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Beyond technology adoption: Examining home energy management systems, energy burdens and climate change perceptions during COVID-19 pandemic

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ABSTRACT

The COVID-19 pandemic has rapidly changed our lives. While the global impacts of the pandemic are shocking, the implications for energy burdens, climate policy, and energy efficiency are salient. This study examines income differences in the acceptance of and willingness to pay for home energy management systems during the COVID-19 pandemic among 632 residents in New York. Additionally, this study examines energy profiles, energy burdens, climate change issues, risk perceptions, and social-psychological factors. Compared with low-income households, our findings suggest that high-income households use more energy, have higher utility bills during quarantine mandates, perceive a higher risk of COVID-19 infection, and perceive climate change issues to be better than before. Low-income households, however, experience the highest energy burdens. Regarding HEMS acceptance, high-income households are more willing to adopt energy and well-being-promoting features of HEMS and more willing to pay a higher monthly fee for all the features than other income groups. Overall, participants were more willing to pay a higher price for the energy features than the well-being-promoting features. Low-income households indicate lower social norms, personal norms, and perceived behavioral control over adopting HEMS; they also perceive HEMS to be more difficult to use and less useful. Higher-income households express a higher trust in utilities than low-income households. Surprisingly, cost concerns, technology anxiety, and cybersecurity concerns relating to HEMS do not differ across income groups. This paper addresses the interactions among technology attributes and social-psychological and demographic factors, and provides policy implications and insights for future research.

1. Introduction

Energy is not classified as a fundamental human right by the U.S. federal government, but has been deemed “essential to meeting our basic needs: cooking, boiling water, lighting and heating, […] a prerequisite for good health” by the World Health Organization [1], making energy critical for vulnerable populations during the COVID-19 crisis. The pandemic has changed energy access, management, and affordability due to increased internet use, home appliance powering, and household heating or cooling [2]. While global energy consumption and greenhouse gas emissions have decreased since March 2020 [3], U.S. residential energy demand has increased by 22% [4], and residential utility bills were anticipated to increase by at least 10% in major U.S. cities during the summer months of 2020 [5]. More importantly, the impacts of the pandemic mean that households already experiencing energy burdens will have to pay even more than before as nearly half of adults in the U.S. at or below the poverty line lose their jobs. Further, almost one-third of adults reported being unable to pay their rent, mortgage, or utility bills in March and April 2020 [6]. These numbers are expected to worsen as the pandemic continues in the U.S., especially during winter when households will use more heat.

Low-income households (LIHs) have the longstanding challenge of energy insecurity or energy burdens, both of which pertain to uncertainty affording utility bills [7–9]. For example, LIHs often pay a disproportionate amount, typically 7.2%–19% [7,10], of their income on utility bills, with low-income, elderly, non-white, and renter

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populations spending more on utility bills and more per square foot than their counterparts [7,10]. LIHs are also more likely to play “catch-up” with their utility bills [1] and make trade-offs between paying their utilities and other necessities (e.g., heat-or-eat dilemma [11]) than other income groups. Additionally, being unable to afford proper thermal comfort can have adverse mental and physical health effects [12,13], and can result in risky behaviors such as payday lending [7] or using unsafe energy alternatives such as wood, peat, and charcoal, which can expose families to indoor air pollution and exacerbate respiratory conditions like asthma or COPD [12,14].

During the COVID-19 pandemic, the link between food, health, medical, and energy insecurity is evident [1,6,15,16]. Unpaid utility bills and use of food pantries or banks have increased since March, 2020 [6,16]. People with certain medical conditions require equipment that uses electricity, and other services, like telemedicine, require internet access. Telemedicine has become increasingly important during the pandemic to help slow hospital traffic, maintain social distancing, and allow frontline doctors to focus on COVID-19 cases [17]. LIHs could significantly benefit from these services, as they are more likely to have disabilities and medical conditions that affect heating and cooling needs than other households [18,19]. The pandemic has revealed a need to understand the energy burdens of vulnerable households, as well as their energy use patterns and perceptions of climate change issues, to develop ways to efficiently manage and reduce energy use, especially since experts warn that pandemics are recurring risks that worsen with climate change [20]. Additionally, vulnerable communities are more susceptible to contracting the coronavirus [21,22] and more likely to experience the effects of climate change than other groups, as they do not have the resources (e.g., temporal, financial, informational) to appropriately respond to such disasters and crises [23]. Environmental injustices, such as low environmental or indoor air quality, exacerbate susceptibility to disease and climate change [24]. Studies have shown that the coronavirus has increased individual anxiety and risk perceptions of disease infection [25,26] and that climate change perceptions are indeed changing [25]; therefore, it is essential to understand how these perceptions vary across income groups to build societies resilient to pandemics and climate change [27]. Hence, this paper aims to investigate the differences in three income groups’ (e.g., low, medium, and high) energy usage patterns, utility bills (including electricity, water, and gas), climate change perceptions, social-psychological and economic factors, and household characteristics that influence residents’ willingness to adopt and pay for HEMS. The issues examined in this paper are critical during and after the pandemic.

1.1. Benefits of home energy management systems (HEMS)

Energy assistance programs designed to help LIHs tend to focus on immediate bill assistance rather than the planning of dwelling, appliance, and energy-behavior improvements. Energy efficiency programs that address these issues are often inefficient for LIHs because of accessibility challenges such as time, language barriers, and renter status [28,29]. Alternatively, HEMS can be especially beneficial for LIHs in the long run, as LIHs are more likely to live in energy inefficient dwellings and have older, inefficient appliances.

A HEMS consists of hardware and software that manage and optimize energy use, maintain thermal comfort, and provide feedback to customers to change energy behavior [30,31]. For instance, displaying energy costs in real-time can reduce energy consumption by up to 15% [5,32]. Additionally, HEMS are part of the smart home concept and considered the next step in everyday life’s electrification process [33]. The main benefits of HEMS include financial savings for users and utility providers, local renewable energy production, smart grid connections, and diachronic energy use comparisons [34]. HEMS can also facilitate demand response (DR) programs that change customer electricity use patterns through time-dependent pricing schemes [35,36]. These programs have the potential to lower electricity prices by over 20% under certain conditions [37], enhance energy efficiency [38,39], reduce residential peak demand by nearly 30%, store unused energy for later [37,40], and contribute to decarbonization efforts. HEMS also have several non-energy consumption-related benefits, including home security monitoring [41,42], telemedical and senior assistance services [43], and job search features [42,44]. Additionally, HEMS can deliver community updates and social networks, provide entertainment [45], and warn of potential storms or dangers in the area [46]. More importantly, HEMS are useful to reduce LIH energy burdens [47], as energy prices, building and appliance inefficiencies, and behavioral patterns most often cause high energy burdens.

