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Investigating intentions and barriers in adopting decentralized home energy management systems: A justice dimension of demand flexibility

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ABSTRACT

The integration of a decentralized home energy management system (HEMS) marks a pivotal advancement in the pursuit of enhanced energy efficiency and sustainability within modern households. While numerous studies focus on developing efficient and innovative programs from technical perspectives, the willingness of individuals to adopt these systems is equally crucial for achieving widespread adoption and ultimately creating a more energy-efficient society. Based on a large-scale online survey with 1,196 participants in California in 2021, we investigated the intentions related to the adoption of decentralized HEMS, particularly considering demand flexibility encompassing both air-conditioning (AC) and electric vehicles (EV) control, specifically focusing on socio-demographic disparities. Our analysis found greater openness for allowing HEMS to control AC usage compared to scheduling EV charging, possibly due to immediate comfort needs or trust in AC predictability. Low-income households showed less flexibility in adjusting both AC and EVs, while high-income households were less likely to decrease EV charging. Furthermore, homeowners exhibited greater flexibility compared to renters. Disparities between different racial backgrounds in EV charging time-shifting were more pronounced than in AC aspects. Our findings indicated that vulnerable populations may lack the flexibility and resources necessary to shift their energy consumption patterns effectively, potentially amplifying energy-related disparities and exacerbating their energy burden. Policy recommendations highlight the need for multifaceted approaches in addressing demand flexibility and energy management, especially with emerging technologies like EVs, to ensure equitable strategies for promoting sustainable energy practices across diverse communities.

1. Introduction

Demand response (DR) programs are initiatives implemented by utility companies and grid operators to encourage consumers to reduce their electricity consumption during periods of high demand or when the grid is under stress [1]. Within this scope, decentralized household Home Energy Management Systems (HEMS) stand out as a noteworthy facet of DR. Integrating decentralized HEMS marks a pivotal advancement in pursuing enhanced energy efficiency and sustainability within modern households. This study embarks on an innovative exploration, shedding light on the motivations and challenges surrounding decentralized HEMS adoption, with a primary emphasis on the justice dimension of demand flexibility. Recognizing the intricate factors that influence decentralized HEMS adoption is paramount, as neglecting specific demographic considerations may undermine the effectiveness of energy efficiency enhancements. Decentralized HEMS are rooted in the principles of decentralized energy systems, which emphasize the proximity of energy production to its consumption point [2]. These systems are designed to manage energy use within households comprehensively. From regulating the temperature through heating and air conditioning (AC) systems to efficiently coordinating the charging of electric vehicles (EVs), decentralized HEMS offers a holistic solution for enhancing energy efficiency and sustainability in residential settings [3,4].

While prior research has touched upon the adoption of HEMS and the concept of demand flexibility, a noticeable gap exists in simultaneously focusing on the dual control of AC systems and EV charging through decentralized HEMS, specifically in the context of socio-demographic factors [5]. These two elements are poised to become fundamental components of residential energy management in the near future. Furthermore, decentralized HEMS represents a newer approach to

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improving building energy efficiency than traditional HEMS, which may influence occupants' intentions to adopt [6]. This study aims to bridge this research gap by exploring the relationship between adopting decentralized HEMS and regulating behaviors related to both AC and EVs, thereby elucidating potential associations.

Our primary objective is to investigate the intentions surrounding decentralized HEMS adoption across diverse demographic groups while identifying potential barriers and variations in technology acceptance. In light of the growing prominence of EVs as integral household appliances, our research centers on understanding residents' intentions to adopt decentralized HEMS for controlling AC operations and EV charging. This focus underscores the dynamic interplay between technology adoption and socio-demographic factors, providing insights into the complexity of residential energy management.

2. Literature review

2.1. Application of energy management system and decentralized HEMS

The growing demand for power system flexibility is driven by the desire to enhance energy efficiency and increase the adoption of renewable energy sources [7–9,49]. DR, considered one of the foremost and advantageous flexibility alternatives, has found extensive adoption across utility companies and organizations worldwide [10]. Specifically, DR provides an opportunity for consumers to play a significant role in the operation of the electric grid by reducing or shifting their electricity usage during peak periods in response to time-based rates or other forms of financial incentives. Electric system planners and operators incorporate DR programs as valuable resources for balancing supply and demand [11]. These initiatives can reduce electricity costs within wholesale markets, ultimately translating into lower retail rates [12,13].

