Perspective

Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19

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ABSTRACT

This study explores the dynamics of energy use patterns, climate change issues and the relationship between social-psychological factors, with residents' acceptance of and willingness to pay (WTP) for home energy management systems (HEMS) during the COVID-19 pandemic in New York. The results of our survey suggest that there were no longer morning or evening usage peaks on weekdays, and a significant portion of respondents are experiencing higher or much higher electricity use than average. Most residents' perception of climate change issues during COVID-19 remained unchanged. Attitude, perceived behavioral control, and social norms are overall the strongest predictors of adoption intention and WTP for HEMS. Regarding WTP for specific well-being features, attitude was the strongest positive predictor of telemedical and home security features, and social norms are the strongest positive predictor of elderly assistance and job search. Technology anxiety, surprisingly, positively influences WTP for the well-being features. Trust in utilities is not related to adoption intention, but is positively associated with WTP for the well-being features. Although cybersecurity concerns are positively associated with HEMS adoption intention for energy and well-being features, this relationship is not significant in WTP. Residents who had moderate perceived risk of getting COVID-19 are willing to pay more than the high- and low-risk groups. This paper addresses the interactions among technology attributes, and users' social-psychological and demographics factors. Additionally, this study provides insights for further research in examining technology adoption and energy dynamics during times of crises, such as the COVID-19.

1. Introduction

Climate change poses threats of global reach, affecting every single person and part of society [1], including our food, water, health, and economic systems [2]. The effects of climate change are multi-dimensional and interconnected, increasing our susceptibility to damages and crises. In 2020, there are additional global crises, with the current COVID-19 pandemic [3] and the looming economic depression [4], which are already affecting daily life across most current societies. As a response to the pandemic, around 30% of the global population has been put in lockdown with different levels of nation-wide quarantines [5–7], having significant economic impacts due to a "great lockdown" that sees over 80% of all global workplaces partly or fully closed and an expected recession of 0.3% (the worst since the Great Depression [4]). Such events are causing a social readjustment of daily routines, practices, behaviors, and expectations; for example, people are having to adjust to being at home during quarantine, often without the option to work or while doing it remotely.

The impacts on the energy and electricity supply system (from production to consumption) have been significant during the current pandemic [8–11]. Electricity and energy systems have also seen considerable drops in demand, mostly due to the partial or full closure of entire industrial activities [8]. Globally, a decrease of 5–6% is expected on both energy and electricity demand within advanced economies, with the US (9%) and countries in the European Union (11%) seeing the largest declines [9]. This overall reduction, combined with growing interest in low-carbon sources of electricity and decreased demand in coal, natural gas and petroleum industries [10] are resulting in an international decline in carbon emissions of ~8% [9]. However, emissions and climate impacts have previously experienced rebound effects after other crises, such as the recession in 2008 [12,13]. For the current situation forecasts show emissions rebounding + 5.8% globally by 2021

[13], likely due to delays in green development programs in Europe [14] or potential second waves of COVID-19 infection [15,16].

From a household standpoint, energy access, energy management, and energy affordability are key elements with the increase in home activities, such as working remotely, online shopping, streaming entertainment services, powering home appliances, and heating or cooling homes [17]. While household energy consumption has increased overall, the more significant change is on the shape of the consumption load profiles, with weekday consumption curves being closely aligned to the typical, pre-COVID-19 weekend consumption curves [18,19]. The change in household load profiles is tied to the change in home's time schedules during the week. Remote work eliminates commuting needs, requiring less structured morning routines and thereby creating both a delayed morning load and reducing morning peaks [20]. The power not consumed in the mornings, however, is being shifted to midday, with reports of a roughly 30% increase in midday consumption in the U.K. [20] and 23% increase in the U.S. during the typical working hours (0900–1700) [21]. The challenge of the system is not only to manage the change in daily profiles, but also in the potential cost effects on residential consumers that are likely to experience increased energy bills while having their economy impacted (i.e. work closures and layoffs [21]). This is particularly felt by more vulnerable consumers [22].

There is a need to understand the multidimensional impacts of pandemics in societies, considering that experts warn that the threat of a pandemic is a recurring risk [23]. Not only with the expected second wave of COVID-19 [15,24], but also as society is likely to experience other pandemics, partly exacerbated by climate change impacts [12,25–27]. Hence, this paper aims to investigate social-psychological and demographic factors influencing residents' willingness to adopt and pay for Home Energy Management Systems (HEMS) and their relationship with the new living dynamics during stay-at-home orders during a pandemic.

1.1. Benefits of HEMS

HEMS is a system that enables consumers to manage energy use more efficiently by changing behavior. The term is considered part of the smart home concept [28–30], and some researchers refer to it as smart home energy management systems [31]. A smart home can also be simply described as "a house equipped with intelligent objects, the most important of which is the smart HEMS since it combines a set of services that transform a normal home into a smart home" [30]. Home energy management systems generally combine both hardware and software to monitor energy use and provide feedback to consumers [32]. These systems can use advanced intelligent monitoring and control to optimize energy use while maintaining consumer comfort [31,33]. When connected to the power grid, they allow for two-way communication between energy providers and end-users, opening several services and management features within that communication channel [34]. Additionally, smart meters are essential for HEMS to employ these features [35,36], which is why there is a strong focus on smart meter rollouts and their criticized slow rollout, particularly in Europe [37]. Below we elaborate on the types of services and management features.

A critical benefit of HEMS is its ability to facilitate demand response (DR) programs [38], which help change customer electricity-use patterns by keeping them apprised of different time-dependent pricing schemes, such as time-of-use tariffs (ToU), critical peak pricing (CPP), and real-time pricing (RTP) [38,39]. Through DR programs, HEMS can better automate and optimize energy use, lower the wholesale price of electricity, ensure the stability of the power grid [38,40], improve energy efficiency [40,41], and contribute to decarbonization. The informational feedback from HEMS for the end-users may also induce more environmentally-conscious behavior by providing CO_2 emission information [42], while also serving in other use-cases, such as a home

device during emergencies.