1.2. Social-psychological and economic factors influencing technology adoption

Understanding households’ motivation to integrate new technology into their daily lives is critical to deploying HEMS, and requires the knowledge of functionally and socially constructed benefits [42]. The Theory of Planned Behavior (TPB) model highlights that an individual’s attitudes, social norms, and perceived behavioral control (PBC) can influence intention to perform a target behavior. Attitudes are (un) favorable evaluations of the perceived benefits and risks, social norms are perceived social pressures from important others [48,49], and PBC is the ease or difficulty in performing a behavior [50]. However, studies show that people are interested in adopting HEMS but are not necessarily willing to pay (WTP) [51,52], as there are different motivating factors between adoption intention and WTP. For instance, overall barriers to technology adoption include a perceived lack of usefulness [53] or ease of use [54], technology anxiety [55], and renter status [56]. In contrast, WTP considers more practical factors like associated costs [57,58]; reference price, or the price the offered price is compared to [59]; and expected quality [60]. However, some studies have found cost was not related to technology adoption [25]; thus, further research is needed to confirm the relationship between costs, WTP, and adoption intention.

Other social-psychological factors, such as trust and risk perceptions, are important, as trust in organizations related to HEMS technology, such as utility service providers, can influence adoption intention [25,42,61]. Individuals with high trust tend to have more positive evaluations of a behavior, which is mediated by perceived fairness in the distribution of costs, risks, and benefits, especially when no other trust-relevant information is available [48,61]. The pandemic also brings new sources of stress for LIHs that can be worsened by energy burdens and risk perceptions in contracting the virus. Studies on risk perception have shown that people with low incomes, autoimmune diseases, or who use public transportation perceived a higher COVID-19 infection risk [21].

Demographic groups also consider different factors for adoption intention and WTP for various new technologies [25,62]. Therefore, this study examines the connection between demographics (income, gender, age, physical ability, etc.) and technology adoption. Challenges different demographics experience and the choices households make in regards to their energy use are compounded by the coronavirus pandemic; therefore, we focus on the socio-technical perspective, considering the social-psychological, policy, and demographic barriers to HEMS adoption during the pandemic [63–66].

1.3. Theoretical frameworks

This study uses an energy justice framework to examine income differences in energy use and related perceptions during the early stages of the COVID-19 pandemic, while integrating two additional theories, the Theory of Planned Behavior (TPB [49]) and Technology Acceptance Model (TAM [50]), to examine specific variables relating to our research questions. The energy justice framework applies social justice concepts
to energy policy by evaluating costs and how they are unequally imposed, benefits and how access to systems are uneven, and procedures and how they lack due process and representation, especially for poor and marginalized communities [67,68]. It is mindful of social, cultural, racial, and gender differences and works to make those different perspectives heard in decision-making processes [68]. Partly, energy justice is concerned with energy insecurity, which is the risk of water, gas, electricity, or internet disconnection due to an inability to meet utility costs, and energy access, which is the lack of access to quality utilities, internet services, and energy efficient technology [9]. Issues of energy justice are not specific to income inequalities, but education, employment, housing, disability, racial disparities, inadequate utility services, and unequal distribution of the benefits of utility and internet services. Therefore, this study includes a diverse sample and examines how the income groups based on demographics like age, gender, occupation, and household size differed in their perceptions and attitudes.

To understand the social-behavioral factors and technological attributes facilitating or inhibiting different income groups’ HEMS adoption intention and WTP, this study utilizes two technology adoption theoretical models: (1) the TAM, which considers variables such as perceived usefulness, ease of use, and cost, and (2) the TPB, which highlights the impacts of attitudes, social norms, and perceived behavioral control (PBC) on a target behavior. The TAM explains the factors that influence technology adoption and usage to argue that the easier and more useful a technology seems to individuals, the more likely they will adopt and use that technology [25,42,50]. The TPB argues that social-psychological factors influence behavioral intention, which is formed by evaluating a specific behavior (attitudes), the expectations of significant others, such as friends and family (social norms), and the perceived ability to perform a behavior (perceived behavioral control, PBC) [49,69]. This study also extends the TPB by examining other social-psychological and economic variables, including personal norms (one’s moral beliefs and values), COVID-19 risk perceptions, perceptions of climate change severity, cost concern, and relationships with utility service providers. Both the TAM and the TPB deal with factors influencing technology adoption and behavioral change, and when combined, have more explanatory power for understanding residents’ willingness to adopt and pay for HEMS during the pandemic [25,42], as well as other energy usage patterns and attitudes.

### 1.4. Purpose of this study

The market for HEMS technology is expected to grow exponentially in the coming years [70], particularly as the market of other technologies continues to mature, such as electric vehicles, solar photovoltaics, and battery storage [71]. This study attempts to examine several empirical questions by exploring different income groups’ energy patterns, climate change perceptions, utility cost, and energy burdens. To better help LIHs overcome energy burdens and implement HEMS, we must understand how energy consumption has increased and time of electricity use has changed, as LIHs likely have unique consumption load profiles and stay-at-home and energy practices compared to other income groups. Therefore, understanding the differences between income groups’ energy practices will better inform the role that HEMS can play in facilitating DR programs or improving overall energy efficiency during and after the pandemic.

Since HEMS can play a critical role in reducing energy consumption for LIHs, we also examined income differences in willingness to adopt and pay (WTP) for different HEMS features during the pandemic, because stay-at-home mandates have increased the importance of household environment improvements (e.g., thermal comfort, indoor air quality) and home-based activities. This study investigated both adoption intention and WTP because they reflect different driving factors and need to be considered together to better estimate actual adoption behaviors [42,72]. This paper also contributes to the recent emphasis on energy justice. In doing so, this paper draws from the evidence in HEMS literature and adopts an energy justice framework, the extended TPB, and the TAM to propose an integrative, socio-technical approach to addressing the multi-dimensionality of technology adoption and WTP during the pandemic. These findings can be applied outside of the pandemic to contribute to greater diffusion of renewable technology across income groups, as well as contribute to the growing body of energy justice literature. This research emphasizes the interaction between demographics, technology attributes, and social-psychological and economic factors by using a unique set of 632 household survey responses during quarantine mandates in New York. Specifically, we ask the following research questions:

- “Are there any changes in time of electricity use, energy consumption behavior, perceived COVID-19 risk infection, and climate change perceptions across income levels?”
- “How do low-, medium-, and high-income households differ in their perceived energy usage and utility bills (including electricity, water, and gas)? Did low-income groups have significant energy burdens during the early months of the pandemic?”
- “How do low-, medium-, and high-income households differ in their intentions to adopt and pay for different features of HEMS?”
- “How do low-, medium-, and high-income households differ in their social-psychological factors, perceived technology attributes, and demographics?”

### 2. Methods

Using Qualtrics Panel Services, this study distributed an online survey (n = 632) in March 2020 to sample the residents of the greater New York metropolitan areas using quotas based on income and gender representations in New York areas. At the beginning of the COVID-19 outbreak, New York was one of the most severely infected areas. As of early May 2020, nearly one-third of known U.S. cases were in New York state, while more than half of the state’s cases were in New York City [73], due to New York City’s dense population.

