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REVIEW ARTICLE

Exploring the impact of the COVID-19 pandemic on residential energy consumption: a global literature review

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The outbreak of COVID-19 made researchers notice some new points and change their focus, such as the economies of scale for residential energy use, energy dependency of societies, etc. This paper provides a bibliometric analysis of 497 articles by VOSviewer, finding that existing studies on building energy use during COVID-19 could be summarized into four keywords, i.e., building occupants, coronavirus, sustainability and monitoring and management. Significant increases in residential energy consumption are found with the increased duration of in-home-activity, while the growth rate varies between different neighborhoods, different times of day and different usage of energy. Attitudes vary toward the changing trend in the post-pandemic period, and the impacts of lockdown, new confirmed cases, social distancing, etc. on residential energy consumption have been given special attention in recent studies. Policy implications are concluded for maintaining normal operation of residential energy systems under the shock of public health emergencies.

Keywords: COVID-19; residential energy consumption; meta-analysis; impact

1. Introduction

The coronavirus disease-19 (COVID-19) is highly infectious (Zavascki and Falci 2020) and was declared a public health emergency of international concern by the World Health Organization (WHO) in 2020 (Yang *et al.* 2020). At the time of writing, the devastating global health emergency has caused 392 million confirmed cases and over 5.7 million deaths globally (WHO 2022). The ongoing global health toll also has a significant and far-reaching impact on society, leading to enormous economic losses (Ruan *et al.* 2020; Umar, Xu, and Mirza 2021; Xu *et al.* 2021), unemployment (Nguyen *et al.* 2020), travel restrictions (Hurford, Rahman, and Loredo-Osti 2021), etc. During the COVID-19 outbreak, factories and large public buildings could not operate normally, while the global energy demand and energy-related carbon dioxide emissions in 2020 dropped by 5% and 7%, respectively, compared to 2019 (IEA 2020). The 7% reduction in carbon dioxide emissions is believed to have occurred at the cost of 100 million infections, 2.2 million deaths, and a 4.4% global economic contraction (Long and Liang 2021). The International Energy Agency (IEA) calls on all

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countries to make their economic recovery as sustainable and flexible as possible, and build a cleaner and safer energy system while solving such core problems as economic recession and soaring unemployment (IEA 2021).

To restrict the virus's spread, mandatory stay-at-home orders were issued in many regions all over the world (Fletcher *et al.* 2021), profoundly affecting various aspects of people's livelihoods (Barr-Anderson *et al.* 2021). Although the mandatory stay-at-home orders effectively alleviate the COVID-19 situation, long-term home confinement significantly affects mental health (WHO 2020). Stay-at-home orders also change people's daily habits (del Carmen Aguilar-Diaz *et al.* 2021; Zhu *et al.* 2021). During their home confinement period, people no longer have to commute between work and home and tend to sleep and wake later (Weingart *et al.* 2021). The mandatory stay-at-home policies resulted in an increase in mobility within the residential sector (Ashkanani, Bahman, and Aljuwayhel 2022).The sudden behavior change and increased mobility leads directly to an increase in residential energy consumption and a dramatic change in the patterns of energy use in residential buildings (Klopfer *et al.* 2021; Sanchez-Ubeda *et al.* 2022), which will eventually have environmental implications (Sugawara *et al.* 2021). The rise in carbon emissions caused by the increase in residential energy consumption may partially offset the beneficial environmental impacts of restricted activities in other industries, such as handicrafts, industry, transport, commerce and service trade (Kanaya *et al.* 2021; Rodriguez-Sanchez *et al.* 2022; Sugawara *et al.* 2021; Werth, Gravino, and Prevedello 2021). During the economic recovery in the post-pandemic period, both energy consumption and carbon emissions would rebound with a vengeance (Long and Liang 2021). The profound impact of the COVID-19 pandemic on residential energy consumption should be considered carefully in terms of energy-saving and emission-reduction accomplishments, which play a key role in the global warming crisis (Forster *et al.* 2020; Tleuken *et al.* 2021a).

In response to the sudden surge in energy demand in the residential sector, the governments of the world made action plans to deal with this urgent situation (Qarnain, Muthuvel, and Bathrinath 2021). The German government promulgated new rules to ensure the basic electricity supply for everyone in the country and allowed the suspension of payments for electricity, gas and water (Germany Visa 2020). The United States noticed residents' requirements for drinking water and electricity and made emergency plans to supply electricity services, even for those who fail to pay electricity bills (KSLA 2020). Financial subsidy is most frequently used to cut energy prices and maintain residents' access to basic energy supplies, which was offered in the UK (DBEIS 2020), Malaysia (Malay Mail 2020), Australia (DCCEEW 2020), Canada (The Canadian Press 2020) and China (Huang *et al.* 2020). Apart from government action plans, some non-governmental organizations also explored and disseminated ways to reduce energy consumption amid the COVID-19 pandemic outbreak for residential buildings (Seventh Generation 2020), commercial buildings (GreenBiz 2020), campuses (Northwestern 2021), etc.

The pandemic situation and degree of control by different countries/regions by the end of 2021 are summarized in Table 1. The total cases and deaths per million for both the United States and the United Kingdom are far above the world average. Although the total cases and deaths per million in China are low compared to other countries/regions, the growing attention from all walks of life since the pandemic's outbreak has led to the country's high number and magnitude of publications (Hadi *et al.* 2020; Rothan and Byrareddy 2020). Table 1's stringency index records the

Table 1. The pandemic situation and control degree of different countries/regions by the end of 2021.