Notably, HEMS technologies provide services beyond monitoring and controlling a household's energy use. While reducing energy demand and having remote management control over the household features are some of the most important benefits to consumers; recent studies suggest there are several non-energy consumption-related benefits of smart home technologies, including security (i.e. physical and home security [43,44]), health (i.e. telemedical functions, assisting the elderly [45,46]), and social and lifestyle benefits (i.e. chat features [46,47]). Additionally, HEMS can also help with other wellbeing functions, such as providing community updates and entertainment [48] and warning users of potential storms or dangers in the area [49]. Considering the new dynamics of day-to-day routines and practices during the COVID-19 pandemic, the usefulness of HEMS can be strongly emphasized, especially with regards to improving management of electricity and thermal features, promoting remote and advanced health monitoring, and supporting individuals with the plethora of additional digital services as described above.

1.2. The present study

In light of the potential benefits of HEMS, the market for this technology is expected to grow exponentially in the coming years [50], particularly as the market of other technologies continues to mature, such as electric vehicles, vehicle-to-grid, solar photovoltaics, and battery storage, all which can be integrated into a smart household energy system [51,52]. However, while some households have indicated interest in HEMS, some studies have shown most residents are still not willing to pay for it [53,54], mostly due to the associated costs [55,56]. Overall reasons for not adopting HEMS include a perceived lack of usefulness of the technology [57], technology anxiety [58], and renters being unable to make decisions on home improvements [59].

This study attempts to examine several empirical questions by exploring residents' acceptance of HEMS and willingness to pay (WTP) for HEMS during the - pandemic, as stay-at-home mandates have increased the perceived value of home-based activities, and to improve household environments (i.e. thermal comfort and indoor air quality). We investigated both adoption intention and WTP because they reflect different driving and impeding factors. While adoption intention is proposed to be primarily influenced by factors such as attitude and social norms, WTP is influenced more by practical and experiential factors such as purchasing power [60], reference price, and expected quality [61]. Adoption intention and WTP need to be considered together in order to better estimate actual adoption behaviors [62,72]. This paper also answers the recent call for studies on the technical aspects of energy systems with social aspects to form a socio-technical perspective [63–65] to promote energy transitions away from fossil-fuel-based systems [66,67]. In doing so, this paper draws from the evidence in HEMS literature, such as the theory of planned behavior [68] and the technology acceptance model [69] to propose an integrative approach to addressing the multi-dimensionality of technology adoption and WTP during the COVID-19 pandemic. This paper pays attention to the interaction between technology attributes, users' attitudes, and social influence factors by using a unique set of 632 household survey responses recorded during quarantine mandates in New York. Specifically, we ask the following research questions:

- "Are there any stated changes in time scheduling, energy consumption behavior, home energy costs, and climate change perceptions?"
- "What are the important social-psychological, -perceived technology attributes, and demographic factors influencing adoption intention and willingness to pay for HEMS with the energy and wellbeing features?"
- "What are the differences in HEMS adoption and WTP in groups, in particular: groups with perceived low versus high risk of COVID-19

infection, and perceived decreasing versus increasing energy usage groups?"

2. Method

This study collected internet-based survey data through Qualtrics Panel Services. The survey was distributed in mid-April to residents in the greater New York metropolitan areas because New York has been the most severely infected area since the outbreak of COVID-19. As of early May 2020, nearly one-third of known U.S. cases were in New York state, with more than half of the state's cases occuring in New York City [70].

2.1. Survey area, design, and measurement

Our survey consisted of four parts. First, it started with a brief explanation of the basic energy-related functions of HEMS, after which participants were asked about their adoption intention and WTP for HEMS with energy use monitoring and optimizing features. While also including, adoption intention and WTP for HEMS with wellbeing features (i.e., assisting elderly, community event updates, job search, home security, and telemedical services) during normal times (non-pandemic) and the COVID-19 pandemic period. Second, the participants were asked to report their time of use electricity, perceived risk of COVID-19 infection, and estimated increased or decreased electricity use, utility bill charges, and climate change issues during -the pandemic. Noting with climate change issues, we are referring to air pollution, environmental impacts, effects on water and food systems, and climatic events [2]. Third, the participants were asked to answer a series of questions measuring social-psychological variables and perceived technology attributes (Table 1). These variables came from two commonly applied theoretical models in explaining new technology adoption intention: (1) the Technology Acceptance Model (TAM [71]), which considers variables such as perceived usefulness, perceived ease of use, and perceived cost and; (2) the Theory of Planned Behavior (TPB [68]), which emphasizes the impacts of attitudes towards this behavior, social norms (expectations from significant others), and perceived behavioral control (PBC) over the targeted behavior. A recent study [72] demonstrated the influence of these TPB variables, as well as other potentially important variables included in this study, such as the impacts of data privacy concerns, technology anxiety, and trust in utilities on HEMS adoption. Finally, demographics (i.e., age, gender, income) and household characteristics (i.e., -, homeownership, household size) were also collected. All measures except for WTP and demographics 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, indicating "*not willing to pay*" to 8, indicating "*$7 or above*" with a consistent 1-dollar interval.

2.2. The participants

Among the 632 participants in the New York areas, 50% were males, and 50% were females. Approximately 58.9% of participants were between the ages of 30 and 49 and 27.7% were between the ages of 50 and 69. Regarding ethnic background, the majority of participants were White (76.1%), followed by Black (9.3%), Latino/Hispanic (6.1%), and other ethnicities. The majority of participants indicated an annual household income of $50,000–$99,999usd (30.4%), followed by $100,000–$199,999usd (24.2%). Approximately 58.9% owned their place of residence, while 39.2% rent. Most participants live in a single-family detached household (51.8%), followed by reinforced concrete apartments (29.1%), and single-family attached households (11.2%). Most participants have two people (27.2%), followed by four people (25.9%), one person (19.5%), three people (17.4%), and five or more people (10%). The largest represented regions were in New York City

Table 1
Descriptive statistics of key variables.