#### 2.1. Survey design and measurement

Our survey consisted of four parts. First was a brief explanation of the basic energy-related functions of HEMS, followed by questions on participants’ willingness to adopt and pay for HEMS. Three questions were about specific HEMS energy features: monitoring energy, controlling appliances, and reducing community environmental impacts during the pandemic. Another three questions were regarding well-being features during the pandemic, including telemedical services, community updates and social networking, and job search features. Second, the survey asked questions about the perceived risk of COVID-19 infection, time of electricity use, energy usage, utility bills, and climate change issues (e.g., air pollution, effects on food and water systems, and climatic events [74]) during the pandemic. Third, the survey measured a set of social-psychological and economic variables (i.e., attitudes, social and personal norms, PBC, cost concern), perceived technology attributes (i.e., perceived ease of use, perceived usefulness, technology anxiety), and perceived relationships with service providers (i.e., trust in utilities and cybersecurity concerns). These social-psychological and technological variables were based on previous HEMS research [42]. Finally, the survey also collected demographic information (i.e., age, gender, income, political orientation) and household characteristics (i.e., dwelling type, homeownership, household size). All measures except for WTP and demographics and household information were based on a 5-point Likert scale, where one indicates “strongly disagree,” “very unlikely,” or “never,” and five indicates “strongly agree,” “very likely,” or “very often”. The WTP questions were measured on a 9-point scale from 0, meaning “not willing to pay” to 8, indicating “$7 or above”, with a consistent one-dollar intervals.
2.2. Participants

Among the 632 participants, 50% were female, and 50% were male, similar to the New York City population (52.3% and 47.7%, respectively) [75]. Most participants (42.9%) were between 40 and 59, 38.8% were under the age of 40, and 18.4% were 60 years old or older. Most participants had an annual household income of $100,000 or more (31%), followed by $50,000-$99,999 (30.4%), less than $35,000 (28%), and $35,000-$49,999 (10.6%). Based on New York income tax data from 2017, our sample is representative, as 32% of New York City residents make less than $35,000 a year, 10.4% make between $35,000-$49,999, 25.6% make between $50,000-$99,999, and 31% make more than $100,000 [76]. Most participants identified as Democrat (43%), followed by Republican (29.6%), Independent (21.4%), and apolitical or other (6%). Approximately 58.9% owned their place of residence, while 39.2% lived in single-family detached houses, own- tions were more likely to have higher incomes. High-income people and income groups (Table 1). The chi-square test of independence is a non-parametric test to determine whether there is an association between categorical variables. A chi-square value is calculated based on

2.3. Chi-square tests on the sample

Chi-square tests of independence were performed to examine the relationship between various demographics, household characteristics, and income groups (Table 1). The chi-square test of independence is a non-parametric test to determine whether there is an association between categorical variables. A chi-square value is calculated based on the differences between observed counts and expected counts (assuming no association) in each condition; if the chi-square value is statistically significant, then the two categorical variables are related [77].

All the examined variables were statistically significant. Men, Republicans, 40-59-year-olds, and management or professional occupations were more likely to have higher incomes. High-income people were also more likely to live in single-family detached houses, own rather than rent their place of residence, and have larger homes in terms of square footage and household size.

3. Results

3.1. Purpose of analysis

The pandemic has altered the daily routine and energy usage of many households. By the summer of 2020, 42% of the U.S. labor force worked from home full-time, while about 33% were not working [78]. Many children also attend virtual lessons at home. Residential electricity usage patterns have changed dramatically as a result. Therefore, our analyses were conducted to address the research questions with these broad purposes in mind: first, to provide timely energy behavioral information to energy sectors, such as utility providers and urban planners; second, to foresee potential problems, such as energy burdens, and to mitigate potential conflicts with companies and institutions; and third, to identify opportunities in improving home and energy infrastructure through HEMS. Specifically, descriptive statistics serve the following purposes: 1) to provide basic distribution information of variables (mean, variance, standard deviation, skewness, etc.) and 2) to highlight potential

Table 1

| Demographic Variables | Income Groups n (%) | Chi-square |
|-----------------------|---------------------|------------|
|                       | Low | Medium | High |        |          |
| Gender                |     |        |      |        |          |
| Female                | 102 | 148    | 66   |       | \(\chi^2\) = 30.302*** |
| Male                  | 75  | 111    | 130  |       |          |
| Occupation            |     |        |      |        |          |
| Management or professional | 17    | 85     | 104  | \(\chi^2\) = 100.206*** |
| Clerical, sales, or services  | 29    | 41     | 27   |          |
| Security, agriculture, production, drivers, construction, or transportation | 12 | 30 | 13 |          |
| Renter vs. Owner Status |    | 15     | 14   | (8.6%) | (5.5%) |
| Political orientation |     |        |      |        |          |
| Democrat              | 77  | 111    | 84   | \(\chi^2\) = 22.999*** |
| Independent           | 47  | 53     | 35   |          |
| Republican            | 35  | 78     | 74   |          |
| Apolitical            | 15  | 14     | 3    | (1.5%) |          |
| Age                   |     |        |      |        |          |
| Under 40 years old    | 67  | 112    | 66   | \(\chi^2\) = 34.956*** |
| 40–59 years old       | 66  | 91     | 114  |          |
| 60 years old or more  | 44  | 56     | 16   | \(\chi^2\) = (21.6%) | (8.2%) |
| Household Size        |     |        |      |        |          |
| 1 to 2 people         | 117 | 140    | 38   | \(\chi^2\) = 91.793*** |
| 3 to 4 people         | 47  | 96     | 131  |          |
| 5 or more people      | 13  | 23     | 27   | (7.3%) | (13.8%) |
| Housing Type          |     |        |      |        |          |
| Single-family detached | 58    | 132    | 121  | \(\chi^2\) = 48.254*** |
| Single-family attached | 14    | 24     | 29   |          |
| Wooden co-residence with 2 stories | 25    | 15     | 3    | (15.5%) | (7.3%) |
| Reinforced concrete with 2 stories | 64    | 76     | 35   |          |
| Renter vs. Owner Status |     |        |      |        |          |
| Non-owner             | 126 | 100    | 32   | \(\chi^2\) = 118.219*** |
| Owner                 | 49  | 159    | 162  |          |
| Owner                 | 49  | 159    | 162  |          |
| Size of Residence     |     |        |      |        |          |
| Less than 1999 square feet | 109    | 128    | 57   | \(\chi^2\) = 96.728*** |
| 2000 to 3999 square feet | 16    | 69     | 96   |          |
| 4000 square feet or more | 3 (2.3%) | 22 | 35 | (9.6%) | (18.6%) |

*p < .05, **p < .01, ***p < .001.
relationships between variables for further analysis [79,80], followed by chi-square tests and analysis of variance (ANOVA).

The results of this paper are presented across five themes. The first and second themes include descriptive statistics of time of electricity use, estimated electricity use, utility bill, COVID-19 infection risk perception, climate change perceptions, and energy burdens. The third theme explores income group differences in intention to adopt HEMS energy and well-being features, followed by the fourth theme on WTP for different HEMS features. The final theme analyzes different income groups’ social-psychological and economic factors, perceived technology attributes, cybersecurity concern, and perceived relationships with services providers. The ANOVA and chi-square tests were conducted for inferential statistics. Specifically, ANOVA was used to test the significance of the differences among sample means in terms of an F distribution, whereas chi-square test of independence determines whether the differences among several sample proportions were significant or not [81].

