hyderabad, India using automated parametric simulations** in 2022 7th International Conference on Sustainable and Renewable Energy Engineering (ICSREE 2022) [To be published in journal IOP Conference Series: Earth and Environmental Science]

2. Md Anam Raihan, Kuntal Chattopadhyay, Aviruch Bhatia, Vishal Garg, Aftab M Hussain **Automated Parametric Simulation Tool for Energy Performance Analysis of Smart Glazing.** In proceedings of Energy Informatics Academy Conference 2022 [DOI : 10.1186/s42162-022-00226-3]

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