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Review analysis of COVID-19 impact on electricity demand for residential buildings

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A R T I C L E I N F O

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A B S T R A C T

In this paper, a systematic review analysis of fully enforced stay at home orders and government lockdowns is presented. The main goal of the analysis is to identify the impacts of stay home living patterns on energy consumption of residential buildings. Specifically, metered data collected from various reported sources are reviewed and analyzed to assess the changes in overall electricity demand for various countries and US states. Weather adjusted time series data of electricity demand before and after COVID-19 lockdowns are used to determine the magnitude of changes in electricity demand and residential energy use patterns. The analysis results indicate that while overall electricity demand is lower because of lockdowns that impact commercial buildings and manufacturing sectors, the energy consumption for the housing sector has increased by as much as 30% during the full 2020 lockdown period. Analysis of reported end-use data indicates that most of the increase in household energy demand is due to higher occupancy patterns during daytime hours, resulting in increased use of energy intensive systems such as heating, air conditioning, lighting, and appliances. Several energy efficiency and renewable energy solutions are presented to cost-effectively mitigate the increase in energy demands due to extended stayhome living patterns.

1. Introduction

The COVID-19 pandemic is having a significant and profound impact on various aspects of the lives and livelihood of people around the globe. In particular, the global health toll is devastating, with over 8.3 million infected cases and 0.45 million deaths as of June 19, 2020 [1]. This health toll continues to deteriorate since the start of the pandemic reaching 79.2 million infected and 1.7 million deaths as of December 27, 2020 [1]. Moreover, the World Health Organization (WHO) has reported an increase in domestic violence by up to 50% in some countries, due to the strain on mental heath because of long term confinement in homes [2]. Moreover, the virus has and is still impacting all social and economic activities worlwide. While the economic impacts are still being estimated in terms of both short and long term effects for various countries, the global economy is projected to contract by 4.9% during 2020 [3]. The impacts are especially severe for manufacturing and service sectors, such as tourism and transportation. For instance, the global tourism industry is expected to experience a 60%–80% decline in its activities during 2020 compared to 2019, translating into losses of 910 USD billion to 1.2 USD trillion revenues and 100 to 120 million direct jobs [4]. Due to the financial shocks and the rising unemployment, the economic impact is already costing 10% of global GDP in rescue and stimulus packages intended to save businesses and keep the overall economy afloat [5].

Government policies intended to slow the spread of COVID-19, such as lockdowns and stay at home orders, have significantly changed the work and living habits for most people around the world [6]. For example, people wake up later since they do not have to commute to work and generally remain at home during daytime hours. Coupled with the rise in telework for many white collar jobs, this sudden change in behavior has impacted the energy consumption patterns that drive electricity demand in buildings, whether residential or commercial. For instance, data collected from an Italian grid operator has shown that electricity use is 8% lower with its peak shifted by more than 1 h later during the early morning as people stay in bed longer. Similar changes in sleep patterns have been observed in other European countries, including France, Spain, and Germany, as the bulk of morning electricity demand has shifted from 6:00 a.m.-8:00 a.m. to 8:00 a.m.-9:00 a.m. [6]. In New York City, weather adjusted electricity demand at 8:00 a.m. has decreased by 18% after the lockdown, as the most energy-intensive systems (i.e., lighting, HVAC, elevators) for office buildings are idle or

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Nomenclature

BIPV	Building Integrated Photovoltaic
CAISO	California Independent System Operator
CDD	Cooling Degree-Days
CFL	Compact Fluorescent Lamp
COVID	Corona Virus Disease
EMIS	Energy Management and Information System
EPIC	Energy Policy Institute at University of Chicago
GDP	Gross Domestic Product
HVAC	Heating, Ventilation, and Air Conditioning
ICSSWH	Integrated Collector Storage Solar Water Heater
IEA	International Energy Agency
IMF	International Monetary Fund
LED	Light Emitting Diode
NYISO	New York Independent System Operator
PCM	Phase Change Material
PV	Photovoltaic
PV/T	Photovoltaic Thermal
TV	Television
UK	United Kingdom
UNWTO	United Nations World Tourism Organization
USD	US Dollar
WHO	World Health Organization

are not fully operated [6]. Electricity demand profiles indicate that people go to sleep later at night as well. Indeed, people are watching more TV and movies, as documented by greater use of video streaming services and higher electricity use in the evening. In Italy, the evening peak electrity demand has increased by 8% during a March day in 2020 compared to the same day in 2019 [6].

The literature review carried out for this study follows recommended methodologies to evaluate peer-reviewed published articles, conference papers, and technical reports that have analyses and assessments that include metered data on the impact of lockdowns and stay at home orders on energy demands of buildings with a special focus on the housing sector [7–9]. The review process includes three main phases consisting of [10]:

(i) literature search and screening using relevant keywords including impact of lockdowns and stay at home orders on energy consumption of buildings as well as metered data of electricity and energy demands specific to individual buildings, large communities and districts, as well as entire countries and regions worldwide.
(ii) extraction of reported data and analysis results from the screened literature, and
(iii) synthesis and summarize the collected data and results.

The main objectives of the review analysis presented in this paper are to assess using metered data the impacts of sudden people behavior during the initial of fully enforced lockdown periods and stay at home orders due to COVID-19 health crisis on energy demands of the residential sector throughout the world. Thus, only filtered metered data that include weather adjusted energy uses as well as weather data before and during the lockdown periods are considered in the analysis [11]. Moreover, the review analysis provides proven energy efficiency and renewable energy mitigation solutions to improve the sustainability of existing housing stocks with the goal to enhance indoor quality and reduce the energy costs for households associated with changes in working habits that are expected to continue even after the resolution of the COVID-19 health crisis.

Specifically, the analysis presented in this paper, assesses electricity demand in various countries as well as US states for periods that coincide to fully enforced lockdowns and stay at home orders, i.e. March through May 2020, as compared to pre-COVID-19 years spanning from 2017 to 2020. Moreover, the review provides analytic assessments of the impact of lockdowns on electricity consumption–in terms of the overall effect of changing electricity demand on the grid–and changes in electricity demand by end-use sectors. In particular, the analysis evaluates the change in energy demand for residential buildings, before and during the lockdown, using metered and/or reported weather-normalized data obtained mainly for three countries (Australia, UK, and US). At the end, a set of recommendations are outlined to mitigate rising household energy consumption and improve the energy efficiency and resiliency of residential buildings.

Table 1
Timing of COVID-19 lockdown orders for selected countries and US States (Source: [13]).

Country	Lockdown Issuance Order	Lockdown Easing restrictions	Total Deaths Reported as of May 31, 2020
China	January 23, 2020	April 8, 2020	4637
Italy	March 9, 2020	May 4, 2020	28236
Germany	March 23, 2020	April 20, 2020	6736
India	March 25, 2020	May 1, 2020	1223
US[a]	March 16, 2020		67848
California	March 19, 2020	May 25, 2020	
New York	March 22, 2020	May 8, 2020	
Illinois	March 21, 2020	May 22, 2020	
Texas	March 19, 2020	May 1, 2020	

[a] US Federal government issued social distancing guidelines on March 16, 2020. US State governments issue stay home orders individually as noted for selected States.

2. Impact on overall electricity demand

A recent analysis of the electricity consumed by several countries since the COVID-19-related lockdown orders reveals a significant reduction in electricity demand. In particular, Italian electricity has fallen by 28% after 42 days from the start of the lockdown [12]. Table 1 lists the specific dates for lockdowns and stay at home orders for four countries and four US states. As a reference, the WHO declared COVID-19 a pandemic on March 3, 2020. In addition, Table 1 lists the reported deaths as of May 31, 2020 when lockdowns have been eased in all the selected countries [12]. Unfortunately, the death tolls in most countries continue to increase at a significant highere levels throughout 2020 and early 2021.