3.2. Time of electricity use and perceived energy use

Overall, our sample indicates that electricity use began to increase significantly between the hours of 4:00–5:59 a.m. and leveled off at 10:00–11:59 a.m. in March and April 2020 (Fig. 1). Electricity usage continued to rise slightly until it reached peak consumption level at 5:59 a.m. in March and April 2020 (Fig. 1). Electricity usage from the absence of electricity usage before the pandemic lockdown, a significant portion of respondents (48.6%) perceived either higher or much higher electricity use, and 40.8% rated their usage as about the same (Fig. 2). The ANOVA test shows that income groups significantly differed in perceived energy usage, F (2,629) = 6.305, p < .01. Post-hoc analysis revealed that HIHs were more likely to report higher energy use during the pandemic (M = 3.62, SD = 1.02) than LIHs (M = 3.29, SD = 0.76) and MIHs (M = 3.40, SD = 0.90). There was no difference between low- and medium-income households. Based on this perception, we further examined utility bills and other indicators of energy burdens.

3.3. Analysis of utility bills, energy burdens, and heating and cooling needs

A chi-square test was conducted to examine the relationship between income and utility bills (Fig. 3). Utility bills in February 2020 were categorized into thirteen levels, ranging from $80 or less to $300 or more. Utility bills were significantly different by income levels, χ² (24, N = 632) = 93.346, p < .001. Most LIHs (39.5%) paid less than $80 for their February utility bill, 12.4% paid $100-$109, 11.9% paid between $80-$89, and 9.6% paid between $110-$124. The utility bill of MIHs was most often less than $80 (24.7%), followed by $100-$109 (13.9%), $90-$99 (11.6%), and $110-$124 (11.6%). The HIHs had the widest range of bill costs and most frequently reported paying $100-$129 (15.8%), $90-$99 (11.2%), $110-$124 (10.7%), and less than $80 (9.7%). Overall, HIHs’ utility bill costs were higher than other income groups, with 23.1% of the HIHs paying more than $200 a month. In comparison, only 3.1% of LIHs and 8.9% of MIHs paid more than $200. The fact that the HIHs had larger homes and more people living in their households could have contributed to a higher bill. To further examine energy bills concerning income level, we analyzed each income groups’ average energy burdens.

Energy burdens were estimated from participants’ reported electric utility bills for February 2020 divided by their monthly household income. For simplicity, we combined the thirteen levels of utility bills into five groups: $99 or less, $100–149, $150–199, $200–249, and $300 or more. The average of the energy burdens experienced by different income groups was then calculated. There was a negative relationship between income and energy burdens (Table 2): low-income and lower-middle-income participants were more likely to spend a higher proportion of their income on utilities. Specifically, the average energy burdens were 4.01% for LIHs, 3.57% for lower-middle, 2.54% for upper-middle, and 1.85% for high-income households. Based on our demographic analysis, LIHs more often contained people over 65 and people with disabilities or medical needs that affected heating and cooling. For example, 13% of our low-income participants reported their medical conditions affected heating and cooling equipment use, whereas only 3% of medium- and 3% of high-income participants reported so. These groups with medical needs are also known for having high energy...

![Fig. 1. Time of electricity use in New York areas in March and April 2020.](image-url)
burdens due to many factors like housing inefficiencies, low wages, and prioritization of other needs [1,83]. Still, participants in this study were not experiencing this high burden level, at least in February 2020.

### 3.4. Perceived COVID-19 risk inflection and climate change perceptions

According to chi-square test results, COVID-19 risk perception differed significantly across income groups, $\chi^2 (12, N = 632) = 42.083, p < .001$. Most low-income participants (38.4%) perceived less than 1% chance of infection, compared to only 17.4% of medium- and 16.8% of high-income participants (Fig. 4). Similarly, 31.6% of low-income participants perceived 21% or more risk, compared to 44.0% of medium- and 46.4% of high-income participants. This indicates low-income participants had lower perceived risk than MIHs or HIHs. This finding is consistent with another study suggesting LIHs are less concerned with contracting the virus and more concerned with dying from it [84]. Differences in risk perception could be due to the awareness of each groups’ relative risk in life; for example, LIHs have poorer health outcomes compared to other households, and therefore, could feel getting sick is inevitable. Additionally, increased worry of dying from the coronavirus may be a reflection of the inequities in the American healthcare system [84].

### Table 2

February 2020 energy burdens by income group.

| Utility Bill | Income - energy burdens (% of participants) |
|--------------|---------------------------------------------|
| $99 or less  | Low (3.90) | Lower-Medium (59.30) | Upper-Medium (59.30) | High (27.00) |
| $100-$149    | 4.27 (30.50) | 3.75 (29.90) | 2.39 (3.80) | 1.49 (34.70) |
| $150-$199    | 5.98 (6.80) | 5.21 (6.00) | 3.29 (16.70) | 2.09 (15.30) |
| $200-$249    | 7.70 (2.30) | 6.69 (3.00) | 4.19 (3.60) | 2.69 (12.20) |
| $250-$299    | 9.41 (2.0) | 8.13 (0) | 5.09 (2.10) | 3.29 (6.60) |
| $300 or more | 10.29 (1.10) | 8.74 (3.00) | 5.40 (4.20) | 3.60 (4.10) |

Fig. 2. Energy use perceptions during COVID-19 by income group.

Fig. 3. February 2020 utility bills in US dollars by income group.
Climate change perception also differed significantly across income groups, \( \chi^2 (8, N = 632) = 21.888, p < .01 \). The low-income group more often thought climate change issues in March and April, 2020 were the same or worse than before, compared to the MIHs and HIHs (Fig. 5). Over 42.4% of high-income participants thought climate change was a little or much better than before, compared to 33.9% of medium-income and 25.4% of low-income participants. Each income group had similar percentages of participants who thought climate change was a little or much worse: 22.6% of low-income, 22.0% of medium-income, and 21.9% of high-income participants. Over half of the low-income participants (52.0%) thought climate change was the same, compared with 44.0% of medium- and 35.7% of high-income participants. When income groups were combined, most participants (43%) indicated that climate change was about the same, 22% indicated it was much worse or a little worse, and 34% indicated better or much better.

Additionally, we conducted several linear regression models to determine the influence of COVID-19 risk and climate change perceptions on HEMS adoption and WTP. Risk perception was positively related to adoption of HEMS energy (\( B = 0.13, p < .001 \)) and well-being features (\( B = 0.14, p < .001 \)), as well as positively related to WTP for energy (\( B = 0.11, p < .001 \)) and well-being features (\( B = 0.15, p < .001 \)). Climate change perceptions, however, were not a significant predictor of adoption or WTP; this may be because participants do not perceive climate change issues as linked to their adoption of HEMS to reduce energy consumption. Yet, our findings may also reflect participants with greater perceived risk of infection staying home to avoid infection and viewing HEMS as beneficial to offset their increased energy consumption.