Variables	Mean	S.D.	Factor Loading
HEMS adoption intention (if HEMS installation were free, please tell us your opinion on the following statements):			
Cronbach's α = 0.93; Composite Mean = 3.86			
I will use HEMS service in the next 6 months	3.89	1.12	0.88
I will use HEMS service in the next year	3.82	1.14	0.96
I would use HEMS service in the future	3.88	1.17	0.88
Willingness to pay for HEMS with energy related features (how willing are you to pay for the overall HEMS services?):			
Cronbach's α = 0.96; Composite Mean = 3.58			
HEMS can visualize and monitor electricity use	3.54	2.69	0.94
HEMS can automatically control your appliance	3.63	2.72	0.94
HEMS can help reduce household electricity and environment impact during COVD-19	3.56	2.77	0.94
Adoption intention of wellbeing features during normal time (beside energy related features, how likely are you to use the following services in your everyday life during normal time?):			
Cronbach's α = 0.90; Composite Mean = 3.56			
Monitor services for the elderly (Assisting seniors)	3.55	1.25	0.81
Tele-medical services	3.62	1.22	0.82
New job search	3.25	1.41	0.75
Community event update for news, social inclusion and online networking	3.66	1.19	0.82
Home security	3.71	1.30	0.84
Adoption intention of wellbeing features during COVID-19 (besides energy related features, how likely are you to use the following services?):			
Cronbach's α = 0.89; Composite Mean = 3.52			
Monitor service for the elderly (Assisting seniors)	3.52	1.29	0.79
Tele-medical service	3.73	1.23	0.80
New job search	3.11	1.42	0.73
Community event update for news, social inclusion and online networking	3.67	1.21	0.78
Home security	3.58	1.37	0.84
Willingness to pay for wellbeing features during COVID-19 (please indicate how much are you willing to pay for each of the following services per month in US dollars):			
Cronbach's α = 0.95; Composite Mean = 3.24			
Assisting seniors	3.26	2.68	0.89
Tele-medical	3.27	2.67	0.87
Job search	2.49	2.64	0.90
Community updates	2.91	2.65	0.81
Home security	3.81	2.91	0.87
Monitor electricity use	3.68	2.80	0.89
Perceived usefulness (during the COVID-19 pandemic, HEMS is…):			
Cronbach's α = 0.92; Composite Mean = 3.99			
Useful overall	4.04	0.94	0.78
Useful in helping residents manage their electricity use	4.04	0.90	0.84
Useful in providing auto-adjusted control	4.01	0.93	0.85
Useful in allowing residents control home appliance	3.95	0.95	0.85
Useful in providing additional service	3.91	0.97	0.83
Perceived ease of use (please tell us whether using HEMS will be easy or difficult for you even if you currently do not own one):			
Cronbach's α = 0.83; Composite Mean = 3.85			
Learning to live with HEMS is easy for me	3.89	0.99	0.80
Interacting with HEMS will not require mental efforts	3.78	0.98	0.69
I will find HEMS easy to use	3.88	0.96	0.88
Attitude towards HEMS during Covid19 (using HEMS during the COVID-19 pandemic will be…):			
Cronbach's α = 0.93; Composite Mean = 3.78			
Beneficial to me	3.83	1.10	0.92
Helpful to me	3.85	1.08	0.91
Important to me	3.64	1.19	0.88
Perceived behavioral control (please tell us your opinions regarding HEMS adoption during COVID-19 if it's available):			
Cronbach's α = 0.88; Composite Mean = 3.73			
I will be able to adopt HEMS services	3.77	1.07	0.86
Adopting HEMS service is entirely within my control	3.75	1.11	0.84

(*continued on next page*)

Table 1 (*continued*)

Variables	Mean	S.D.	Factor Loading
I have resources and ability to adopt HEMS services	3.68	1.12	0.82
Cyber security (during the COVID-19 pandemic, I am concerned that…):			
Cronbach's α = 0.92; Composite Mean = 3.41			
Some cyber hackers would break into HEMS network to access and misuse my personal information	3.48	1.21	0.89
Some cyber hackers will break into HEMS network to manipulate my usage information	3.38	1.19	0.93
Some cyber hackers will bring down HEMS to cause the system unstable	3.37	1.20	0.86
Social norms (if there were a chance to adopt HEMS during COVID-19..):			
Cronbach's α = 0.93; Composite Mean = 3.42			
My family would think I should use HEMS	3.55	1.20	0.89
My close friends would think I should use HEMS	3.38	1.13	0.92
My close neighbors would think I should use HEMS	3.32	1.14	0.89
Trust utility company (could you tell us what you think about your utility company?):			
Cronbach's α = 0.88; Composite Mean = 3.76			
My utility company is reliable in general	4.08	0.83	0.76
My utility company always keeps promises	3.79	0.95	0.80
My utility company always keep customers' best interests	3.64	1.03	0.82
My utility company has a plan to prevent scams or any threat to disconnect services for nonpayment during COVID-19	3.67	0.96	0.71
My utility company has taken several protection steps for customers during the COVID-19 pandemic	3.69	0.96	0.76
Cost concern (I am concerned about):			
Cronbach's α = 0.89; Composite Mean = 3.91			
HEMS basic installation fee	3.85	1.02	0.79
Additional HEMS service fee	3.91	1.00	0.93
HEMS maintenance fee	3.98	0.99	0.86
Technology anxiety (overall, we would like to know your attitude toward the use of this new technology):			
Cronbach's α = 0.89; Composite Mean = 2.94			
Working with HEMS will make me nervous	2.99	1.21	0.85
A new technology like HEMS will make me feel uncomfortable	2.88	1.26	0.93
I hesitate to use a new technology like HEMS, for the fear of making major mistakes	2.96	1.25	0.79

Source: the authors.