Fig. 1 compares daily weather adjusted electricity consumption in 2020 to similar days in 2019 from March 4 to May 20, 2020 [13]. Similar to Italy, the US has seen a significant reduction in electricity demand, with the highest reduction occurring on March 27, 2020. Moreover, Fig. 1 shows that electricity demand in India was still decreasing in late May 2020 as the virus continued to spread. The limited data available for China indicate that March saw the highest reduction in electricity demand [12]. Fig. 2 summarizes the average monthly reductions from 2020 to 2019 for electricity consumption for March, April, and May specific to the same countries considered in Fig. 1. This change seemed to follow the rate of COVID-19 spread in each country, with electricity demand significantly lower for China in March (11.5%), for Italy and the US in April (19%), and for India in May (9.5%) [14].

In the US, the impact of COVID-19 on energy demand because of stay at home orders and related restrictions depends on the decisions made by state and local governments. Fig. 3 shows the reduction in daily weather adjusted electricity demand, comparing 2020 to 2019, for four

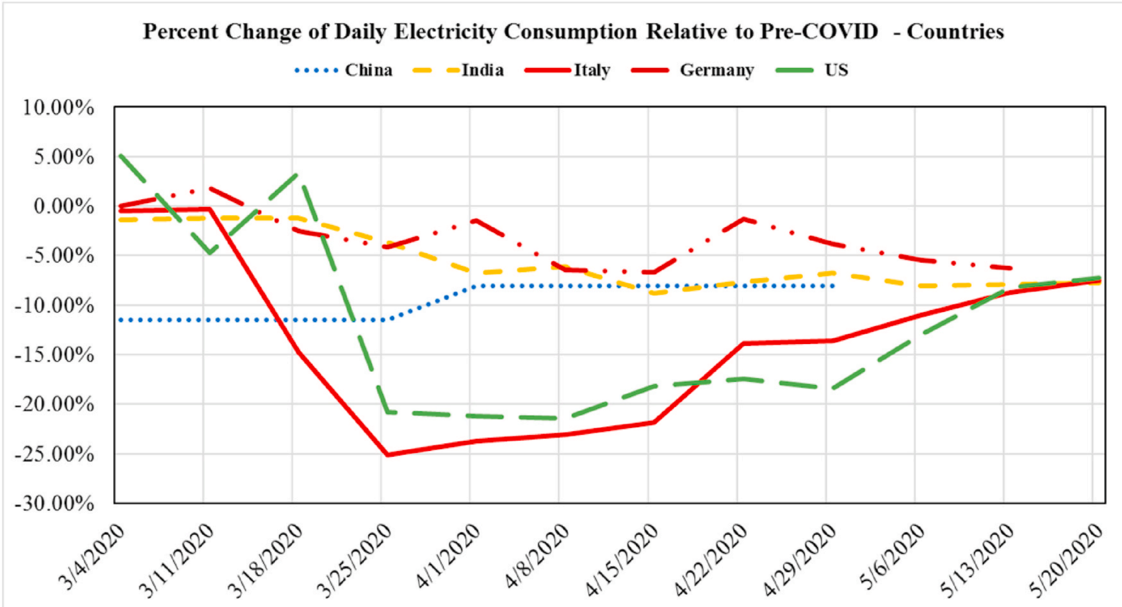


Fig. 1. Percent change in daily weather adjusted electricity demand comparing 2020 to 2019for March 4 – May 20 in selected countries.

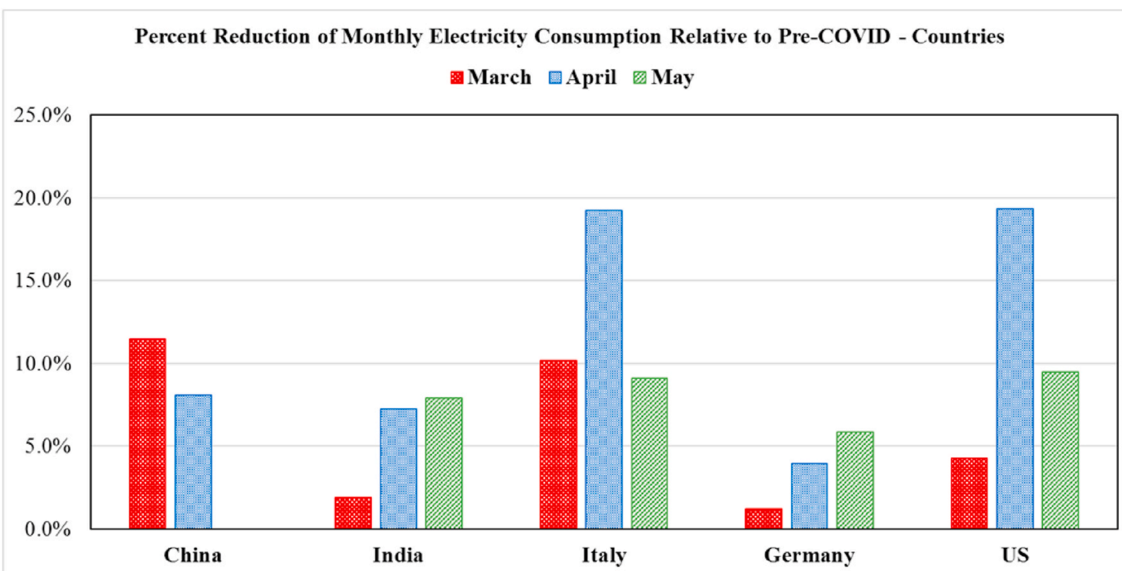


Fig. 2. Average reduction of monthly weather adjusted electricity demand comparing 2020 to 2019 for March, April, and May 2020 in selected countries.

US cities, each with variations in the rate of the virus spread, death toll, and timing and duration of stay at home orders as listed in Table 1. Fig. 4 summarizes the average monthly reductions in electricity demand comparing 2020 to 2019 for the same US cities in March, April, and May [13]. New York City, the US city most impacted by COVID-19 in this time period saw its energy demand significantly reduced, especially in May, with a 17% average reduction relative to the same month in 2019. The electricity demand in Los Angeles was most affected during April 2020 with an average reduction of 12%. The reduction in energy demand was not large in Chicago (about 7% for April and May), and was either negligible or slightly higher in Houston (4.6% higher energy consumption in April and no change in May).

It seems that lockdowns did not just have an effect on electricity demand, but also on the power mix. Renewables seemed to consolidate their position in the power mix to meet the depressed electricity demand. For example, renewables outpaced coal and nuclear to become the second largest source of electricity after natural gas in the US. A similar trend has been observed in China, where renewables were the second largest source of electricity after coal. In Europe, renewables increased their dominance in the electricity mix over both nuclear and natural gas [12]. In particular, variable renewables (i.e., solar and wind) contribution to the power mix reached 90% in Germany, 80% in Spain, and 65% in Italy during the lockdown period from March to May 2020 [12].