Region	Country	Total cases	Total deaths	Total cases per million	Total deaths per million	Stringency index
Europe	Denmark	823,282	3,272	141,620.4	562.8	35.2
	France	10,237,147	123,915	151,836.9	1,837.9	72.2
	Germany	7,196,154	112,157	85,770.1	1,336.8	84.3
	Poland	4,120,248	97,559	109,009.9	2,581.1	42.6
	Spain	6,294,745	89,405	134,660.7	1,912.6	43.5
	Sweden	1,314,784	15,310	129,405.8	1,506.8	49.1
	United Kingdom	13,127,965	148,891	192,472.1	2,182.9	48.6
Americas	Canada	2,219,811	30,340	58,311.9	797.0	74.5
	United States	54,958,865	827,967	165,083.7	2,487.0	50.5
South East Asia	Malaysia	2,761,472	31,513	84,252.4	961.4	50.5
South Asia	India	34,889,132	481,770	25,038.7	345.7	59.7
	Pakistan	1,296,527	28,941	5,757.2	128.5	30.1
East Asia	China	119,555	5,486	81.4	3.7	79.5
	Japan	1,732,752	18,389	13,746.5	145.9	47.2
	South Korea	639,083	5,694	12,456.5	111.0	45.4
West Asia	Saudi Arabia	557,082	8,878	15,763.1	251.2	49.1
Australia	Australia	462,955	2,257	17,952.2	87.5	40.3
Africa	Nigeria	242,877	3,033	1,148.9	14.3	38.0
Oceania	New Zealand	14,255	51	2,780.8	9.9	44.0
World		*289,509,840*	*5,443,856*	*36,763.3*	*691.3*	

Note: Sourced from Our World in Data (OWD n.d.).

strictness of "lockdown style" policies that primarily restrict people's behavior, which is calculated using ordinal containment and closure policy indicators, plus an indicator recording public information campaigns (Hale *et al.* 2021). The stringency indices for France (located in Europe), Germany (located in Europe), Canada (located in the Americas) and China (located in East Asia) are the highest, which indicates there is no direct relationship between lockdown strictness and geographic location.

Since the start of the COVID-19 pandemic, studies have tended to focus on the change in residential energy consumption. Existing studies have proved the significant impact of COVID-19 on residential energy consumption both with real data (Bionda *et al.* 2020; Iannarelli *et al.* 2020) and by using simulation methods (Garcia *et al.* 2021; Zhang *et al.* 2020). The increases in global residential energy consumption after the start of the pandemic are uncontroversial, while the specific changes in different regions remain to be collated. The sudden and huge impact of the public health emergency on residential energy consumption fails to be well studied in previous literature, making previous research findings inapplicable or insufficient during COVID-19. It is, therefore, worthy to conduct a systematic review of research to date for an in-depth understanding of the impact of COVID-19 on residential energy consumption and give policy implications on new directions for the evolution of the residential energy system when confronting public health emergencies in the future. Hence, this paper conducts a bibliometric analysis of existing publications from a macro perspective and reviews the changes in residential energy consumption caused by the pandemic. The impact factors of residential energy consumption during the COVID-19 pandemic period are studied by meta-analysis. Finally, the advice for promoting sustainable energy retrofitting, considering the impact of COVID-19, is examined. This article is expected to systematically sort out relevant literature on the impact of the COVID-19 pandemic on residential energy consumption and benefit both governments and residents when facing a public health emergency that restricts people to stay at home.

2. Research methodology

This research adopts a literature review to explore the impact of COVID-19 on residential energy consumption, with specific methodologies including bibliometric analysis and meta-analysis. The bibliometric analysis shows the research change trends and characteristics of a large number of documents by quantitative analysis and infographics (Van Raan 2005). Meta-analysis relies on the collection of existing or unpublished literature with comparable characteristics, and applies statistical methods for analysis and comprehensive evaluation (Sacks *et al.* 1987).

In order to achieve the objective to systematically review the impact of the COVID-19 pandemic on residential energy consumption and give policy implications, we designed the following research process. As Figure 1 shows, the literature review was carried out in four parts: overview of previous studies, changes caused by Covid-19, impact factors of residential energy consumption and new directions for the evolution of the residential energy system.

A comprehensive literature review of previous studies on the topic of building energy during the pandemic was conducted by bibliometric analysis based on VOSviewer. The Web of Science Core Collection is used to search the journal and conference papers, with *building energy*, *residential energy*, and *COVID-19* as the search keywords. The basic information in these articles was imported into VOSviewer to enable co-country/region analysis and co-word analysis. The occurrence and relationships are calculated and visualized in VOSviewer. The results of VOSviewer are further analyzed and interpreted in Section 3.