(69.9%), Buffalo (8.7%), and Rochester (7.6%). The majority of participants (40.5%) were employed in service occupations; 20% were in professional occupations, and 1.3% were students, while 23.1% reported that they were not employed or retired. Finally, about 61% of the participants had children who were under 18 years old at home.

3. Results

The results of this paper are presented across six themes. The first four include analyses of time of use electricity, estimated electricity use, electricity bill, COVID-19 infection risk perception, climate change perception, and HEMS adoption intention and WTP for HEMS wellbeing features. The remaining two themes explore the factors predictive of HEMS adoption and WTP through analysis of variance (ANOVA) and multiple regression models. Integrated across these themes is the contextual effects of the current COVID-19 pandemic.

3.1. Electricity time of use and estimated energy use

Regarding energy use patterns during COVID-19, electricity use picked up between 8:00 A.M. and 9:59 A.M. and stayed reasonably consistent until 6:00 P.M.–7:59 P.M. and 8:00 P.M.–9:59 P.M. during
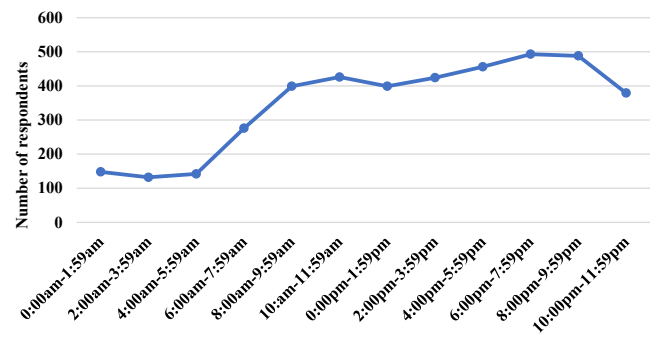

Fig. 1. N.Y. Residents' weekday electricity time of use during COVID-19 (March & April 2020).

weekdays when there was an increase in electricity use (see Fig. 1). The peak of consumption did not decrease until 10:00 pm–11:59 pm, which is a later peak than pre-pandemic. When looking at the shape of the daily curve inferred from our participants' responses, it resembles the shape found in the U.S. and Europe during coronavirus quarantines; particularly with a distinct increase in consumption during typical working hours that continues to rise until the evening peak [20,21,73,74]. Compared with the use curve during the non-pandemic time, the usage increase in the morning starts later, and the "valley" during daytime becomes non-existent.

Approximately 43.5% of participants indicated their utility bill in February 2020 was less than $100, while 32.4% of the participants' bill was $100–$149, 16.10% of participants' bills were $150–$199, and 7.9% of participants reported $200 or more. In comparison with previous months before the pandemic, a significant portion of respondents (48.3%) were experiencing either higher or much higher electricity use than average, while a large part (41.3%) rated their usage as about the same (Fig. 2). This result echoes the widely reported trend of home energy and electricity consumption increased due to stay-at-home mandates during the pandemic [21,74,75]. Based on the survey question relating to estimated electricity use compared with previous months, we divided participants into three energy usage groups: increasing usage, no-change, and decreasing usage for later analyses (Sections 3.5. and 3.6). We further investigated the demographic composition of the three groups and found that the "no-change" group contained significantly more elderly, lower-income people, and females than the increasing-and-decreasing groups.

3.2. Analysis of perceived risk of COVID-19 and climate change

One of the essential variables related to COVID-19 is risk perception. Approximately 23% of participants felt that they had less than a 1% chance of getting the virus during April and May of 2020, followed
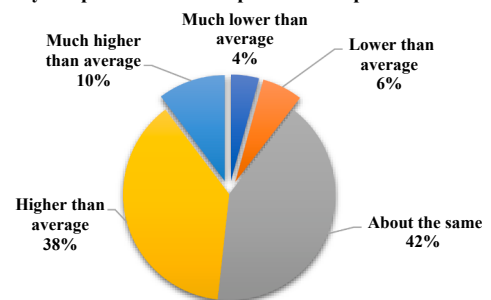

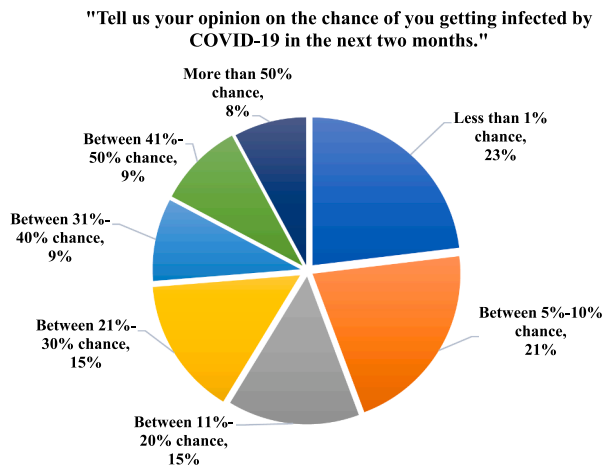**Fig. 2.** Estimated home electricity usage during COVID-19.

Fig. 3. perceived risk of getting infected by COVID-19 during April and May 2020.

by a good proportion of residents (~17%) who thought that their chance was over 40% (Fig. 3). Based on this survey question, we divided the participants into three groups: perceived the risk of being infected by COVID-19 as low ($\leq$20%), moderate (20%–40%), and high ($\geq$40%). Examining demographics closely, we found that the three risk groups were similar in all demographic characteristics, except for age and income. Older participants perceived less chance of getting infected by COVID-19 than younger participants, with higher-income participants having a higher level of risk perception. The moderate-risk group had a significantly higher income than the low-risk group and the high-risk group had a marginally higher income than the low-risk group.