3. Impact of electricity demand profiles

3.1. Hourly demand for California

Fig. 5 shows the impact of the US state of Calinfornia's COVID-19-related stay at home order on electriciy demand using historical data for March 23–29, 2020 and March 25–30, 2019 [15]. The California

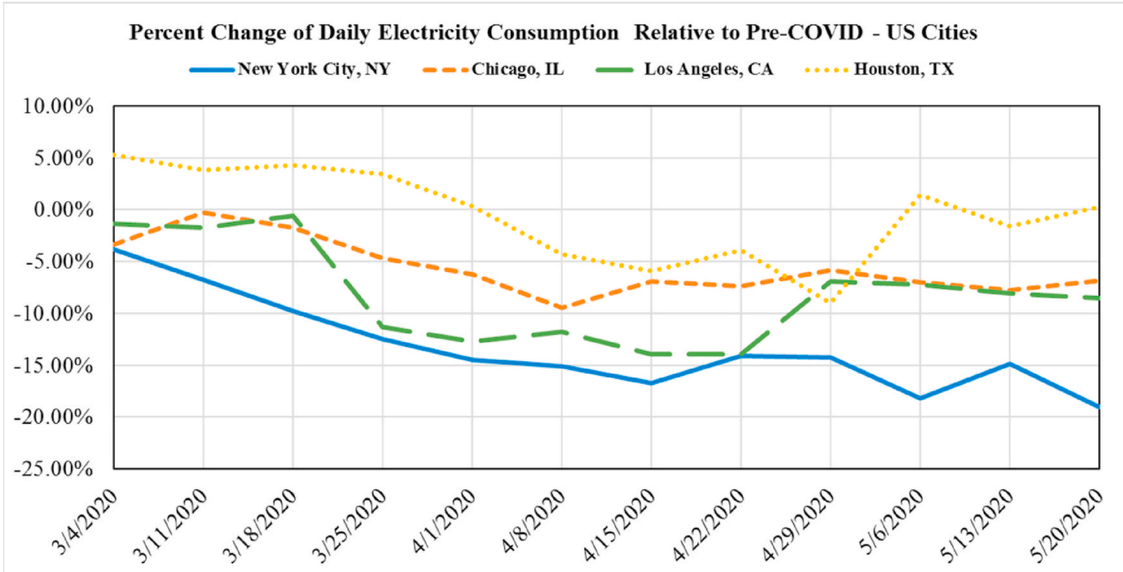


Fig. 3. Percent change in daily weather adjusted electricity demand comparing 2020 to 2019 for March 4 – May 20 in selected US cities.

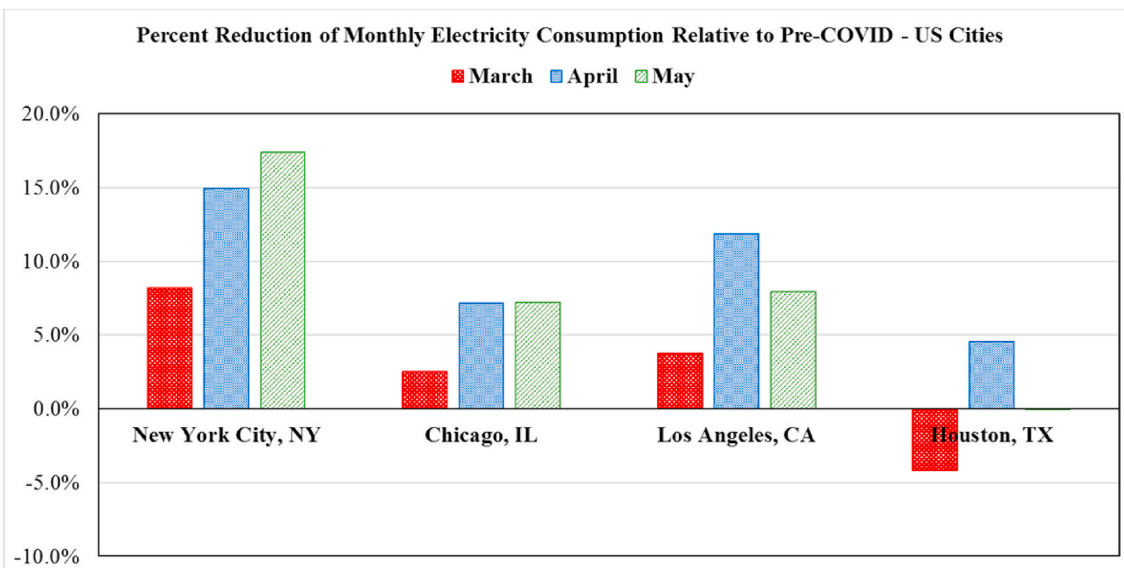


Fig. 4. Average reduction of monthly weather adjusted electricity demand comparing 2020 to 2019 for March, April, and May in selected US cities.

independent system operator (CAISO) manages the flow of electricity across high-voltage and long-distance power lines for the grid serving 80% of California and a small part of Nevada, estimated to be 35% of the entire electricity demand in the western region of the US, and serving a mix of residential, commercial, and industrial customers. Moreover, CAISO relies heavily on variable renewables, with wind and solar providing 23% of its electricity generation. Due this high penetration of renewables, the CAISO net electricity demand profile follows a duck curve, as shown in Fig. 5, with both morning and evening peak demands. The stay at home order reduced overall electricity demand during the last week of March 2020 by about 5.6% compared to March 2019, with the highest reduction occurring around 3:00 p.m. with a 9.8% reduction, or 2000 MW, of electricity demand, as indicated in Fig. 5. Moreover, CAISO determined that the reduction during weekend days was minimal, with an average decease of 1.3% for these days. Specifically, CAISO carried out its own weather adjusted analysis for March 23 – May 24, 2020 to assess the impact of the stay at home order on peak demand and energy sales. Table 2 summarizes their ISO weather adjusted analysis, which shows that the impact on morning and evening peak demand, for week and weekend days. Fig. 6 shows the impact of the stay at home order on week and weekend daily electricity demand profiles by comparing the reported data for March 23–29, 2020 and March 25–31, 2019 [15]. In particular, the lower electricity consumption from 2019 to 2020 is more evident and consistent throughout the week days [Fig. 6 (a)] than that during the weekend days [Fig. (b)] especially during 11:00 a.m. through 2:00 p.m. period. Indeed, during this period the stay at home order has actually increased the energy consumption during the weekends when the residential loads dominate the commercial demands.

3.2. Hourly demand for New York City

Fig. 7 shows the impact of the stay at home order on electricity demand in New York City (NYC) by comparing data for March 23–29, 2020 and March 25–31, 2019 [16]. This demand includes commercial customers (51%), residential buildings (35%), and industrial facilities

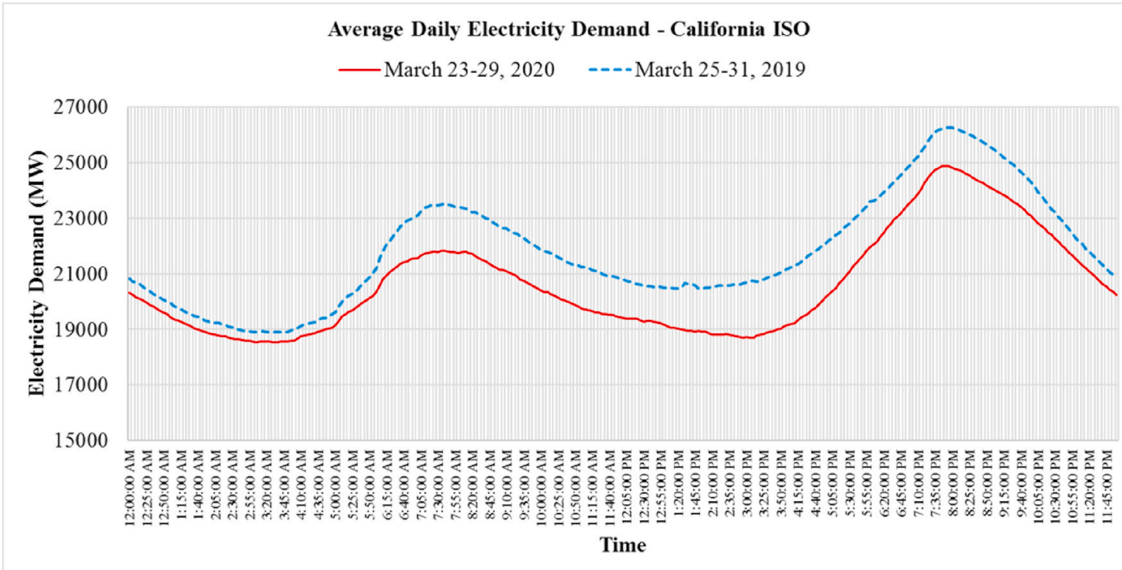


Fig. 5. Average hourly electricity demand for March 25–31, 2020 and March 23–29, 2019 for California (Source: [15]).