Changes in residential energy consumption caused by COVID-19, including changes in total residential energy consumption, changes in residential energy consumption pattern and its changing trend are analyzed by intensive reading and summary. Articles related to residential energy consumption during the COVID-19 pandemic were read through carefully. The data on residential energy consumption changes and daily residential electricity

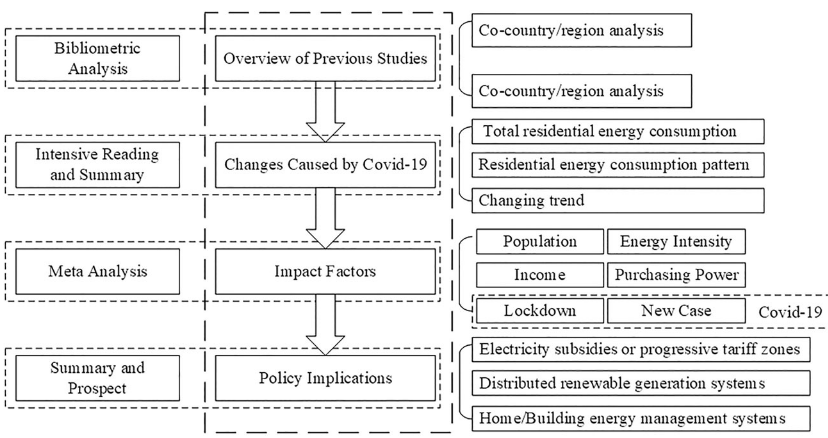

Figure 1. The workflow of the review.

demand were collected in the course of reading. Different attitudes towards the changing trend in residential energy consumption were also summarized in this part.

A meta-analysis was then conducted which analyzed the contribution of each impact factor to changes in residential energy consumption. Based on careful and thorough reading of previous studies, the impact factors emerging in relevant research after the onset of the COVID-19 pandemic were given special analysis. In the final stage, new directions for the evolution of the residential energy system considering the impact of COVID-19 were given on the basis of summary and prospect.

3 Bibliometric analysis based on VOSviewer

As there are insufficient articles on the topic of residential energy during COVID-19 to provide a full bibliometric analysis, publications relating to building energy were collected to understand research to date from a macro perspective. Thomson Reuters' Web of Science Core Collection bibliographic database was used to collect publications on the topic of building energy during COVID-19. Using the query TS = (building energy OR residential energy) AND TS=(COVID-19) for retrieval, a total of 497 articles were identified. Their title, abstract, author, publication year, and cited references were downloaded for a bibliometric analysis based on VOSviewer's visualization technology.

3.1. Co-country/region analysis

Figure 2 shows the relationships between each co-author's country/region. Here, the circle size represents the number of documents involving the country/region, with those labeled with the same color showing greater cooperation with others: those located in the middle of the graphic cooperated more frequently, while those on the edge of this graphic cooperated less. The highest number of countries/regions per continent comes from Europe (33), followed by Asia (25), Africa (10), the Americas (8) and Oceania (3). The co-country/region analysis shows China (28 links, 85 co-authorships), England (28 links, 53 co-authorships), Spain (19 links, 48 co-authorships), Australia (19 links, 28 co-authorships), and the United States (18 links, 79 co-authorships) to be the countries/regions that published the most articles concerning building energy during COVID-19 and cooperated the most with each other. From Figure 2, it is obvious that countries on the left side of the graphic mainly consist of developed European and American countries/regions, such as England, the USA, Norway and Denmark. Thanks to the rapid development after the second industrial revolution and the close geographical location, their pandemic situation, work modes, and lifestyles are similar to each other and it is more likely for them to face common problems with residential energy consumption during the COVID-19 pandemic. On the right side of the graphic most are Asian and African developing countries/regions, except South Korea, Russia and Scotland. However, South Korea is located in Asia and Russia is a country spanning Asia and Europe geographically, which could explain why they cooperated more with the developing countries on the topic of residential energy consumption during COVID-19.

3.2. Co-word analysis

The title and abstract of the publications were used to extract the terms with the highest occurrence. Unrelated words and repetitive words were excluded. Figure 3 shows

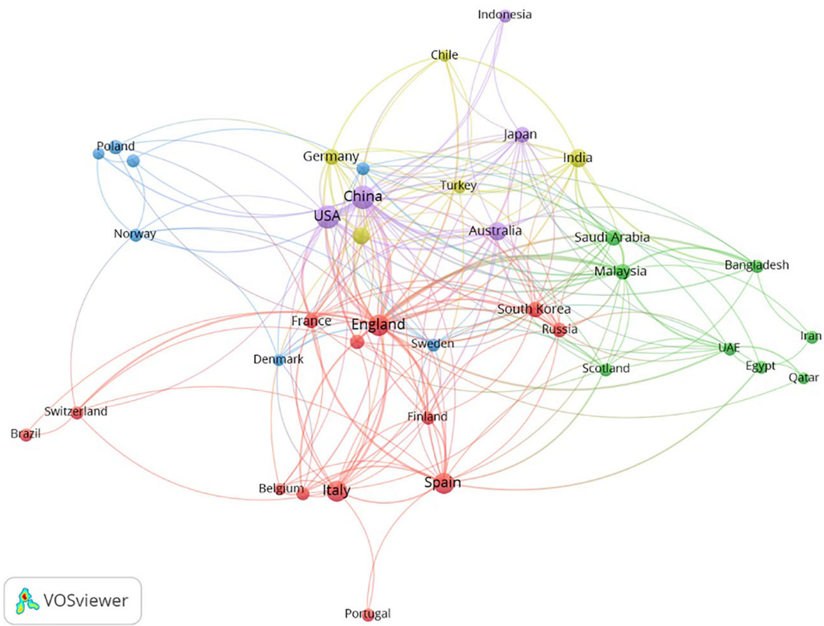

Figure 2. Co-country/region network analysis.