3.5. HEMS adoption intention

There were significant differences across the income groups in willingness to install a HEMS in the future if the installation was free, \( F (2,629) = 29.997, p < .001 \). Post-hoc tests showed that low-income participants were less willing to adopt HEMS (\( M = 3.46, SD = 1.14 \)) than medium- (\( M = 3.80, SD = 1.12 \)) and high-income participants (\( M = 4.30, SD = 0.84 \)). The medium-income group was less willing to install than the high-income group.

For the adoption of HEMS’ well-being features (telemedical, community updates/social networking, and job search) during the pandemic, there were also significant differences across the income groups, \( F (2,629) = 23.720, p < .001 \). Post-hoc tests revealed that income levels significantly differed in the intention to adopt telemedical services, with the high-income participants being the most willing to adopt (\( M = 4.04, SD = 1.13 \)) followed by the medium- (\( M = 3.75, SD = 1.22 \)) and low-income participants (\( M = 3.36, SD = 1.24 \)). On the community update/social networking and job search features, high-income participants (\( M = 4.03, SD = 1.09; M = 3.57, SD = 1.34 \)) had
significantly higher intention to adopt than medium-income participants (M = 3.58, SD = 1.23; M = 2.97, SD = 1.47), who were more willing to adopt than low-income participants (M = 3.41, SD = 1.23; M = 2.81, SD = 1.33). In general, participants were most willing to adopt the telemedical feature (M = 3.73, SD = 1.23) and least willing to adopt the job search feature (M = 3.11, SD = 1.42).

### 3.6. WTP for energy and well-being features

In addition to understanding adoption intention, we also consider how much participants would be willing to pay for different HEMS features. While our survey questions about adoption intention asked how likely participants were to use each service in everyday life, WTP questions asked participants to indicate how much they were willing to pay for each service per month. In this section, we investigated income group differences in WTP for three energy features, which are, respectively, monitoring electricity use, controlling appliances, and reducing community environmental impacts during the pandemic (Fig. 6), as well as three well-being-promoting features of telemedical, community updates and social networking, and job search (Fig. 7). To simplify, we combined the nine WTP categories into four groups: $0.01-$1.99, $2.00-$3.99, $4.00-$5.99, and $6.00 or more.

For the monitoring electricity feature, there was a significant relationship between WTP and income, F (2,629) = 46.866, p < .001, with low-income participants willing to pay the least (M = 2.46, SD = 2.46), followed by medium- (M = 3.24, SD = 2.53) and high-income participants (M = 4.90, SD = 2.54). The relationship between WTP for control appliance feature and income was significant, F (2,629) = 43.245, p < .001; low-income participants were willing to pay the least (M = 2.55, SD = 2.50) compared to medium- (M = 3.37, SD = 2.57) and high-income participants (M = 4.95, SD = 2.57). The relationship between reducing community environmental impacts and income was also significant, F (2,629) = 54.161, p < .001. Low-income participants were willing to pay less (M = 2.47, SD = 2.57) than high-income participants (M = 5.09, SD = 2.59), who were willing to pay more than the medium-income participants (M = 3.15, SD = 2.54).

The WTP for the telemedical feature differed significantly across income groups, F (2,629) = 43.867, p < .001. The low-income group was willing to pay the least (M = 2.29, SD = 2.41), followed by the medium- (M = 2.93, SD = 2.47) and high-income groups (M = 4.61, SD = 2.64). The relationship between WTP for community updates and social networking feature and income was significant, F (2,629) = 39.204, p < .001. High-income participants were willing to pay the most (M = 4.20, SD = 2.72), compared to low- (M = 2.13, SD = 2.26) and medium-income participants (M = 2.46, SD = 2.48). The low- and medium-income groups, however, did not significantly differ from each other. Similarly, the relationship between WTP for the job search feature and income was significant, F (2,629) = 24.094, p < .001; high-income participants were willing to pay the most (M = 3.55, SD = 2.44) compared to low- (M = 2.03, SD = 2.37) and medium-income participants (M = 2.02, SD = 2.44), who were not significantly different from each other.

Regarding specific dollar amount, the majority of low-income participants (38.7%) were willing to pay $0.01-$1.99 for monitoring energy usage, while most medium- (31.2%) and high-income participants (40.9%) were willing to pay $4.00-$5.99 a month. Similarly, to control appliances and reduce community environmental impact, most low-income participants (32.8% and 35.7%, respectively) were willing to pay $0.01-$1.99, while most medium- (33.5% and 29.1%) and high-income participants (39.8% and 41.9%) were willing to pay $4.00-$5.99. For telemedicine, most low- (46.7%) and medium-income participants (32.3%) were willing to pay $0.01-$1.99, and most high-income participants (34.3%) were willing to pay $6.00 or more a month, indicating the perceived usefulness of telemedicine. For community updates and social networking, the majority of low- (41.2%) and medium-income participants (35.8%) were willing to pay $0.01-$1.99, while most high-income participants (32.5%) were willing to pay $4.00-$5.99. Lastly, for job search features, most low- (36.3%) and medium-income participants (40.7%) were willing to pay $0.01-$1.99, while
most high-income participants were willing to pay $4.00-$5.99. It is likely that because the well-being features are still not widespread, there is little reference in pricing, which could have pushed our participants to the conservative side when reporting their WTP.

3.7. Comparisons of social-psychological variables, perceived technology attributes, and relationships with service providers

This section presents the results of the different factors related to HEMS technology adoption, such as social-psychological factors, perceived technology attributes, and the relationship participants have with their utility providers.

ANOVA results revealed significant differences in social norms across income groups, \( F(2,629) = 33.152, p < .001 \). Post-hoc tests showed that low-income participants regarded their neighbors’, friends’, and family members’ opinions on whether they should install a HEMS as less critical (\( M = 3.06, SD = 1.04 \)) than high-income participants (\( M = 3.89, SD = 0.94 \)). Low- and medium-income (\( M = 3.30, SD = 1.09 \)) groups did not significantly differ from each other. Personal norms also differed significantly across income groups, \( F(2,629) = 10.659, p < .001 \). Low-income participants tended to feel less morally obligated to save energy and less guilty for not reducing their energy usage (\( M = 3.77, SD = 0.92 \)) than medium-income participants (\( M = 3.97, SD = 0.80 \)), who, in turn, had lower personal norms than high-income participants (\( M = 4.15, SD = 0.66 \)). However, high income is not often associated with higher social or personal norms, probably because high-income people tend to be less egalitarian and less likely to act in pro-social ways [85, 86]. Other factors are likely to mediate the relationship between income and social and personal norms, such as PBC, which was also significantly different among the income groups, \( F(2,629) = 26.708, p < .001 \). Post-hoc tests revealed that low-income participants reported the lowest PBC in using a HEMS of the three groups (\( M = 3.34, SD = 1.05 \)), medium-income participants were in the middle (\( M = 3.74, SD = 0.97 \)), and high-income participants had the highest (\( M = 4.06, SD = 0.81 \)). These higher income households often have greater access to the conditions that facilitate HEMS adoption and use, such as time, financial, linguistic, and housing factors [50], which may explain why medium- and high-income participants had higher PBC. Cost concern was not affected by income levels, indicating people have similar cost concerns, which is consistent with previous findings [25].