As for perceived climate change issues during COVID-19, approximately 34.2% of respondents noted climate change was either slightly or much better than before the pandemic (see Fig. 4). This result can be representative of the reports across the world showing the effects of quarantine mandates on both carbon emissions and the physical environment, particularly, with images of emissions reduction in urban hotspots [8] and depictions of empty beaches, rivers, and towns resulting in clearer waters and increases in fauna sightings [76]. Nonetheless, most respondents (43.70%) noted climate change issues stayed the same, and 22.10% thought they were worse than before. There are already some indications of potential rebounding effects with even higher emissions to be reported post-pandemic lockdowns, as well as a de-prioritization of climate-related issues in global agendas due to the health crisis [8,77].

Interestingly, we found a significant positive relationship between electricity usage ($B = 0.22$, $P = 0.000$), and perceived climate change issues after controlling for demographics (age, gender, and income) and electricity bill in the regression analysis. People who observed an increase in electricity usage during COVID-19 were more likely to think climate change issues were much better than six months ago. This result could come from them observing that most businesses and
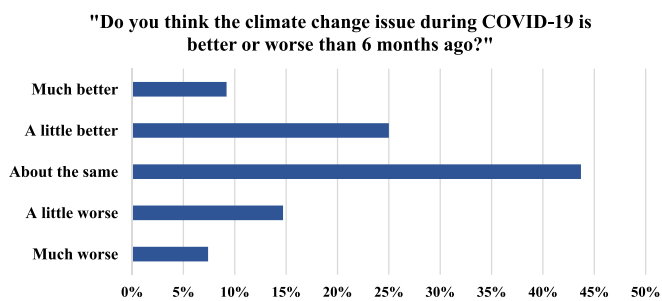
transportation systems were closed during the pandemic; therefore, the overall carbon emissions have reduced.

3.3. Distribution of adoption intention for HEMS

Overall, participants indicated they were somewhat interested in adopting HEMS energy features ($M = 3.86$, $SD = 1.10$) and wellbeing features during non-pandemic time ($M = 3.56$, $SD = 1.08$) and COVID-19 ($M = 3.52$, $SD = 1.09$). A series of paired-sample t-tests were further conducted to examine whether the adoption intention of each wellbeing feature differs between non-pandemic and pandemic time. Results of t-tests show that the participants reported higher intention to adopt the telemedical feature during the pandemic, $t(631) = -3.39$, $p = 0.001$. The intention to adopt the job search feature was actually lower, $t(631) = 4.57$, $p < 0.001$, as was the intention to adopt home security services, $t(631) = 4.39$, $p < 0.001$. These results might explain the effects of stay-at-home orders and certain job decreases. The intentions to adopt elderly assistance and community update services remained the same in non-pandemic and pandemic time. The results suggest that N.Y. residents may have higher needs and possibilities to use telemedical services during the COVID-19 pandemic and lower needs or possibilities to use home security and job search services then.

3.4. Distribution of WTP for HEMS energy and wellbeing features

One-fifth of participants indicated they were unwilling to pay for HEMS with the energy and wellbeing features, such as reducing community environmental impacts during the COVID-19 pandemic, automatically controlling the use of appliances, and visualizing and monitoring electricity usage (Fig. 5). About 80% stated they were willing to pay at least $1/month for HEMS features, whereas about 30% of these reported they were even willing to pay more than $5/month for those features.

Of the five wellbeing features (see Fig. 6), participants were most *unwilling* to pay for the feature to search for jobs, followed by community updates, and other features. Alternatively, when looking at the features with higher WTP, the results show that 46.68% of participants were willing to pay over $5/month to add a home security monitoring feature to their HEMS; followed by 38.61% for telemedical; 36.71% for monitoring service for the elderly; 31.49% for community updates; and 27.37% for job search (see Fig. 6). In fact, about 25.16% of participants were willing to pay more than $7.00 for the home security monitoring feature. On the other hand, the results also show the features that participants were willing to pay for less than 5 dollars per month ($1–4) with 39.71% for community updates, 38.93% for telemedical, 37.81% for monitoring service for the elderly, 34.65% for job search, and 31.17% for monitoring home security. Overall, such breakdown may be considered an indication of the perceived value across such features when considering implementing HEMS.

3.5. Comparisons of WTP for HEMS across electricity-use and risk-perception groups

This section particularly addresses two research questions: 1) are there any differences in WTP for energy features among the groups who perceived their electricity usage as increasing, no-change, or decreasing during the COVID-19 pandemic? 2) are there any differences in WTP for wellbeing features among the groups who perceive a high, moderate, and low risk of getting infected by COVID-19? A one-way analysis of variance (ANOVA) test was first conducted to explore whether the three electricity-use groups (decreasing, no-change, and increasing) differ in their WTP for HEMS energy features. The ANOVA result was significant (Table 2). The Post-hoc test results revealed that both the "decreasing-usage" ($M = 4.54$, $SD = 2.48$) and the "increasing-usage" groups ($M = 4.21$, $SD = 2.60$) were willing to pay more than the "no-change"
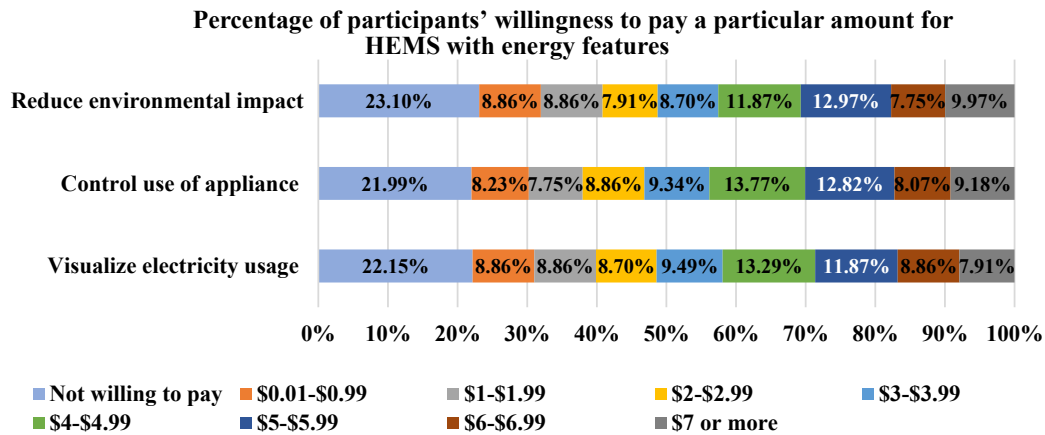