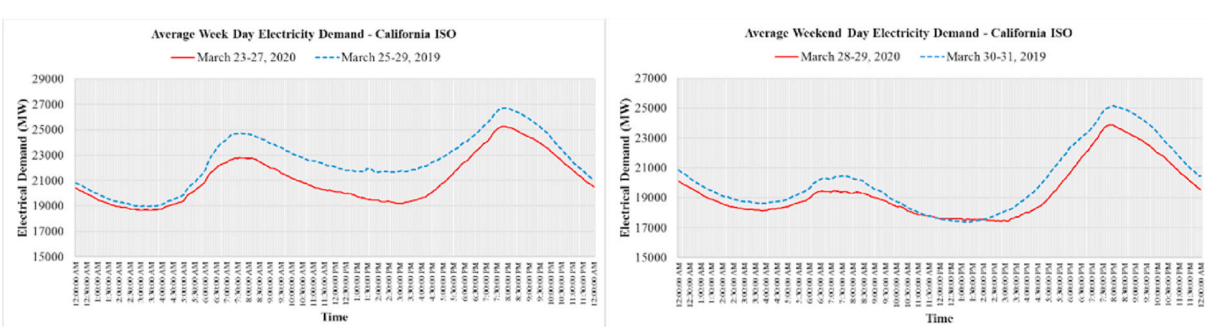
Table 2
Weather adjusted impact of stay home order on peak demand and electricity use in California (Source: [15]).

Type of Day	Electrical Peak Demand reduction		Electricity Consumption Reduction	
	MW	Percent	MWh	Percent
Week Day				
Morning	1862	7.4%		
Evening	1298	5.3%	23,816	4.2%
Weekend Day				
Morning	662	3.2%		
Evening	184	0.8%	7150	1.4%

(14%). As summarized in Table 3, New York Independent System operator (NYISO) which serves the power needs for the entire state of New York, and relies on fuel-based and nuclear power plants to generate electricity [16]. Specifically, the generating capacity of NYISO is dominated by fuel-fired units (66%), followed by renewables (20.1%) comprised primarily of hydro (11%), and then nuclear plants (13.9%). The annual electrical energy produced from the available generating capacity is split between fuels (39.2%), nuclear (32.1%), and renewables (28.6%).

As noted in Fig. 7, NYC's hourly electricity demand during March follows a spring season profile, and is high during most of the daytime with a slight peak occurring at 10:00 a.m. for the week of March 25–31, 2019. The stay at home order reduced the overall electricity demand during March 23–29, 2020 by about 11.9% compared to the last week of March 2019, with the highest reduction occurring around 10:00 a.m. with a 16.4% reduction, or 974 MW, of electricity demand, as indicated in Fig. 7. NYISO has normalized its energy data for weather to pinpoint the impact of the lockdown on electricity demand, and found that the reduction in electricity demand for the last week of March 2020 is about 8% for the entire state of New York and about 11% for New York City [16]. Their analysis indicates that the decline of electricity demand in New York City continued during the month of April to reach 16% during the week of April 13, 2020 with the weekday decrease reaching as high as 21%.

The reduction in the electricity demand for New York City during both week and weekend days is similar, as shown by Fig. 8 for the last week of March 2020 and 2019. Typically, energy demand is lower on weekend days by 5.8%, with the peak shifted from 10:00 a.m. for week days to 8:00 p.m. for the weekend days. A similar pattern is observed for March 23–29, 2020, even though overall demand was reduced on weekend days, as summarized in Table 4. In particular, the peak demand is reduced by 16.6% and 15.3%, while electricity consumption is lowered by 12.0% and 11.6%, when comparing the impact of the stay at home order for week and weekend days, respectively.



(a) (b)

Fig. 6. Average hourly electricity demand for (a) weekday and (b) weekend during March 25–31, 2020 and March 23–29, 2019 for California (Source: [15]).

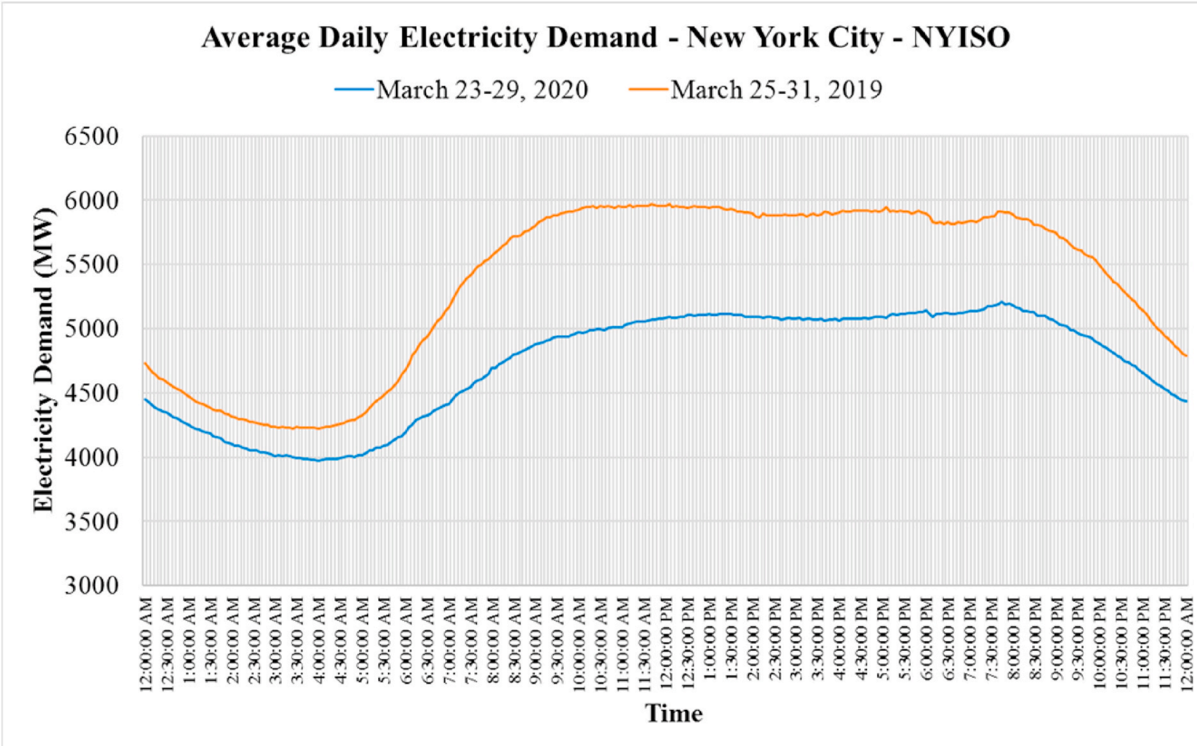


Fig. 7. Average hourly electricity demand for March 25–31, 2020 and March 23–29, 2019 for New York City (Source: [16]).

Table 3
New York State power mix for generation capacity and energy production (Source: [16]).