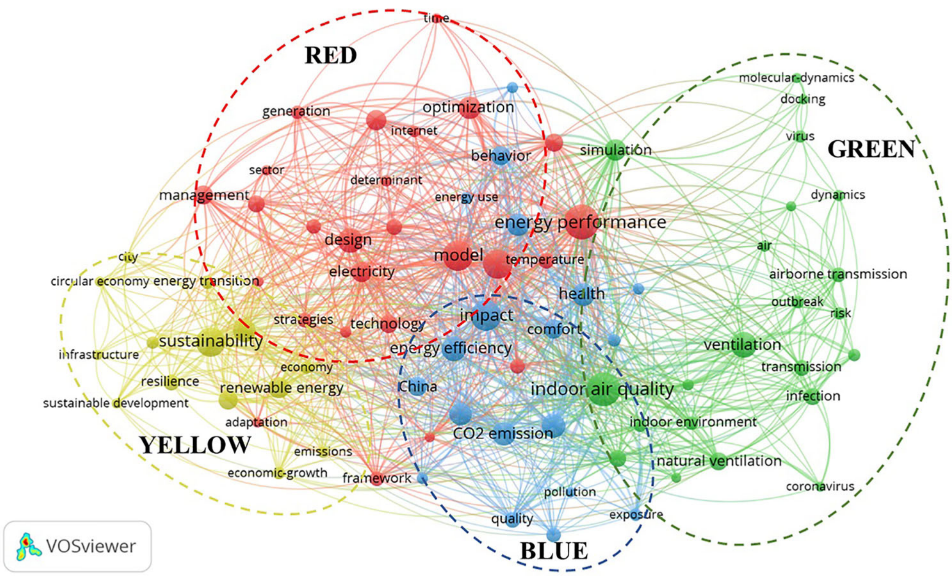

Figure 3. Co-occurrence of terms of clusters.

the final results. Here, the size of the circle represents the number of occurrences of a term, and the distance and line between two terms represents their relationship, which is measured by calculating the total strength of the co-occurrence links with other keywords.

Terms can be grouped into four categories by cluster analysis according to the analysis result, where each cluster is marked with different colors. As Figure 3 shows, cluster 1 (marked in blue) is focused more on the building occupants. For instance, the finding of Kawka and Cetin (2021) on the electricity use of 225 housing units in the United States during 2018–2020 indicates that the increased electricity use is during periods when the occupants would usually be away from home, and that the shifts in electricity use are associated with household income. Similarly, Franco, Miserocchi, and Testi (2021) demonstrate that implementing occupant-centric control strategies in buildings after the start of the COVID-19 pandemic is of great significance.

Cluster 2 (marked in green) mainly comprises coronavirus studies. Liu *et al.* (2022), for example, propose a collaborative control strategy for an air conditioning system and ventilation system to reduce the risk of COVID-19 infection and save energy by the communication system, which can also reflect building energy consumption, virus concentration, and risk of COVID-19 infection. Likewise, Mokhtari and Jahangir (2021) use a Tehran university building as a case study for the relationship between COVID-19 infection risk, energy consumption, and occupant density, finding that an optimal population distribution can reduce the number of infected people and energy consumption by 56% and 32%, respectively.

Cluster 3 (marked in yellow), is concerned with the sustainability of building energy systems after the outbreak of COVID-19. Ascione *et al.* (2022) collect information on implementation by different countries to improve building energy efficiency and promote its sustainable development after the onset of the COVID-19 pandemic. Motuziene *et al.* (2022) analyze the occupancy change during the COVID-19 pandemic considering its significant impact on building energy performance and its sustainability level. Ayub *et al.* (2022) demonstrate the fundamental role of Renewable energy-based Smart Home Energy Management Systems for residential buildings, especially during the COVID-19 pandemic because of the increased and dynamic household electricity demand.

Cluster 4 (marked in red) focuses on the monitoring and management of building energy performance during COVID-19. Su *et al.* (2022) monitor the energy performance of a large green commercial building in Dalian, China during its five COVID-19 lockdowns separately to quantify the impact of the lockdown orders on commercial building energy consumption. Huang and Gou (2022) collect the electricity consumption data for 35 public buildings during the period of 2020 to 2021 and analyze the relationship between restriction and easing policies and energy consumption. Hu *et al.* (2022) use the improved Wells-Riley model to explore the optimization strategy for reducing infection risk, as well as building energy consumption according to season and spatio-temporal population distribution.

4. Changes in residential energy consumption during the pandemic period

The near-term COVID-19 shock had a far-reaching impact on the economy and people's daily lives. The mandatory lockdown to slow down the spread of the virus resulted in changes in residents' behaviors, which are observable in the changes in residential energy consumption during the pandemic period.

4.1. Changes in total residential energy consumption

Mandatory stay-at-home orders have been shown to force residents to spend more time, and consume more energy, in residential buildings for their daily routine activities and telecommuting work (Aliero *et al.* 2022; Alola and Bekun 2021). Figure 4 shows how the time spent at home changed since the beginning of the pandemic in some representative countries on various continents. With people spending more time at home, their daily habits changed significantly (Krarti and Aldubyan 2021), causing residential heating energy consumption and carbon dioxide emissions to increase by 182% in Barcelona, Spain, for example (Monzon-Chavarrias *et al.* 2021). An 80% increase in daily average in-home-activity duration was found during the lockdown period and a 32% increase was found after the lockdown in Canada (Khalil and Fatmi 2022). Similarly, Qarnain *et al.*'s (2020) study of five cities in India that imposed a total lockdown recorded a 12% increase in residential energy consumption; while Jang *et al.*'s (2021) analysis of the New York shut down identified a 7% and 4% increase in weekday and weekend residential energy consumption, respectively. Compared with the traditional neighborhood, a greater increase in residential energy consumption during the pandemic was found for a smart neighborhood, equipped with IoT-enabled devices (Chinthavali *et al.* 2022).