Fig. 4. Perceived climate change issue during COVID-19.

Percentage of participants' willingness to pay a particular amount for HEMS with energy features

Fig. 5. Percentage in the U.S. dollar amount of willingness to pay for HEMS energy features monthly.

group ($M = 2.60$, $SD = 2.34$), p's < 0.001. The difference between the decreasing-and increasing-usage groups was not significant.

Similarly, an ANOVA test was conducted to explore whether WTP for wellbeing features differ across the three risk-perception groups. The test result was significant (Table 2). The Post-hoc tests revealed that the moderate-risk group was willing to pay more ($M = 3.77$, $SD = 2.51$) than the low-risk ($M = 2.96$, $SD = 2.38$) groups. The difference between high and low-risk groups ($M = 3.44$, $SD = 2.40$) was marginally significant ($p = 0.069$). In further investigation of each wellbeing feature, results of five separate ANOVAs indicate that the moderate-risk group was consistently willing to pay more than the low-risk group for all features; however, the moderate-risk group was only more willing to pay for tele-medical feature than the high-risk group but not for other features. The high-risk group, in comparison with the low-risk group, was more willing to pay for the features of assisting the elderly, community updates, and home security - but not other features. See Fig. 7 for details.

3.6. Factors influencing adoption intention of HEMS with energy and wellbeing features

Multiple linear regression analysis was conducted to explore social-psychological and demographic factors influencing the adoption intention of HEMS with energy features. The regression model was significant, $F(14,617) = 41.32$, $p < 0.001$, $R^2 = 0.48$. Among all the predictors, social norms had the strongest effect (see Table 3). Attitude, perceived usefulness, and cost concerns were also positively related to

adoption intention, while cybersecurity concerns were negatively related. Among demographics, only income was a significant predictor, and was positively associated with adoption intention. We further explored the factors influencing the adoption intention of HEMS' wellbeing features during COVID-19; a similar multiple linear regression analysis was conducted with one more predictor, the adoption intention of HEMS energy features. The regression model was significant, $F(15,616) = 86.50$, $p < 0.001$. $R^2 = 0.68$. Among all the predictors, attitude had the strongest effect, followed by Perceived Behavioral Control (PBC) and adoption intention of HEMS energy features, and then social norms and cybersecurity concern, which were all positively associated with the dependent variable. Cost concern, however, was not a significant predictor in this model. Among demographics, results suggested that younger people and people in larger households had higher adoption intentions than their counterparts (see Table 3). It is worth noting that risk perception was not significant in this model when considering other social-psychological variables, but it was found to be positively related to adoption intention of HEMS with both energy ($B = 0.08$, $p = 0.02$) and wellbeing features ($B = 0.04$, $p = 0.02$), while demographics served only as control variables in another regression model.

3.7. Factors influencing WTP HEMS with wellbeing features

A set of multiple linear regression analyses were conducted to explore the factors influencing the WTP for each of HEMS wellbeing features during COVID-19. All the regression models were significant
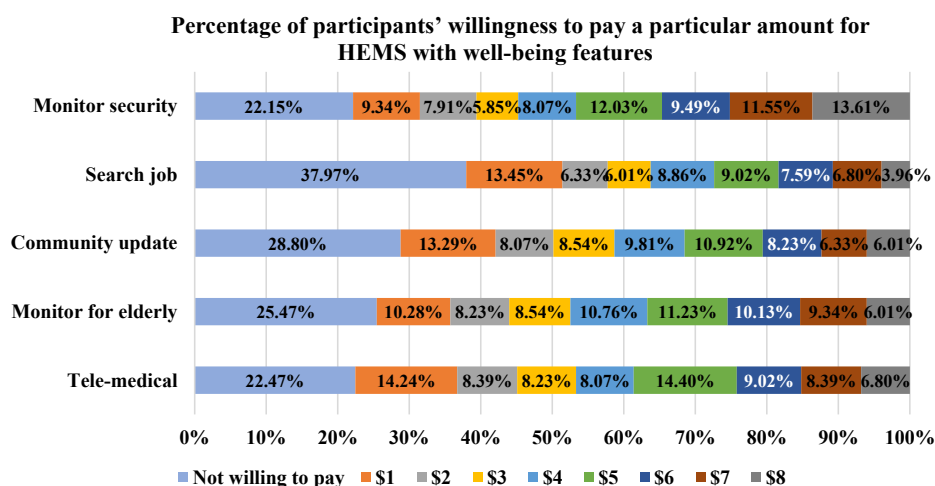
Percentage of participants' willingness to pay a particular amount for HEMS with well-being features

Fig. 6. Percentage in the U.S. dollar amount of willingness to pay for HEMS wellbeing features monthly.

Table 2
Results of ANOVAs on WTP across energy-use and risk-perception groups.