Power Source	Generating Capacity		Energy Production	
	MW	Percent	GWh	Percent
Fuels	***25,627***	***66.1%***	***51473***	***39.2%***
Oil	2499	6.4%	74	0.1%
Dual (Oil/Gas)	18,529	47.8%	44,135	33.6%
Gas	3588	9.3%	6697	5.1%
Coal	1011	2.6%	567	0.4%
Nuclear	***5375***	***13.9%***	***42,175***	***32.1%***
Renewables	***7776***	***20.1%***	***37534***	***28.6%***
Hydro	4251	11.0%	29,554	22.5%
Hydro Pumped Storage	1407	3.6%	795	0.6%
Wind	1740	4.5%	4219	3.2%
Other	378	1.0%	2966	2.3%
Total	***38,778***	***100%***	***131,182***	***100%***

4. Impact on sectorial electricity demand

Limited analyses have thus far been conducted to evaluate the impact of lockdown and stay at home orders on energy use for various sectors. Table 5 summarizes the findings of the primary studies that have assessed the impact of COVID-19-related lockdowns on electricity demand for the residential, commercial, and industrial sectors in four countries (Argentina, Australia, United Kingdom, and Ireland) and one US state (Texas). Argentine electricity demand was reduced by 20% between the week before and after the lockdown order on March 20, 2020, with a 32.4% reduction for large users (i.e., industry) and a decrease of 18.2% in other sectors [17].

Data from a smart metered distribution station has been analyzed to isolate the specific impact of the lockdown in an Australian region on electricity demand by sector. The station, located northwest of Melbourne, serves 350,000 homes, as well as several commercial and industrial facilities, including an airport. The analysis indicated that, comparing one week before (March 1–7, 2020) and one week after (March 22–28, 2020) the lockdown, weather adjusted electricity consumption decreased by 7% for commercial buildings and by 1% for industrial facilities, while it increased for homes by 14%, resulting in an overall increase of 1% for the entire station [18].

In the United Kingdom, electricity used by households increased by 17% after the lockdown even though the national demand has reduced by 15%, according to data from 2000 customer smart meters [19]. The higher energy demand occurred mostly during daytime hours and especially at lunchtime (higher by 25%). During the morning and evening hours, the energy demand has lower by an average of 12% (morning) and 8% (evening).

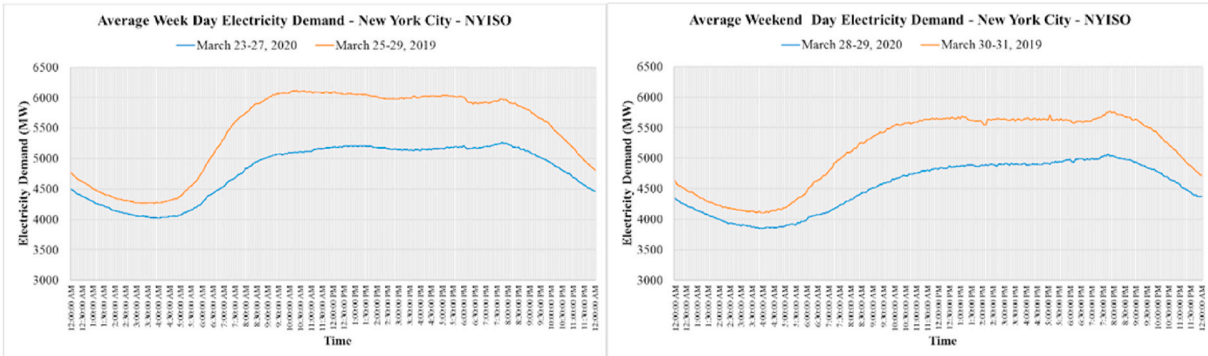
Using a survey-based analysis, the energy consumption for houses in Ireland was found to be 11%–20% higher during the lockdown, with an increase of almost 30% between 9:00 a.m. and 5:00 p.m. [20]. Moreover, energy demand by Irish homes was 30% lower during early morning hours and 10% lower during evening hours due to shifts in living patterns, such as waking up later and eating dinner earlier [21].

Finally, residential weather adjusted electricity demand for the US city of Austin, TX was found to be almost 32% higher when comparing the week of February 29-March 6, 2020 before the lockdown to March 21–27, 2020 after the lockdown, as most residents started to work from home and transitioned to online education [22].

5. Impact on residential electricity demand patterns

5.1. Analysis of international cases

The pattern of using energy in homes changed during the lockdown periods, since residents have generally stayed indoors during daytime hours. This change has been documented through the analysis of data obtained from smart meters specific to residential communities typically made up of several individual homes. Fig. 9 shows the percent change in hourly electricity demand reported for homes in Australia [18] and



(b)   (b)

Fig. 8. Average hourly electricity demand for (a) weekday and (b) weekend during March 25–31, 2020 and March 23–29, 2019 for New York City (Source: [16]).

Table 4
Impact of stay at home order on weather adjusted peak demand and electricity use in New York City (Source: [16]).

Type of Day	Electrical Peak Demand reduction		Electricity Consumption Reduction	
	MW	Percent	MWh	Percent
Week Day	1015	16.6%	189,913	12.0%
Weekend Day	883	15.3%	173,070	11.6%

Britain [19]. In both countries, the pre- and during lockdown periods are selected so the outdoor temperatures are similar and follow the same patterns [18,19]. As indicated by Fig. 9(a), Australian hourly load profiles show that while morning demand was lower between 5:00 a.m. and 7:00 a.m. as people wake up later, more electricity is used throughout the day, including during the evening peak demand [18].

A similar pattern is observed for electricity demand in British homes, as shown in Fig. 9(b), with lower use during the morning and late night hours but higher demand throughout daytime hours. Indeed, people normally not home from 7:00 a.m. to 5:00 p.m. were either teleworking from home, attending school remotely, or simply watching TV or videos [19]. Consequently, residents were heavier users of electrical devices and appliances, such as computers, lighting fixtures, and televisions.

5.2. Analysis of homes in Austin, Texas

Over the last decade, the Pecan Street organization has monitored electricity use and rooftop photovoltaic (PV) generation patterns for 113 homes in their research network [23]. Of these monitored homes, 74 have rooftop solar PV systems. The monitored data include energy end-uses specific to appliances; heating, ventilation, and air conditioning (HVAC); and electric vehicles. The energy data have been normalized to account for any weather variations between 2020 (i.e., stay at home order period) and 2017–2019 data (i.e., pre-COVID-19 periods). Fig. 10 shows the net electricity demand for solar homes (i.e., accounting for the excess electricity generated by PV that is fed to the grid) for (a) March 23–71, 2020 compared to the average for March during 2017–2019, and (b) April 2020 and average for April during 2017–2019 [24]. As indicated in Fig. 10, the stay at home order increased net electricity demand, especially during the daytime hours, with a slight reduction during early morning hours. Considering only net electricity demand, a significant increase in energy consumption was observed because of home confinement, estimated at 49% for March 23–31, 2020, and at 65% for the month of April when compared to the averages for each month during 2017–2019.

The main electrical systems that drove the observed increase in energy demand include HVAC, lighting, and appliances. Table 6 compares the HVAC energy use per cooling degree-days (CDD) compiled for periods in March and April 2020, and averages for the same periods during 2017–2020 [23]. As indicated in Table 6, HVAC energy use per CDD increased from 0.53 kWh/CDD for the March average in 2017–2019 to 0.73 kWh/CDD for March 24–31, 2020, that is, an increase of 37.7%. For the month of April, the HVAC electricity demand was 25% higher in 2020 than the average in April for 2017–2019.