Although total residential energy consumption shows an overall obvious trend to increase in most countries/regions (Balest and Stawinoga 2022; Shanableh *et al.* 2022), COVID-19 may cause a decrease in residential energy consumption in some dimensions. The COVID-19 pandemic inescapably brings strict travel restrictions and the increased mortality rate (Al-Awadhi *et al.* 2022; Rovira *et al.* 2022), and the decreased number of residents may cause a partial offset of the increase in residential energy consumption. As more people of the same household share household energy use, the growth rate for residential energy consumption would drop to some extent because of the energy-related economies of scale (Andreoni 2022).

Some studies analyze the changes in residential electricity and gas energy consumption separately under the COVID-19 pandemic. Surahman *et al.* (2022) investigated changes in electricity for household appliances and gas consumption in Indonesia during the COVID-19 pandemic through face-to-face interviews. In 2020, Kang *et al.*'s (2021) South Korean study found an average change of around 2.5% and −3% in residential electricity and gas energy consumption, respectively, compared to

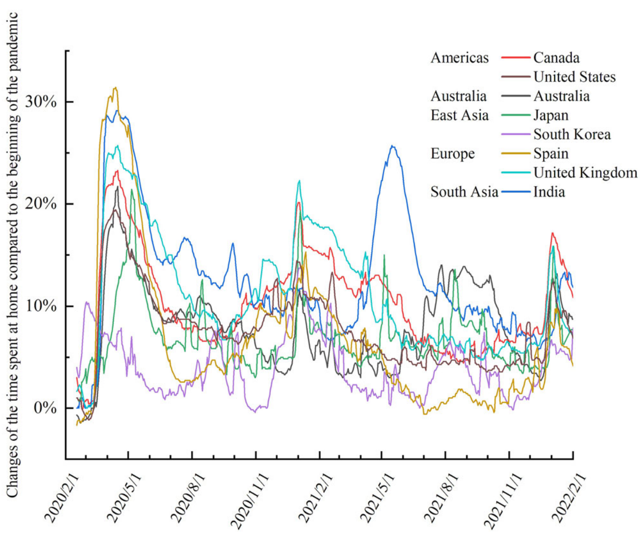

Figure 4. How the time spent at home changed since the beginning of the pandemic. Data source: Google COVID-19 Community Mobility Trends (Google n.d.).

the previous year; residential gas energy consumption dramatically decreasing in April with a −11% average rate of change when the country adopted strong social distancing to control COVID-19's expansion. The impact of COVID-19 was found to be stronger on the cooling loads than the heating loads during the quarantine (Gounni *et al.* 2022; Todeschi *et al.* 2022).

4.2. Changes in residential energy consumption pattern

During the COVID-19 pandemic, great changes can be found in people's daily habits (Broersma and Swart 2021; Yu 2021). Since the mandatory stay-at-home regime forced people to work at home and generally remain there during daytime hours, they tend to sleep later at night and wake up later in the morning (Morison 2020). Thus, several studies find changes in residential energy consumption patterns, especially in electricity consumption. By analyzing 225 housing units in the US, Kawka and Cetin (2021) find the largest electricity consumption increase and decrease occurred at 11 a.m. or 12 p.m. and between 7 p.m. and 8 p.m., respectively, with the majority of increases occurring between 10 a.m. and 1 p.m. The peak increase was during typical lunch hours, indicating an increased use of kitchen appliances. Telework compels people not to commute home, but to assume their evening routines sooner compared to pre-pandemic periods, resulting in an earlier evening peak. Daily residential energy consumption in New York is found to peak earlier in the morning at 9 a.m., because of the impact of stay-at-home behavior (Jang *et al.* 2021). April and October are the largest increase months, while September is the smallest (Kawka and Cetin 2021). Figure 5 shows the hourly electricity demand for California (located in Americas) in 2019 and 2020 respectively, with the 2019 curve representing the pre-pandemic hourly demand and the 2020 curve as the energy demand during the pandemic. The hourly electricity percentage change curves for Australia and Britain both show an increase in residential electricity demand during the daytime, while the Australia and Britain

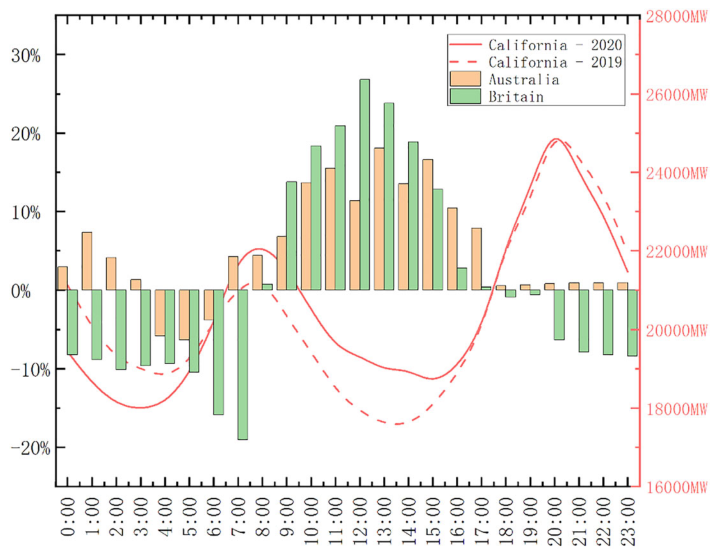

Figure 5. Hourly electricity demand and its percentage change in California (CAISO n.d.), Australia (Farrow 2020), and Britain (Gausden 2020).

curves differ a lot during other hours. The discrepancy is also found between Australia and California. The difference between the hourly electricity demand change in California, Australia and Britain may attribute to their different lockdown degree and lifestyles.