Preceding research has explored and advocated for the advantages of various DR programs, each offering unique perspectives on grid management and energy conservation [14]. These programs such as HEMS [11,15], which empower individual households to optimize energy consumption, direct load control (DLC) programs enable utility companies to remotely manage specific appliances during peak demand [10], price-based demand response (PBDR) programs incentivize consumers to adjust their electricity usage based on fluctuating rates, incentive-based demand response (IBDR) programs offer financial incentives to motivate consumers to participate actively in reducing energy consumption during critical periods [16]. These distinctions highlight the versatility and effectiveness of different DR approaches in achieving grid stability and energy conservation objectives. These DR programs examined in previous research have demonstrated their merit in improving grid flexibility, reducing electricity costs, and enhancing energy efficiency. However, previous studies related to DR have predominantly concentrated on programs and their applications in household appliances, such as AC units [17], HVAC system [18], refrigerators, and laundry [11,19], with limited attention given to EVs. While there have been instances where researchers like Luo et al. [20] have considered the energy consumption of an EV within the context of household appliances, there remains a dearth of in-depth investigations and modeling methodologies specifically dedicated to understanding and incorporating the nuances of EVs within the broader framework of DR studies. Decentralized HEMS, one of the programs within demand response, empowers households to actively manage their energy usage by providing real-time data on consumption, optimizing the operation of energy-intensive appliances, and even integrating renewable energy sources like solar panels [6,21]. By allowing households to make informed decisions about their electricity usage and, in some cases, automatically adjusting settings to minimize demand during peak periods, decentralized HEMS contribute to the overall effectiveness of DR programs. They help consumers save on their energy bills and play a crucial role in enhancing grid stability and reducing the need for costly peak power generation [2].

The previous research mentioned above has demonstrated the effectiveness of various DR programs in enhancing grid flexibility and conserving energy. However, most studies have primarily focused on applying DR programs and flexibility in household appliances [14,22], with limited attention devoted to integrating EVs into the DR framework to investigate the relationship between EVs and other appliances in terms of DR.

2.2. HEMS acceptance and socio-economic factors

The significance of examining energy consumption patterns within the context of demand response is emphasized, particularly considering how incentives [23], technological advancements [24,25], and individual circumstances play a pivotal role in shaping consumers' decisions regarding their energy usage [10,26]. Despite the evident advantages offered by the DR programs and initiatives, the levels of participation fell short of expectations [10]. Consequently, both industry professionals and researchers are investigating the socio-economic factors, particularly customer attributes and social barriers [27,28], that influence the public's willingness to adopt the program [26,29,30]. Parrish et al. [31] conducted a comprehensive systematic review regarding international demand response trials, programs, and surveys. Their work unveiled the motivations driving participation, alongside the barriers and enablers influencing engagement. Moreover, they provided insights into the design and delivery of residential demand response. Notably, the study underscored the diverse levels of flexibility among users, suggesting that engagement with demand response evolves with experience and technological progress. Additionally, they highlighted the mixed evidence concerning the effectiveness of socio-demographic data, such as income and household size, in predicting flexibility, making it challenging to draw definitive conclusions on these dimensions. Xu et al. [10] examined residential DLC as a demand response strategy to reduce peak-hour electricity consumption by allowing utility companies to control household appliances while considering both financial incentives and a control option. Despite its benefits, customer concerns about losing control have limited adoption. The study found that approximately half of the participants are willing to accept DLC without conditions, but both a $30 incentive and an override option increase the acceptance rate, with the override option being more effective; moreover, socio-demographic factors influence these decisions. This study suggested that factoring in these variables can enhance power system stability when designing and implementing DR programs.

Chen et al. [32] conducted a study investigating the factors influencing residents' willingness to adopt and pay for HEMS in New York and Tokyo, aiming to explore the disparities between Eastern and Western societies. Their findings indicated that perceived usefulness, a positive attitude toward HEMS, and social norms positively impacted adoption intention in both areas. However, Tokyo residents faced barriers related to perceived behavioral control, while New York residents expressed concerns about privacy and cybersecurity. Overall, the study revealed differences in the reasons influencing the willingness to adopt HEMS in these distinct cultural contexts. Consequently, it is essential to consider these factors from a social and psychological perspective. Yamaguchi et al. [11] conducted a comparative study between Japan and Europe and proposed a more accurate estimate of demand flexibility potential, explicitly focusing on domestic laundry appliances. They considered household heterogeneity and various factors related to household activities, scheduling, and behavioral intention, a crucial yet often overlooked aspect in the literature on DR flexibility. Their findings revealed that per-household potential in Japan is significantly smaller than in Europe due to differences in willingness to participate in DR driven by social factors and culture.