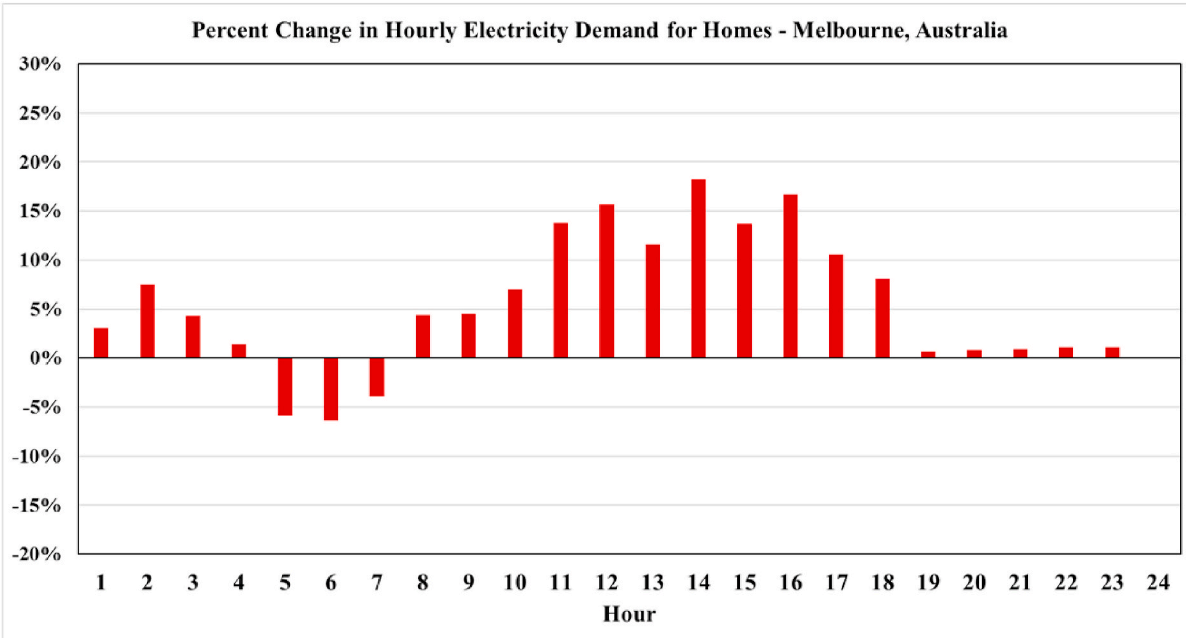
Fig. 11 shows the average daily electricity demand associated with lighting and appliances (without HVAC) for all monitored houses for (a) March 23–31, 2020 and average during March during 2017–2019, and (b) April 2020 and the average for April during 2017–2019. The non-HVAC load was much higher during daytime hours, estimated at 18% for March 23–31, 2020 and 16% for April 2020. Energy used by refrigerators was 12% on average, most likely due to frequent opening and closing of the appliances throughout the day [23].

6. Mitigation options for homes

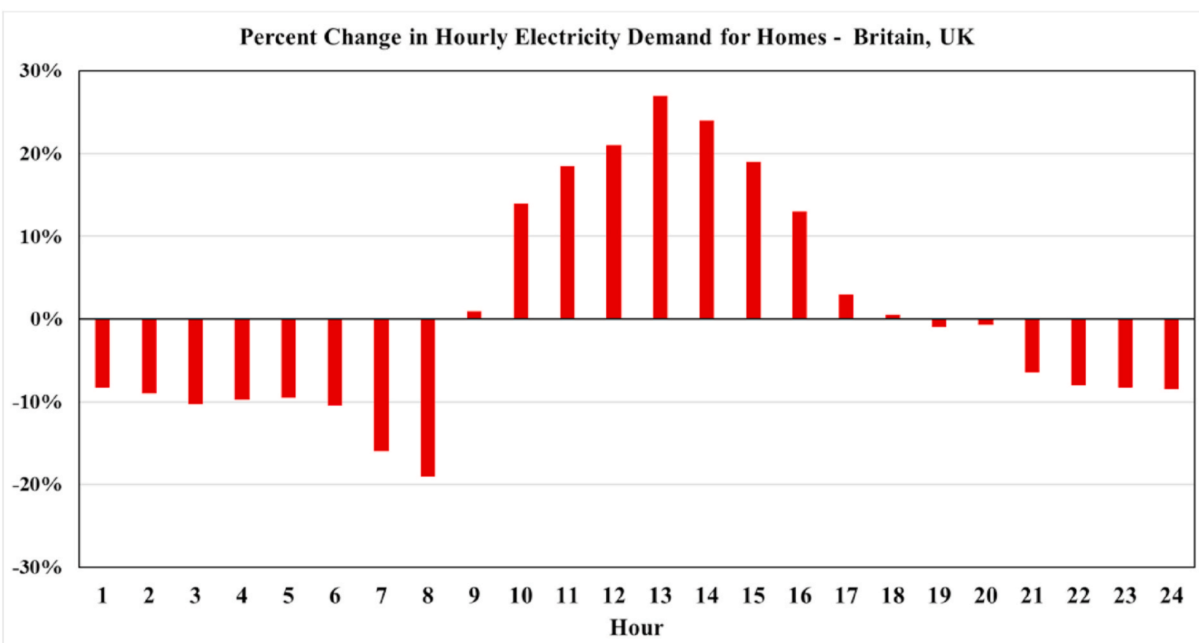
As outlined in the analyses presented in this study, people have been staying at home for more hours because of forced lockdowns and stay at

Table 5
Summary of reported impact of lockdown/stay at home order on electricity demand for various sectors.

Country/State	Impact of electricity demand by sector (+is increase and – decrease)				Period of Analysis	Comment (reference)
	All	Residential	Commercial	Industry		
Argentina	−20%	NA	−18.2%	−32.4%	One week before and after lockdown	National Electricity [17]
Australia	+1%	+14%	−7%	−1%	One week before and after lockdown	One distribution station in Melbourne [18]
United Kingdom	−15%	+17%	NA	NA	Same periods for 2020 and the previous year	Data from smart meters [19]
Ireland	NA	+ (11%–20%)	NA	NA	Two weeks before and after lockdown	Data from smart metered homes [20]
Texas, USA	NA	+32%	NA	NA	3 weeks after stay home vs same periods of 2017–2019	Data from smart metered home in Austin [22–24]



(a)



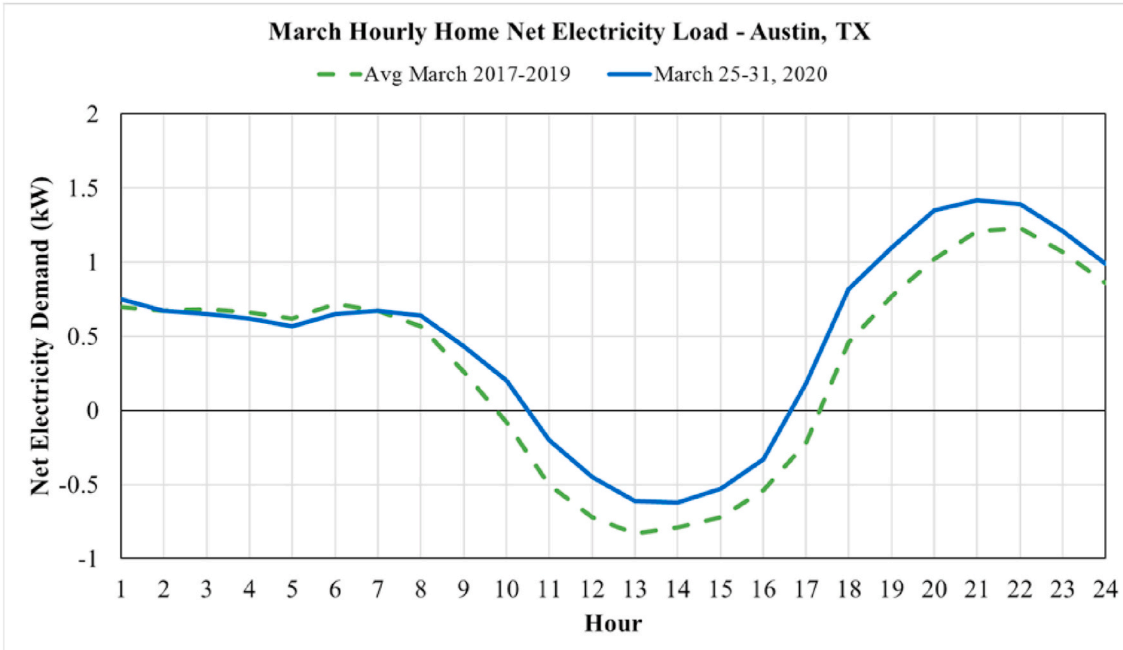
(b)

Fig. 9. Percent change in hourly electricity demand for homes in (a) Australia (Source: [18]), and (b) Britain (Source: [19]).

home orders. However, this observed shift in living patterns is expected to remain even after the resolution of the COVID-19 health crisis [25–27]. Due to higher utility costs, the stay home living provides more incentives to homewoners and governments to enhance the sustainability of the housing sector to reduce its energy consumption and improve its indoor quality.