4.3. Changing trend in the post-pandemic period

The changes in residential energy consumption, caused by the drastic change in people's lifestyles, influences global CO_2 emissions (Forster *et al.* 2020; Le Quere *et al.* 2020; Liu *et al.* 2020). Although residential energy consumption increased considerably compared to 2019 during the COVID-19 outbreak, global energy demand decreased by 5% in 2020 because factories, large public buildings, and other entertainment places could not operate normally, and energy-related CO_2 emissions decreased by approximately 7% (IEA 2020). The ongoing COVID-19 pandemic has created a radical departure from previous residential energy consumption trends, while it is still unclear how longer-term energy transition will evolve in the post-pandemic recovery period (Kikstra *et al.* 2021).

When analyzing the impact of COVID-19 on residential energy consumption, the changing trend reduces to two categories. One possible trend is that residential energy consumption keeps increasing and does not return to its pre-lockdown state (Rouleau and Gosselin 2021). Considering that public and personal behavior during the lockdown, such as remote work (Novianto *et al.* 2022), could continue in the post-pandemic period even without any lockdown measures (Mitra, Chu, and Cetin 2022), the increase in residential energy consumption caused by COVID-19 will not offset. While some hold that the effect on residential energy consumption during the pandemic period is temporary, the residents' lifestyle, including cooking, entertainment, and lighting patterns, will all return to the pre-pandemic level (Rouleau and Gosselin 2021; Tleuken *et al.* 2021b). Tleuken *et al.* (2021b) reveal that the increase in residential energy consumption was not significant compared to similar timeframes without pandemic measures in Kazakhstan at least, and opine that the increase during lockdown is only temporary.

5. A meta-analysis of the impact factors

To formulate corresponding solutions avoiding high utility bills and energy wastage due to the unusual residential energy usage during COVID-19, there is an urgent need to analyze the drivers responsible for higher residential energy consumption (Qarnain *et al.* 2020). The pre-pandemic factors impacting on residential energy consumption are also worthy of attention. Referring to J. Wang *et al.* (2019), this paper provides a meta-analysis of the factors involved. Table 2 summarizes the main features of the studies of drivers of residential energy consumption, in which most typical drivers before and during the COVID-19 pandemic are identified.

Figure 6 shows the contribution of each driver to residential energy consumption according to each reference. The combination of Table 2 and Figure 6 shows that only the impact of income and new cases is positive across all the studies; while the impact of population, energy intensity, purchasing power, and lockdown is volatile. The contribution of population after the outbreak of COVID-19 in Tleuken *et al.* (2021b) is far above the average level of pre-COVID-19 papers, and is the only paper in which lockdown has a negative correlation.