As for perceived ease of use, income had a significant effect, \( F(2,629) = 17.561, p < .001 \). Low- (\( M = 3.63, SD = 0.93 \)) and medium-income (\( M = 3.80, SD = 0.85 \)) participants tended to perceive HEMS to be more difficult to use than high-income participants (\( M = 4.12, SD = 0.69 \)). The relationship between perceived usefulness and income was also significant, \( F(2,629) = 13.623, p < .001 \), with the low- (\( M = 3.79, SD = 0.89 \)) and medium-income group (\( M = 3.95, SD = 0.82 \)) perceiving HEMS to be less useful than the high-income group (\( M = 4.21, SD = 0.66 \)). The results did not show a significant effect on technology anxiety. In part consistent with our findings, other studies have shown that LIHs are more likely to have a hard time using technology and find it less useful [41, 54].

Trust in utility providers pre-pandemic differed significantly across income groups, \( F(2,629) = 17.978, p < .001 \). Low- (\( M = 3.66, SD = 0.92 \)) and medium-income participants (\( M = 3.75, SD = 0.79 \)) were less likely to trust their utility provider (\( M = 3.66, SD = 0.92 \)) than high-income participants (\( M = 4.04, SD = 0.72 \)). During the pandemic, trust in utility providers also varied significantly across income groups, \( F(2,629) = 11.753, p < .001 \). Similarly, low- (\( M = 3.47, SD = 0.99 \)) and medium-income participants (\( M = 3.60, SD = 0.82 \)) were less likely to trust their utility providers than high-income participants (\( M = 3.97, SD = 0.75 \)). Trust in utility providers was overall lower during the pandemic than pre-pandemic, regardless of income. High-income participants may have higher levels of trust due to lower perceived risk and greater perceived benefits of HEMS adoption [48]. Lastly, cybersecurity concerns did not significantly differ across income levels.

4. Discussion

This research has identified five main takeaways: First, COVID-19 risk perceptions differed significantly across income levels. While the overall perceived COVID risk was low, LIHs had the lowest perceived risk, despite LIHs having a higher risk of actual infection [87]. One study suggests that low-income individuals in the U.S. were more concerned with dying from the virus than getting sick [84]. Additionally, during economic hardship and environmental disasters, LIHs tend to have higher rates of mental and physical distress, fewer resources to respond to disasters appropriately, and more concerns on their plate than just the disaster [23]. In the context of COVID-19, LIHs are likely to have more worries about their loss of income, paying bills, buying food, etc., than if they will get the virus. However, the reasons behind the differences in perceived risk are beyond the scope of this study. Future research would benefit from revealing the potential underlying factors.

Second, the COVID-19 pandemic has impacted how people view climate change issues. HIHs more often felt climate change was better than six months before March, 2020 than other income groups, likely due to the reports around the world of carbon emission reductions in urban hotspots [88] or depictions of empty beaches, rivers, and towns resulting in clearer waters and wildlife sightings [89]. Besides, in our study, over 37% of HIHs identified as Republican, and previous studies have found those with politically-right leaning views are more likely to reject mainstream climate science [90]. This could explain why some HIHs in our study perceive climate change as getting better, despite the de-prioritization of climate-related issues due to the health crisis and possible post-pandemic rebound effects with even higher emissions [88, 91]. Alternatively, LIHs and minorities are more likely than others to experience the direct impacts of climate change [92], and live in disaster-prone areas, but less likely to have the knowledge and materials to respond to climate disasters effectively [23]. LIHs may be aware of environmental impacts, while HIHs can distance themselves from the causes and consequences of climate change; for example, HIHs could perceive themselves as practicing more social distancing and consuming less energy in the workplace, which reduces their carbon footprint.

Third, overall positive relationships exist between income and HEMS adoption and WTP; MIHs and HIHs tended to be more willing to adopt and pay a higher price for different HEMS features than LIHs. We found that LIHs perceived HEMS to be less useful and harder to use than other groups, which may explain why they were not willing to adopt a HEMS, even if the installation fee were free. Other factors, such as housing barriers, lack of knowledge and awareness, trust in utility providers, or technology anxiety may also explain LIHs’ low adoption intention [5, 10, 25]. Additionally, MIHs were willing to pay more for the energy features than for the well-being features, suggesting a greater perceived value of energy features, possibly due to well-being features being newer and less emphasized in HEMS-related literature and policy. On the other hand, HIH’s high WTP for telemedical indicates the importance of this service. It is possible that HIHs had a higher perceived risk of COVID-19 infection, and they placed more value on this service. Additionally, most LIHs are either uninsured or covered by Medicaid [93], which does not guarantee coverage of telemedical services, even during the pandemic [94]. Without insurance to cover some of the costs of telemedical, LIHs are less likely to be able to use this feature, leading to a lower perceived value of HEMS.

Fourth, there is a disconnect between intention to act pro-environmentally and actual pro-environmental behavior. While HIHs in this study felt the most morally obligated to save energy, they also reported having the highest utility bills, highest perceived energy use during the pandemic, and perceived better climate change during the pandemic than the non-pandemic. These results suggest there is intent to be environmentally conscious, but the actions of HIHs do not necessarily reflect that. Scholars argue that people see the connection between human activity and climate change when explicitly asked about it [95, 96], but our results indicate that it is more complicated. For instance,
when behavioral costs are low and require less efforts, people are more likely to engage with some targeted behavior [90]. HIHs have more financial and physical resources than LIHs, so saving energy is behaviorally easier for them. Additionally, HIHs are more likely to work from home, thereby reducing their carbon footprint by cutting transportation and workplace energy use; therefore, they might not feel the need to reduce energy use at home, which could also influence their climate change perceptions. It’s possible when people act sustainably in one way, it legitimizes them not acting sustainably on other occasions [97, 98]; however, further research is needed to confirm this relationship.

Fifth, trust in utility service providers impacts energy-saving and technology adoption behavior. Our findings show that all income groups show lower trusting levels of their utility providers during the pandemic than before, but LIHs had lower trust than other households. This finding indicates that utility providers were not meeting the expectations of LIHs, and this situation has only worsened during the pandemic. In previous research, trust in utility providers has been associated with the acceptance of smart grid technology [99], sustainable energy technology [48], and smart meters [100,101], as individuals with high levels of trust tend to have more positive evaluations of the behavior and are more willing to adopt. Our HIHs were more willing to adopt HEMS and had higher levels of trust, suggesting that trust in utilities play a role in adoption intention.

4.1. Limitations and future research

Despite the unique findings, this study has several limitations. The survey was distributed in the early stages of the pandemic (March and April, 2020); therefore, residents’ perceptions, opinions, and attitudes may have changed since businesses and schools reopened after the lockdown. Additionally, our survey is only limited to New York City and the surrounding areas; therefore, future research would benefit from expanding this research to other cities to compare results from different samples. More importantly, qualitative methods such as interviews or focus group discussions could elucidate the reasons for underserved communities’ concerns about HEMS and further explore issues that have not been discussed here.