In this section, a wide range of energy efficiency and renewable energy solutions are recommended to reduce the energy consumption of residential buildings, while also to provide healthy indoor environment. In particular, several energy efficiency retrofit measures are simple to implement by households including:

- Replace any compact fluorescent lamps (CFLs), especially incandescent bulbs, with LED lighting fixtures. Indeed, LED fixture can reduce electricity consumption by 40% compared to a CFL and over 800% compared to a 60 W incandescent bulb [28].
- Use smart power strips to ensure that standby electricity consumption is lower for plug-in devices such as computers, printers, and TVs. It is estimated that standby power losses can vary between 2 and 20 W for each electronic device at home [28].



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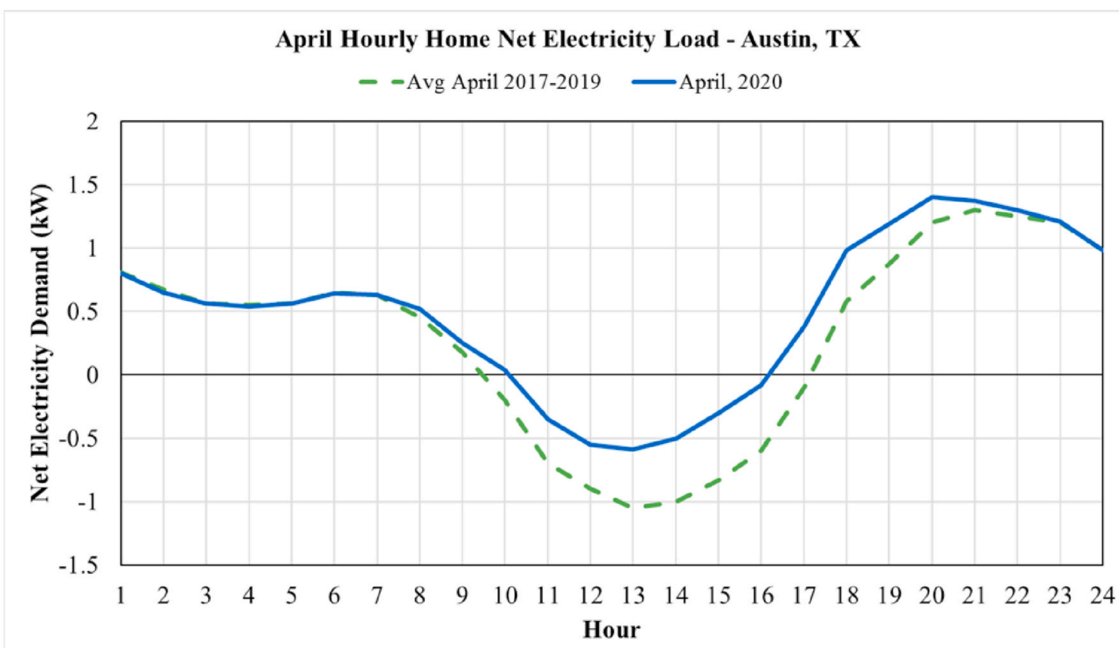


(b)

Fig. 10. Net electricity demand for Pecan Street monitored homes with roof PV systems for (a) March 23–31, 2020 and (b) April 2020 compared to the averages in 2017–2019 (Source: [24]).

- Purchase energy efficient (Energy Star rated) equipment, such as appliances and electronic equipment–including TVs, when new systems are needed. A US household can save up to $575 on their annual energy costs when Energy Star appliances are used [29].
- Use of smart thermostats to adjust temperature settings based on changing occupancy patterns, especially when a large number of residents are staying at home. Potential energy savings of 10%–15% can be achieved with reduced heating and cooling resulting from smart thermostats [30]. Even higher savings can be achieved for residential buildings equipment with several air conditioning units that can be independently controlled [31].
- Install and use shades and blinds to minimize heat loss and optimize solar gains, as well as access to daylight, depending on the season and particular heating and cooling needs. Optimally controlled automated shades have shown a potential energy saving of 15% [32].
- Regularly replace the air filters in centralized air conditioners to both improve the quality of air ventilation and reduce electricity

Table 6
Average HVAC Energy use expressed in kWh/CDD for various periods (Source: [23]).

Month	Average for Years 2017–2019	Year 2020	Percent Change
March	0.53	0.59	11.3%
March 1–14		0.49	−7.5%
March 15–22		0.65	22.6%
March 23–31	0.53	0.73	37.7%
April	0.56	0.7	25.0%

consumption associated with air circulation. Studies have indicated that such changes can achieve a 5–10% energy cost savings [28].

Some other basic actions can improve the indoor conditions within homes to maintain healthy environments. It is important to introduce fresh air to ventilate homes by simply opening windows to dilute the concentration of any virus and limit airborne transmission. Studies have indicated that the type of materials used in buildings can affect indoor air quality and occupant health. Indeed, natural unfinished wood surfaces have been shown to reduce the abundance viruses more quickly than other common indoor surfaces such as stainless steel and plastic [33]. Access to natural lighting can also reduce the concentration of indoor pathogens, enhance indoor lighting, and improve indoor environment quality [34].

In addition, renewable energy technologies can be deployed to improve the energy efficiency and sustainability of new as well as existing residential buildings [35–37]. Among the renewable energy based solutions that are suitable for residential buildings include the following measures:

- Install building integrated Photovoltaic (BIPV) systems to generate electricity using roofs, walls, windows, as well as shading devices [38–42]. For instance, PV-integrated dynamic overhangs have shown that be able to reduce heating and cooling needs as well as produce electricity to achieve almost net-zero energy status for residential buildings [42].
- Specify solar cooling technologies to meet air conditioning needs using solar thermal cooling, solar electrical cooling, or solar combined power cooling [43]. It has been reported that solar assisted air conditioning systems can be used in some climates to cool cost-effectively residential buildings compared to direct expansion systems especially when integrated with variable speed pumps [44–46].
- Deploy building integrated solar thermal systems to supply the majority of domestic hot water and space heating demands for a wide range of climates [47–49].
- Consider integrated solar systems to combine both PV and solar thermal technologies such as Photovoltaic thermal (PV/T) collectors [50–52] and Photovoltaic - integrated collector storage solar water heater (PV-ICSSWH) modules [53].

To better operate the energy efficiency and renewable energy systems, wireless sensors, smart meters, and energy management and information systems (EMIS) can cost-effectively enhance the energy efficiency of buildings as well as improve their resiliency levels [54]. Reported studies have indicated that:

- EMIS can achieve 13% energy savings for retrofited buildings due mostly to their fault detection and diagnostic features [55].
- Appliances with integraed smart controls such as dishwashers, refrigerators, and water heaters can reduce by up to 20% both energy consumption and electrical peak demand [56–59].
- Other smart building technologies are being developed to interact with smart grids to achieve energy efficiency and demand flexibility while providing valuable grid services and meeting occupant needs for comfortable and healthy indoor environments [60]. Some of these smart technologies include dynamic building envelopes [61–65] and tunable phase change materials (PCMs) [66–68].