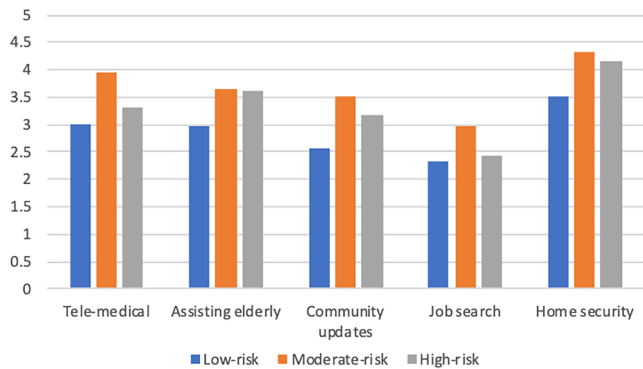|		Sum of Squares	df	Mean Square	F	p
WTP for energy features across energy-use groups	Between Groups	430.50	2	215.25	34.86	< 0.001
	Within Groups	3883.70	629	6.17		
	Total	4314.20	631			
WTP for wellbeing features across risk-perception groups	Between Groups	310.57	2	155.285	28.394	< 0.001
	Within Groups	3439.96	629	5.469		
	Total	3750.53	631			

Fig. 7. Means of WTP for wellbeing features with different perceived risk levels.

Table 3
Regression result of intention to adopt HEMS with energy features and wellbeing features.

	HAEMS energy features		HEMS wellbeing features	
	β (Std.Coefficient)	p	β (Std. Coefficient)	p
Constant				
Gender	0.011	0.721	−0.005	0.837
Age	−0.058	0.072	−0.085	0.001
Income	0.089	0.007	−0.011	0.670
Household size	−0.006	0.872	0.086	0.002
Risk perception	0.040	0.184	0.006	0.789
Energy feature adoption			0.213	0.000
Perceived usefulness	0.143	0.003	0.034	0.362
Perceived ease of use	0.045	0.289	−0.064	0.054
Attitude	0.181	0.001	0.340	0.000
PBC	0.092	0.055	0.224	0.000
Social norms	0.270	0.000	0.110	0.005
Cost concern	0.079	0.011	−0.029	0.241
Cyber security	−0.075	0.021	0.069	0.007
Trust in utilities	−0.017	0.624	0.000	0.988
Technology anxiety	−0.014	0.683	−0.005	0.868
R^2	0.484		0.678	
Adjust R^2	0.472		0.670	
F	41.315		86.499	
p	0.000		0.000	

Note: PBC = Perceived Behavioral Control; Attitude = attitude towards HEMS

(see Table 4). Among demographics, older residents were less likely to pay for all wellbeing features, while larger-size households were more likely to pay for them. Higher-income residents reported a higher level of WTP, except for the features of community updates and job search. Males reported higher WTP for job search, community updates, and telemedical services but not for elderly assistance and home security. Notably, the TPB variables (i.e., attitude, social norms, and PBC) had significant and positive effects on WTP for all wellbeing features, except for the impacts of PBC on the WTP for job search and home security features, which were not significant.

Interestingly, people who reported higher technology anxiety had

higher WTP for almost all wellbeing features except for home security features, where the effect was marginal. Trust in utilities was positively associated with WTP for community updates, job search, and telemedical services, but not others, indicating utilities have the potential to improve residents' wellbeing through the three features mentioned above during the COVID-19. Perceived usefulness and ease of use were unexpectedly not significant predictors in most cases, except that perceived usefulness was negatively related to WTP for the job search feature. Cost concern had no impacts on almost all features, except for a negative relationship with WTP for telemedical and job search features. Cybersecurity concerns seem to be irrelevant to WTP for all wellbeing features. It is worth noting that, although risk perception was not a significant predictor of WTP for wellbeing features in this regression model (Table 4) with other social-psychological variables considered, higher perceived risk was associated with higher WTP for wellbeing features during the pandemic ($B = 0.08$, $p = 0.02$) when only demographic variables were controlled for. In contrast to what we expected, adoption intention of HEMS energy features was a significant predictor, indicating that residents were likely not considering HEMS wellbeing features as necessarily affiliated to its major energy features; the wellbeing features may be promoted without the context of energy features.

4. Conclusions

This study is placed in the light of the coronavirus pandemic and its multidimensional effects across daily social routines, energy system dynamics, carbon emissions, and, more generally, climate change. It particularly investigates the factors influencing residents' willingness to adopt and pay for HEMS and their relationship with the new living dynamics during the quarantine in a pandemic. The main findings of this research fall into four streams:

(1) The reported electricity consumption resembles the actual consumption patterns found elsewhere during the pandemic, which has no morning or evening usage peaks during weekdays and is different from the daily curves during non-pandemic weekdays. About half of the respondents reported a higher volume of electricity usage than before the pandemic, while only a few reported lower usages. Interestingly, people who have used more electricity or perceived a higher risk of getting COVID-19 think climate change issues are much better than before, probably due to those participants perceiving themselves as self-isolating more, commuting and travelling less, consuming less energy at workplace, and therefore leaving a reduced carbon footprint. Scholars suggest that many Americans may be seeing the connection between their actions and climate change issues [78,79], which echoes the finding of the Yale Program on Climate Change Communication that about 50% of the American population are viewing climate change as primarily caused by human activities [80]. However, this percentage is still low in comparison with many countries [81]. Recent studies have also emphasized that tackling COVID-19 and climate change issues both rely heavily on reducing non-essential economic activities, and that our future resides largely in the ability to build a society resilient to pandemics and climate change [82].

Table 4
Regression results of willingness to pay for HEMS with wellbeing features.