5. Policy implications and conclusion

Overall, this research provides policy implications and research directions for considering energy justice and vulnerability in implementing energy efficiency programs, HEMS, and smart home technology. We highlight the following essential suggestions:

First, policymakers and utility companies need to recognize the energy burdens and efficiency challenges that vulnerable populations face. HIHs are more likely to own energy-efficient appliances and have more income to spend on utility bills and home insulation than LIHs. Energy efficiency improvements would be most beneficial to LIHs in the long run. Our findings suggest LIHs are interested in HEMS adoption but cannot afford it, and are more likely to perceive HEMS attributes negatively (e.g., less useful, easy to use, and PBC) than other income groups. A successful energy justice approach to energy policy requires restorative justice measurements that acknowledge and work to rectify past harms faced by LIHs [8,102], such as leaving LIHs out of decision-making processes, charging late fees, or shutting off services for late payments, and so on. Therefore, LIH energy-related policy needs to focus on: 1) affordability of technology, maintenance costs, utilities, etc.; 2) accessibility to resources, supplies, technology, education, and energy efficiency programs; and 3) taking responsibility for any (un)intentional past harms through policies that actively works to remedy these harms (e.g., bill assistance, retrofits, LIH-specific policy), and 4) promoting unique technology design and tailored programs for LIHs.

Second, researchers and developers need to consider consumers’ social-psychological factors, lifestyles, behavioral patterns, and household routines to reduce LIHs energy burdens through HEMS [9,55], rather than merely considering economics and technology in decision-making processes. For instance, LIHs perceived HEMS to be harder to use and less useful (Table 3), yet still indicated their willingness to adopt HEMS. Additionally, there is a need to understand how energy consumption load profiles are changing and how to alter DR programs in response to future extreme weather events or pandemics. Third, utility providers should improve their relationship of trust with LIHs to increase HEMS and related smart grid technology adoption. One of the most important steps is to increase transparency and accountability [5,102]. Additionally, utilities need to provide grace and leniency to families financially impacted by the COVID-19 pandemic. While moratoriums assure that utilities will not be shut-off, the most prominent challenge families face post-pandemic is debt accumulation.

Table 3

| Variable Name | Income groups (Mean, SD) | F ratio |
|---------------|--------------------------|---------|
| **COVID-19 related perceptions** | | |
| Perceived energy usage | (3.29, 0.764) | (3.40, 0.989) | (3.62, 1.024) | 6.305*** |
| Perceived risk of infection | (2.77, 1.962) | (3.39, 1.902) | (3.20, 1.841) | 8.222*** |
| Climate change comparison | (2.99, 0.997) | (3.12, 1.001) | (3.30, 1.055) | 4.191* |
| **HEMS adoption intention** | | |
| Future HEMS adoption | (3.46, 1.141) | (3.80, 1.121) | (4.30, 0.842) | 29.997*** |
| **HEMS well-being features adoption intention** | | |
| Telemedical | (3.36, 1.240) | (3.75, 1.221) | (4.04, 1.129) | 15.021*** |
| Community updates/ networking | (3.41, 1.227) | (3.58, 1.234) | (4.03, 1.086) | 13.881*** |
| Job search | (2.81, 1.330) | (2.97, 1.468) | (3.57, 1.340) | 16.284*** |
| **WTP for energy features** | | |
| Monitor electricity | (2.46, 2.461) | (3.24, 2.532) | (4.90, 2.543) | 46.866*** |
| Control use of appliances | (2.55, 2.504) | (3.37, 2.569) | (4.95, 2.570) | 43.245*** |
| Reducing environmental impact | (2.47, 2.570) | (3.15, 2.536) | (5.09, 2.594) | 54.161*** |
| **WTP for well-being features** | | |
| Telemedical | (2.29, 2.490) | (2.93, 2.465) | (4.61, 2.624) | 43.550*** |
| Community updates/ networking | (2.13, 2.261) | (2.46, 2.481) | (4.20, 2.715) | 39.204*** |
| Job search | (2.03, 2.371) | (2.02, 2.440) | (3.55, 2.836) | 24.094*** |
| **Social-psychological variables** | | |
| Social norms | (3.06, 1.037) | (3.30, 1.092) | (3.89, 0.937) | 33.152*** |
| Personal norms | (3.77, 0.919) | (3.97, 0.799) | (4.15, 0.658) | 10.659*** |
| Perceived behavioral control | (3.34, 1.050) | (3.74, 0.967) | (4.06, 0.807) | 26.708*** |
| Cost concerns | (3.85, 1.049) | (3.92, 0.867) | (3.95, 0.833) | 0.579 |
| **Perceived technology attributes** | | |
| Perceived ease of use | (3.63, 0.928) | (3.80, 0.846) | (4.12, 0.688) | 17.561*** |
| Perceived usefulness | (3.79, 0.890) | (3.95, 0.818) | (4.21, 0.664) | 13.623*** |
| Technology anxiety | (2.95, 1.111) | (2.86, 1.075) | (3.03, 1.189) | 1.207 |
| **Relationship with service providers** | | |
| Trust in utilities general | (3.66, 0.920) | (3.75, 0.793) | (4.04, 0.718) | 11.753*** |
| Trust during COVID-19 | (3.47, 0.990) | (3.60, 0.820) | (3.97, 0.746) | 17.597*** |
| Cybersecurity concerns | (3.34, 0.919) | (3.47, 1.051) | (3.40, 1.196) | 0.760 |

<.05, **p < .01, ***p < .001.
With the inconsistency in shut-off policies nationwide, it is essential for utilities to acknowledge their role by allowing families time afteratoriums to pay back their debt and resisting raising utility rates to offset lost profits [103]. Cooperation and understanding between utility companies and consumers will increase the trust consumers have for providers, thereby increasing HEMS adoption.

Fourth, the non-energy-related benefits of HEMS should be emphasized along with the technological and environmental benefits. Our study shows that participants had higher WTP for the energy features than the well-being features, regardless of income. More knowledge on well-being features could increase WTP for these features and their potential benefits (e.g., promoting a healthier lifestyle, reducing carbon emissions) so that policymakers and industry can promote HEMS based on a broader set of advantages. HEMS can facilitate important and useful telemedical services to vulnerable populations, along with other healthcare services such as real-time health data collection to manage existing health conditions or anticipate future health needs [104]. Utilizing these online HEMS services can decrease the number of trips out of the house, lower the chance of COVID-19 infection, and help emergency healthcare providers focus on more prevalent, COVID-19 related cases [17].

Fifth, households need better education on pro-environmental behaviors and climate change issues. In addition to increasing education, policymakers and organizations need to consider the drivers of pro-environmental behavior across income groups. For instance, while HHIs were more likely to feel morally obligated to save energy than LIHs, they reported the highest energy consumption and perceived climate change issues to be less severe during the pandemic than before. This behavior-attitude discrepancy suggests a gap in households’ climate change issues to be less severe during the pandemic than before. More importantly, increasing pro-environmental education and energy literacy could help align intentions with behavior.