7. Summary and recommendations

The analysis of weather normalized energy demand data reported for several countries as summarized in this paper indicates that electricity consumption has shifted more heavily to the residential building sector from both commercial buildings and manufacturing facilities due to fully enforced lockdowns and stay at home orders in response to COVID-19 during March–May 2020 period. Indeed, the results of the electricity demand analyses have clearly shown that energy use, and thus the cost for households, is higher because of significant changes in living and occupancy patterns. The magnitude of the increase in home energy use depends on the size of the households, climatic conditions, and locations. However, weather normalized time series data for energy demand have clearly indicated that fully enforced lockdowns and stay home orders have increased the residential sector energy demand by a range from 11% to 32% for several countries with available metered data. These higher electricity use is mainly driven by HVAC and appliance use during daytime hours.

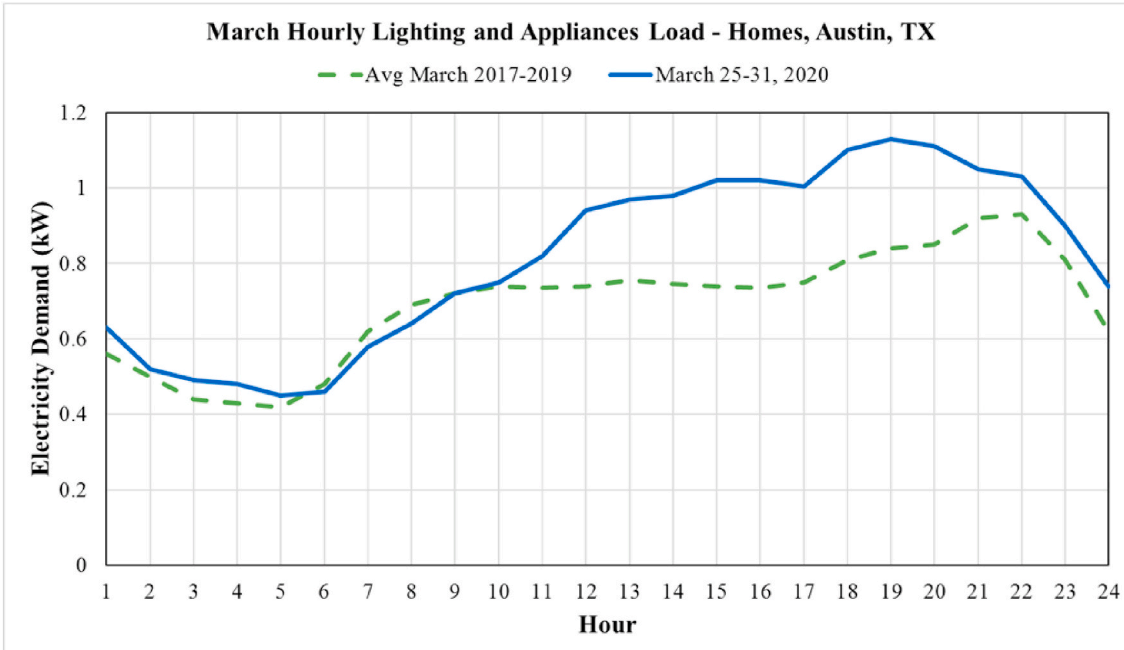
The higher energy demands documented in this study associated with the extended home living which is expected to be prevalent even after the resolution of the COVID-19 health crisis provide opportunities to enhance both the sustainability and the resieliency of the residential building sectors. Indeed, the higher energy use improves the cost benefits of several energy efficiency and renewable energy technologies for both households and governments. In this paper, easy-to-implement measures as well as smart systems are described to reduce energy consumption and improve the indoor air quality of living spaces. Moreover, the transition to working from home calls for the need to consider resiliency of the energy supply is an important factor to design and retrofit residential buildings to ensure that on-site power is still available during grid outages. Renewable energy technologies offer both the benefits of added sustainability and resiliency for the housing stocks. Policy makers should include the impacts of working at home living style on designing and deploying energy policies and programs targeting residential buildings.

It is important to note that the experience of lockdowns and home confinements have created a wide range of opportunities and potential new benefits from working at home. Indeed, several businesses and companies have realized that homes offer a safe environment for some of their employees, who can work productively as compared to performance in often-crowded office buildings. Moreover, working from home permits employees and their families to save substantial time and stress often experienced when commuting with private or public transportation. The saved commuting time allows employees to sleep longer and improve their physical and mental health. In addition, work from home reduces the need for mobility, resulting in lower fuel use associated with driving cars, which in turn reduces carbon emissions.

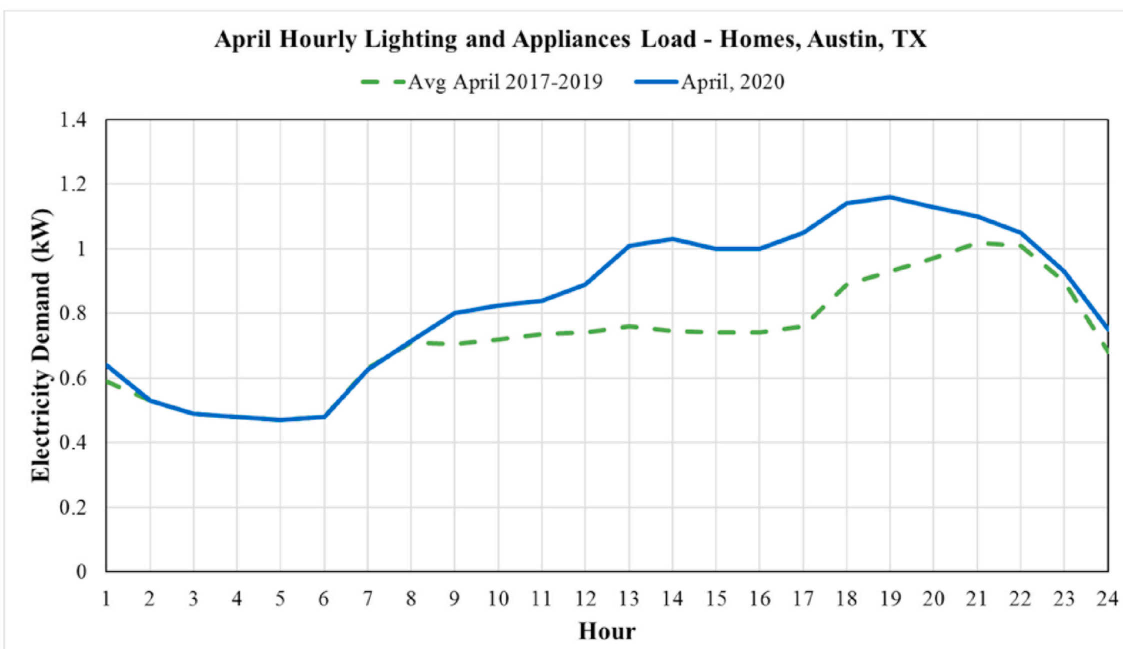
In summary, new design and operating approaches need to be considered for buildings and cities that not only enhances energy efficiency, but also enables more resiliency, health, and safety for residential occupants, especially during extreme weather conditions and pandemic events.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



(a)



(b)

Fig. 11. Net electricity demand for Pecan Street monitored homes with roof PV systems for (a) March 23–31, 2020 and (b) April 2020 compared to the averages in 2017–2019 (Source: [24]).

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