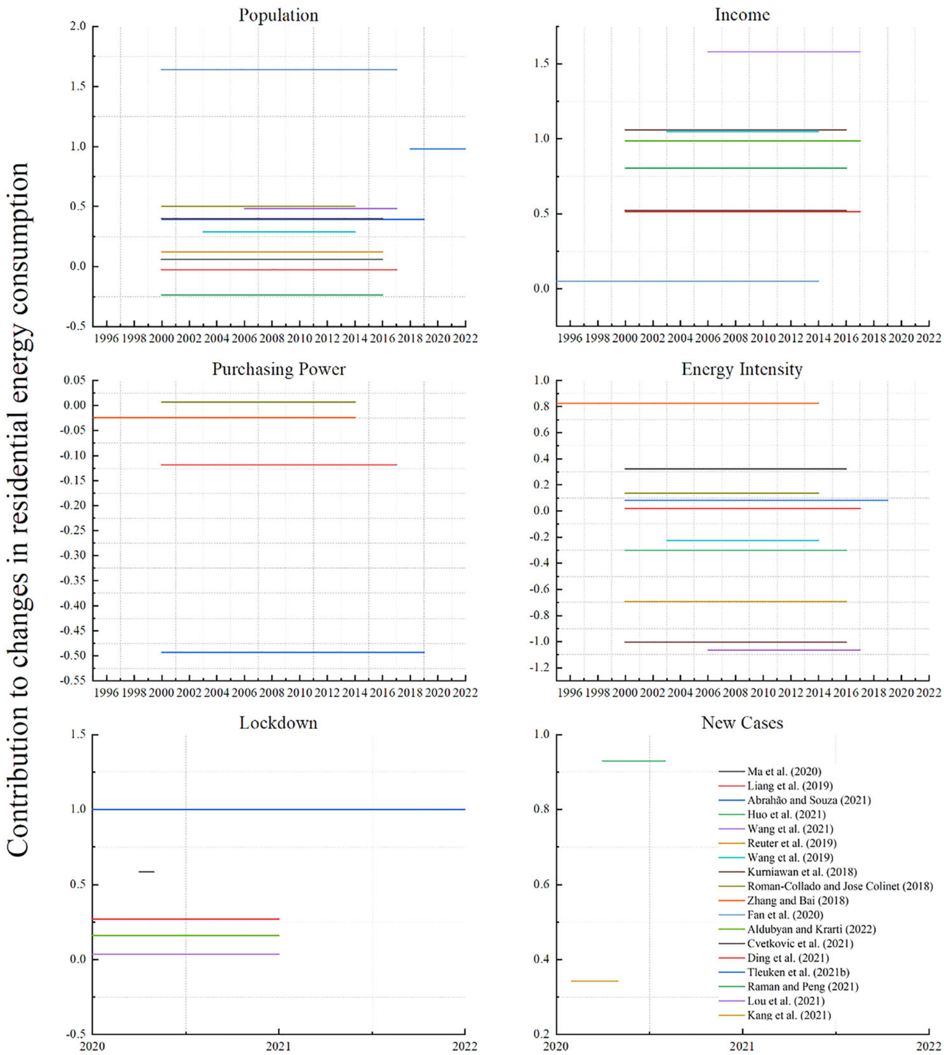

Figure 6. Contribution of drivers to residential energy consumption.

Since the outbreak of the pandemic, studies have paid more attention to how a mandatory stay-at-home regime or number of confirmed cases influence residential energy consumption, while COVID-19 may have altered the contribution of the historical residential energy consumption drivers. For instance, except for the studies listed in Table 2, Qarnain *et al.* (2020), Edomah and Ndulue (2020), and Bielecki *et al.* (2021) find a significantly positive correlation between lockdown and residential energy consumption during the COVID-19 pandemic period, although Tleuken *et al.* (2021b) find this to be negative in Kazakhstan: on the other hand, the majority of studies just concentrate on the impact of a specific period of lockdown. In addition, Aldubyan and Krarti's (2022) analysis of the impact of long-term stay-home living finds that the effect of long-term lockdown on residential energy use varies from season to season, being small during the winter months and increasing during the summer months (Aldubyan and Krarti 2022).

Table 2. Summary of the main features across studies on drivers of residential energy consumption.

Reference	Country\Region	Studied period	Energy type	Method	P	I	EI	PP	LD	NC	O	T
Ma *et al.* (2020)	China	2000–2015	Energy	LMDI	+	+	+				✓	6
Liang, Cai, and Ma (2019)	4 cities in China	2000–2016	Energy	LMDI	−	+	+	−			✓	6
Abrahão and Souza (2021)	Brazil	2000–2018	Electricity	LMDI + IDA	+		+	−			✓	3
Huo *et al.* (2021)	China	2000–2015	Energy	LMDI	−	+	−				✓	4
Wang *et al.* (2021)	Suzhou, China	2006–2016	Energy	LMDI	+	+	−					3
Reuter, Patel, and Eichhammer (2019)	European Union	2000–2015	Energy	LMDI	+		−				✓	4
C. Wang *et al.* (2019)	Guangzhou, China	2003–2013	Energy	LMDI	+	+	−				✓	7
Kurniawan, Sugiawan, and Managi (2018)	Indonesia	2000–2015	Energy	LMDI	+	+	−				✓	5
Roman-Collado and Jose Colinet (2018)	Spain	2000–2013	Energy	LMDI	+		+	+			✓	4
Zhang and Bai (2018)	Shandong, China	1995–2013	Energy	LMDI		+	+	−			✓	5
Fan *et al.* (2020)	China	2000–2016	Energy	Extended STIRPAT	+	+					✓	6
Aldubyan and Krarti (2022)	Saudi Arabia	2019–2020	Electricity	Regression analysis					+		✓	2
Cvetkovic, Nesovic, and Terzic (2021)	Serbia	2020.03	Natural gas	Scenario analysis					+			1
			Electricity						+			
Ding *et al.* (2021)	Norway	2016–2020	Electricity	Scenario analysis					+		✓	2
Tleuken *et al.* (2021b)	Atyrau, Kazakhstan	2018–2021.05	Energy	Regression analysis	+				−			2
Raman and Peng (2021)	Singapore	2020.03–2020.06	Electricity	Vector Error Correction Model						+	✓	5
Lou *et al.* (2021)	United States	2019–2020	Electricity	Regression analysis					+			1
Kang *et al.* (2021)	South Korea	2020.01–2020.03	Electricity	Statistical Analysis						+	✓	3
			Gas energy							+		

Note: LMDI denotes the Logarithmic Mean Divisia Index, P population, I income, EI energy intensity, PP purchasing power, LD lockdown, NC new case, O indicates that other factors are considered in the reference, and T is the total number of factors studied in the reference. "+" means the reference contains a positive correlation between residential energy consumption and the factor, and "-" means a negative correlation.

The number of new cases found by Raman and Peng (2021) to have a positive correlation with residential energy consumption is also true for the cumulative number of COVID-19 cases and incidence rate, although not significant for single-family residences, which are temporarily occupied by students or workers (Kang *et al.* 2021). Affected by the pandemic, schools and educational facilities, and parts of businesses could not operate normally, leading to a considerable increase in empty single-family residences (Jewan, Shin, and Choi 2020; Martin 2021). This neutralized the increase in residential energy consumption due to the change in residents' daily routine and increased time at home, which resulted in a non-significant correlation for single-family residences.