	Tele-medical		Assist senior		Community update		Job search		Home security	
	β	p	β	p	β	p	β	p	B	p
Constant										
Age	−0.08	0.02	−0.08	0.03	−0.10	0.00	−0.17	0.00	−0.14	0.00
Gender	0.07	0.03	0.03	0.35	0.08	0.02	0.12	0.00	0.04	0.17
Income	0.14	0.00	0.10	0.01	0.06	0.09	0.00	0.92	0.09	0.01
Household	0.09	0.02	0.08	0.04	0.15	0.00	0.14	0.00	0.10	0.01
Risk	0.03	0.32	0.05	0.16	0.05	0.13	−0.00	0.91	0.04	0.19
Intention	−0.06	0.15	−0.00	0.98	−0.02	0.59	−0.06	0.16	−0.01	0.76
Attitude	0.23	0.00	0.12	0.05	0.17	0.00	0.20	0.00	0.25	0.00
PBC	0.11	0.02	0.13	0.02	0.15	0.00	0.08	0.12	0.08	0.13
Norms	0.18	0.00	0.27	0.00	0.16	0.00	0.23	0.00	0.19	0.00
Usefulness	−0.05	0.36	−0.07	0.18	−0.01	0.92	−0.13	0.01	0.00	0.94
Ease of use	0.08	0.09	0.08	0.07	0.02	0.74	0.06	0.22	0.02	0.74
Cost	−0.07	0.04	−0.06	0.06	−0.05	0.13	−0.02	0.50	−0.05	0.14
Anxiety	0.16	0.00	0.15	0.00	0.23	0.00	0.19	0.00	0.06	0.09
Cyber	−0.03	0.45	0.01	0.71	−0.03	0.44	−0.04	0.22	0.01	0.88
Trust utility	0.07	0.04	0.03	0.35	0.10	0.01	0.09	0.01	0.06	0.08
R^2	0.44		0.40		0.45		0.41		0.45	
Adjust R^2	0.43		0.39		0.44		0.40		0.44	
F ratio	32.09		27.50		33.93		28.94		33.59	
P-value	0.00		0.00		0.00		0.00		0.00	
					0.00					

Note: Household = Household size; Risk = Risk perception; PBC = Perceived behavioral control;
Attitude = Attitude towards HEMS; Intention = Adoption intention of HEMS with energy features; Norms = social norms, Cyber = cyber security concern;
Cost = cost concerns; Anxiety = Technology Anxiety.

(2) There are relatively high intentions to adopt HEMS among respondents, with nearly 80% willing to pay in general and ~30% willing to pay more than \$5/month for its energy features. A third of the respondents would consider paying for the feature that reduces community environmental impacts. For wellbeing features, respondents were more willing to pay for features like monitoring home security and telemedical during COVID-19, but not for job search and community updates through HEMS. There can be different factors influencing the preferences of features and WTP. We suspect that, for example, home security services are preferred over job searching services because the former are perceived as more directly related to home management systems and the technology more mature. Interestingly, people who have a moderate perceived risk of getting COVID-19 are willing to pay more than high- and low-risk groups. However, this may be tied to the group composition, as those perceiving moderate levels of risk also tend to have significantly higher incomes.

(3) Social-psychological variables are important factors for explaining HEMS technology adoption intention and WTP during COVID-19. The TPB variables (attitude, PBC, and social norms) are overall the strongest predictors of adoption intention and WTP for HEMS. Regarding adoption intention for energy-related features, close friends, and family's behavior (social norms) appear to be the strongest predictor, followed by perceived usefulness, after controlling other factors. For wellbeing feature adoption intention, attitude is the strongest predictor, followed by social norms, and adoption intention of energy features. Regarding specific wellbeing features, attitude is the strongest predictor of WTP for telemedical service and home security, norms are the strongest predictor of WTP for elderly assistance and job search, and technology anxiety is the strongest predictor of WTP for community updates. Of the averaged WTP for wellbeing features, social norms are the strongest predictor. Surprisingly, technology anxiety does not hinder the participants from paying for HEMS's wellbeing features, although it was not related to adoption intention. Trust in utilities is not associated with adoption intention. Still, people who have higher levels of trust in their utility company are more willing to pay for

the wellbeing features, suggesting that utilities have the potential to improve residents' wellbeing through community updates, job search, and telemedical services. Surprisingly, the effects of cost concerns vary across different dependent variables. Residents with higher HEMS cost concerns are actually more willing to adopt HEMS energy features, but no relationship is found with wellbeing feature adoption. Regarding WTP, people with higher cost concerns are less willing to pay for the telemedical feature, not other features. We also found people with higher cybersecurity concerns have higher adoption intention for both energy and wellbeing features, but this relationship is not significant with WTP.

Finally, (4) regarding demographics, we find gender is not related to adoption intention, but women tend to be less willing to pay for HEMS wellbeing features than men. Overall, higher-income residents and larger households are more willing to pay for all wellbeing features. Elderly residents are less willing than younger residents to adopt and pay for HEMS, regardless of the features. Income level affects WTP for wellbeing features during COVID-19, but it does not affect adoption intention for these features.

This study identifies several important and interconnected concepts relating to changes in daily energy use profile, climate change, and risk perceptions during -the padenmic in New York, while looking at the factors influencing adoption intention of and WTP for HEMS with the wellbeing functions for improving home environment and energy efficiency. Given the stay-at-home orders in place in most countries, these wellbeing functions are critical features for specific populations. Our study is limited to a small sample in the New York; therefore, it is not representative of the entire New York City area or other cities in the U.S. Given the range and scale of current and anticipated impacts of the pandemic, this study provides a foundation for researchers to conduct larger-scale energy studies by considering the opportunities to build transdisciplinary collaborations through integrated methods and matching datasets. For example, this study could be expanded to other energy studies by considering cultural differences in social distancing, energy burden (including water), access to technology and energy efficiency appliances, healthy built-home environments, and social-

psychological factors (e.g., perceived fairness, social networks, etc.). These transdisciplinary research topics could be analyzed through the design of integrated methods and matched data sets.

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.

Acknowledgements

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