While this study’s context is during the pandemic, our findings and research design can be applied to non-pandemic times, as energy burdens are a persistent issue. These unprecedented times have worsened these burdens, which will not lessen without understanding the interplay of factors like energy consumption patterns, energy-efficient technology adoption, social-psychological characteristics, and technology attributes across income groups and different demographics. In particular, HEMS can lessen LIH energy burdens. In sum, our study emphasizes the causes of this discrepancy. More importantly, increasing pro-environmental education and energy literacy could help align intentions with behavior.

Author credit

Chien-fei Chen develops the original research idea, survey design and leads the manuscript writing. Xiaojing Xu leads the data analysis and revises the manuscript. Hannah Nelson leads the literature review writing and revise the final manuscript. Nick Jones and Gregory Bonilla lead the graph and table designs.

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.

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References

[1] Hernández D. Understanding ‘energy insecurity’ and why it matters to health. Soc Sci Med 2016;167:1-10. https://doi.org/10.1016/j.sciage.2016.08.029.
[2] Biot F. The coronavirus crisis reminds us that electricity is more indispensable than ever. IEA; 2020. https://www.iea.org/commentaries/the-coronavirus-ue-crisis-reminds-us-that-electricity-is-more-indispensable-than-ever.
[3] Wilson G, Godfrey N, Sharma S, Basseet T. We analysed electricity demand and found coronavirus has turned weekdays into weekends. Conversat 2020. http://theconversation.com/we-analysed-electricity-demand-and-found-coronavirus-has-turned-weekdays-into-weekends-134666.
[4] Sense. Sense data shows that home energy demand increased 22% since covid-19, driving up utility bills, and most people decided to stay home before government mandates. CISION; 2020. https://www.prnewswire.com/news-releases/sense-data-shows-that-home-energy-demand-increased-22-since-covid-19-driving-up-utility-bills-and-most-people-decided-to-stay-home-before-government-mandates-301062944.html.
[5] Carleton A. Energy use at home will spike this summer — here’s what that means for you. Arcadia 2020. https://blog.arcadia.com/home-energy-use-covid-spike/.
[6] Karpman M, Zuckermand S, Gonzalez D, Kenney GM. The COVID-19 pandemic is straining families’ abilities to afford basic needs: low-income and Hispanic families the hardest hit. 2020. p. 1–21.
[7] Graff M, Carley S. COVID-19 requires energy needs to target energy insecurity. Nat Energy 2020;5:352–4. https://doi.org/10.1038/s41560-020-0560-z.
[8] Sovacool BK, Burke M, Baker L, Kotikalapudi CK, Wlosok H. New frontiers and conceptual frameworks for energy justice. Energy Pol 2017;105:677–91. https://doi.org/10.1016/j.enpol.2017.03.080.
[9] Xu X, Chen C. Energy efficiency and energy justice for U. S. low-income households: an analysis of multifaceted challenges and potential. Energy Pol 2019;128:763–74. https://doi.org/10.1016/j.enpol.2019.01.020.
[10] Drechsel A. Explaining the energy burdens of low-income households. ACEEE; 2016 [burden means the percentage, the scope of the analysis], https://www.aceee.org/blog/2016/05/explaining-uniform-energy-burden-low#text=Energy.
[11] Jessel S, Sawyer S, Hernández D. Energy, poverty, and health in climate change: a comprehensive review of an emerging literature. Front Public Health 2019;7. https://doi.org/10.3389/fpubh.2019.00357.
[12] D’Amato G, Holgate ST, Azzolini M, Lepori MG, Cucchi C, Al-Ahmad M, et al. Metabolicological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization. World Allergy Organ J 2015;8:25. https://doi.org/10.1016/j.waojou.2014.01.007-3.
[13] Thomson H, Snel C, Bouzarovski S. Health, well-being and energy poverty in Europe: a comparative study of 32 European countries. Int J Environ Res Publ Health 2017;14. https://doi.org/10.3390/ijerph14060584.
[14] Gastan Broto V, Kirchner J. Energy access is needed to maintain health during pandemics. Nat Energy 2020;5:419–21. https://doi.org/10.1038/s41560-020-0625-6.
[15] Coleman-jensen A, Rabott MP, Gregory C, Singh A. Household food security in the United States in 2014. 2015.
[16] Hake M, Engelhardt E, Devey A, Gundersen C. The impact of the coronavirus on child food insecurity. 2020.
[17] Armour S. What you need to know about telehealth during the coronavirus crisis. BMJ 2021;373:n4. https://doi.org/10.1136/bmj.n4.
[18] Meinrenken CJ, Modi V, Mckeown KR, Culligan PJ. New data suggest COVID-19 deaths in the United States during the first 10 Weeks of the pandemic. Front Public Health 2020;8:156. https://doi.org/10.3389/fpubh.2020.00156.
[19] Amato G, Holgate ST, Pawankar R, Ledford DK, Cecchi L, Al-Ahmad M, et al. Metabolicological conditions, climate change, new emerging factors, and asthma and related allergic disorders. A statement of the World Allergy Organization. World Allergy Organ J 2015;8:25. https://doi.org/10.1016/j.waojou.2014.01.007-3.
[20] Thomson H, Snel C, Bouzarovski S. Health, wellbeing and energy poverty in Europe: a comparative study of 32 European countries. Int J Environ Res Publ Health 2017;14. https://doi.org/10.3390/ijerph14060584.
[21] Costa MF. Health belief model for coronavirus infection risk determinants. Rev Saude Publics 2020;54:1–11. https://doi.org/10.11606/S1518-8787.2020054002494.
[22] Finch WH, Hernandez Finch ME. Poverty and covid-19: rates of incidence and deaths in the United States during the first 10 Weeks of the pandemic. Front Social 2020;5:1–10. https://doi.org/10.3389/fsoc.2020.00047.
[23] Johnson K. SAMHSA disaster technical assistance center supplemental research bulletin greater impact: how disasters affect people of low socioeconomic status. Phys Heal Heal Profi 2017.
[24] Sovacool BK, Parszyfer Del Rio D, Griffiths S. Conceptualizing the Covid-19 pandemic for a carbon-bounded world: insights for sustainability transitions, energy justice, and research methodology. Energy Res Soc Sci 2020;68. https://doi.org/10.1016/j.erss.2020.101701.
[25] Chen C, Zarauza de Bocabella G, Xu X, Li J. Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. Energy Res Soc Sci 2020;68:101688. https://doi.org/10.1016/j.erss.2020.101688.
[26] Dryhurst S, Schneider CR, Kerr J, Freeman ALJ, Recchia G, van der Bles AM, et al. Risk perceptions of COVID-19 around the world. J Risk Res 2020;1–13. https://doi.org/10.1080/13669877.2020.1758193.
[27] Mair S. How will coronavirus change the world? BBC. 2020. https://www.bbc.co.uk/ﬁlm/article/20200031-covid-19-how-will-the-coronavirus-change-the-world.
[28] Pivo G. Unequal access to energy efficiency in US multifamily rental housing: opportunities to improve. Build Res Inf 2014;42:551–73. https://doi.org/10.1006/j.sce.2014.09.0035.