Except for the factors mentioned above, social distancing, home quarantine, home transformation, and psychological factors have also been emerging factors for energy consumption in homes during COVID-19 (Bhuiyan *et al.* 2021; Ezquiaga Domingez 2020; Qarnain *et al.* 2020; Tsai 2021). The degree of influence of COVID-19 related factors, for example, varies for different groups. Mid-income households experience less change in residential energy consumption compared to both low-income and high-income households (Jang *et al.* 2021; Kawka and Cetin 2021). Unlike mid-income and high-income households who switched to working remotely at home after the outbreak of COVID-19, low-income households still have to work outside (Mitra, Chu, and Cetin 2022) because their job positions require in-person work (Helppie-Mcfall and Hsu 2020). Debnath *et al.* (2022) hold that the impact of COVID-19 on residential energy demand would be more profound for low-income households. Similarly, residential energy consumption in hotter and larger areas increases with stronger growth rates (Aldubyan and Krarti 2022; Jang *et al.* 2021).

6. Policy implications

The COVID-19 pandemic has changed residential energy consumption and its pattern significantly, and several new impact factors have been found. Therefore, the path of sustainable energy transition in residential sectors has changed from pre-pandemic times, and recent studies are exploring the new directions for the evolution of the residential energy system.

First is to offer electricity subsidies or adjust progressive tariff zones according to a region's COVID-19 trends (Bienvenido-Huertas 2021; Kang *et al.* 2021). Although telework is popular during COVID-19 to keep society operational, mandatory stay-at-home lockdowns certainly cause unemployment, especially to lower income groups (Guo *et al.* 2021). As has been mentioned earlier, the pandemic's impact on lower income households is significant, with their residential energy consumption increasing more. Affected by the pandemic, the income of most lower income families reduces while they tend to consume more residential energy than the pre-COVID-19 period, which can soar exponentially (Kang *et al.* 2021). Therefore, without subsidies from regional governments, lower income families will be under great economic pressure during the pandemic period (Sanchez-Lopez *et al.* 2022). The electricity price for residents is suggested to be deflated with the subsidies provided by regional governments during mandatory stay-at-home periods. For the region implementing multistep electricity prices, local government can also increase the quantity of electricity scaled to each step according to the situation of the local epidemic.

Second is to install distributed renewable generation systems such as solar PV with a battery energy storage system (Carere, Bragatto, and Santori 2020; Daggash and

Mac Dowell 2021; Haohui *et al.* 2020). The spread of COVID-19 is not only by droplet transmission but also by close contact transmission (Shafaghi *et al.* 2020; Zhao *et al.* 2020), and therefore it is difficult to control and may resume at any moment. Hence, there is an urgent need to develop sustainability strategies for regulating residential energy consumption. The distributed renewable generation system is necessary for unexpected situations during the pandemic due to the rapid change in residential energy usage during an outbreak. Installing distributed renewable generation systems can successfully manage unpredictable residential energy use, and simultaneously reduce the economic losses of the government and electricity utilities (Punda *et al.* 2017). Installing solar PV with a battery energy storage system ultimately increases the efficiency of renewable energy generation and the sustainability of the residential energy system (Nassereddine *et al.* 2018; Parmeshwarappa, Gundlapalli, and Jayanti 2021), which is regarded as the best way to keep energy self-sufficient and maintain the normal run of daily life during COVID-19 (Elavarasan *et al.* 2020).

Third, the changeable residential energy consumption during COVID-19 makes it urgent for the residential energy system to save energy, and home or building energy management systems applicable to residential buildings can help to improve energy consumption efficiency (Lou *et al.* 2021; Ruensukon *et al.* 2021). These are acknowledged as more secure and sustainable and have been introduced for a long time because they can increase the efficiency of residential energy usage, which has been proved to save energy consumption (Li *et al.* 2017; Munankarmi *et al.* 2020). In response to the increased and dynamic residential energy demand during COVID-19, the distributed renewable energy system is suggested to be introduced to better deal with the dynamic residential energy demand during the COVID-19 pandemic (Ayub *et al.* 2022). In a study exploring residents' acceptance of, and willingness to pay for, home energy management systems, approximately 80% of the residents in New York have been found willing to use such systems during the COVID-19 pandemic (Chen *et al.* 2020).

7. Conclusion

This paper conducts a literature review of existing studies of residential energy consumption during the COVID-19 pandemic period. These are classified into four categories, focusing on building occupants, coronavirus, sustainability and monitoring and management. From a global perspective, residential energy consumption is found to have significant increases. The increase rate differs substantially between different regions, which may be the result of their different climatic characteristics, epidemic situations, lockdown degrees, religious beliefs, work modes, lifestyles, etc. The significant increase in residential energy consumption has been confirmed in the typical and representative countries of Europe, the Americas, Asia and Australia. A decrease in residential gas energy consumption in South Korea can be attributed to the neutralization of the increase in residential electricity consumption. The increase is found to peak during typical lunch hours – an earlier time than experienced in the pre-pandemic era.

The changing trend in residential energy consumption in the post-pandemic period is still unclear. Lockdowns and new cases have a significant correlation with residential energy consumption and the impact of COVID-19 on residential energy usage varies according to the temperature and area of different regions. Several policy implications are summarized, including 1) offering electricity subsidies or adjusting progressive tariff zones according to the region's COVID-19 trends; 2) installing distributed renewable generation systems such as solar PV with a battery energy storage system; and 3) building home or building-energy-management systems applicable to residential buildings to improve energy consumption efficiency.

For further research, exploring the impact of COVID-19 related factors on residential energy consumption on the basis of specific region data is suggested. The pandemic situation and control level of different regions vary and new findings may be discovered with specific region data. Another possible area for future investigations is analyzing the relationship between people's home behavior change during COVID-19 and residential energy consumption using questionnaires, experiments and interviews.

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