According to the findings of previous research above, they emphasize the importance of promoting DR adoption among diverse populations, including underserved communities, and addressing the behavioral and cultural barriers to its implementation. Moreover, it is worth investigating the impact of psychological factors such as privacy, cost, and environmental concerns, as these are factors that may influence individuals' decisions regarding the adoption of HEMS [15,32,33].

2.3. Justice in demand flexibility

During the energy transition, the notion of justice has gained prominence as a vital and intricate aspect, receiving increasing attention [50]. The concept of "energy justice" [34] involves using principles of justice to critically analyze the structure and operation of energy systems [35,36]. In the context of energy justice, DR plays a crucial role in bridging the access gap and ensuring fairness in energy distribution. Historically marginalized and underserved communities often face higher energy costs, limited access to clean energy sources, poor living conditions, and infrastructure disparities [37]. By reducing their electricity demand during peak periods, community members can contribute to a more equitable distribution of energy resources. This not only decreases the pressure on disadvantaged communities but also helps lower overall energy costs for everyone [38]. However, while the issue of energy justice has been broadly explored in recent years, justice in the context of DR, demand flexibility, and the adoption of HEMS has received less focus despite its close association with energy systems and energy consumption.

Powells and Fell [39] introduced the concept of "flexibility justice", suggesting that levels of flexibility capital differ across populations, both in absolute terms and in their reliance on technological or social factors. Moreover, the study contended that the freedom to choose how to leverage flexibility capital may be constrained by factors like financial resources. Additionally, they highlighted the potential long-term entrenchment of such injustices in energy infrastructure, market design, and governance. Philippa Calver et al. [40] indicated that the capacity to be "flexible" and shift energy consumption in response to a demand side response (DSR) signal is highly unequal and that those with minor flexibility capital are also often those who are vulnerable to energy poverty. Moreover, these households may encounter infrastructural, psychological, and skills-related barriers that hinder their access to DSR schemes. Furthermore, they proposed that directing support towards enhancing the flexibility capital of the least advantaged, enabling their access to DSR, such as offering subsidized access to smart appliances, would help maximize potential opportunities for improving energy affordability for the most vulnerable. Ingvild Firman Fjellså et al. [33] investigated the justice implications of household electricity consumption in future smart energy systems. Their findings revealed that highly flexible individuals can quickly adapt, whereas those with limited flexibility find their daily lives significantly impacted by energy consumption management. This disparity underscores the need for justice initiatives to distribute the burden of flexible work more equitably, especially considering that inflexibility may be influenced by factors such as individuals' occupations, income levels, and other social factors.

Vulnerable populations, such as marginalized and underserved communities, often encounter difficulties adapting their schedules to align with incentives and programs, thus facing obstacles in participating in demand flexibility initiatives. These challenges emphasize the importance of providing targeted support and ensuring equitable access to energy-saving programs. However, despite the critical role that demand flexibility plays in addressing energy justice concerns, there remains a scarcity of studies examining the justice implications within this realm. Therefore, there is an urgent need for further research to explore and identify the challenges related to demand flexibility, as well as to identify the vulnerable populations affected by this issue, along with their intentions and behaviors.

3. Purpose of the study

This study investigated the willingness and barriers to adopt decentralized HEMS and the demand flexibility in AC and EV control, explicitly focusing on the disparities across socio-demographic factors. We initiated the analysis by examining the relationship between demand flexibility in AC and EV usage and respondents' willingness to adopt decentralized HEMS, allowing these systems to control their AC and EV settings. This investigation aims to uncover potential synergies between AC and EV demand flexibility, contributing to a more comprehensive understanding of energy management across various income groups, homeownership statuses, and racial backgrounds. Additionally, we emphasize diverse intention patterns regarding AC and EV operating schedules, temperature settings, and load reductions within various demographic segments, offering valuable insights into how different groups perceive and prioritize the flexibility of AC and EV usage. These insights inform the development of targeted strategies to promote energy-efficient practices. In addition to exploring the intention of adopting decentralized HEMS and the demand flexibility of AC and EV, we have specifically identified populations that may face challenges in adjusting their behaviors regarding AC operating modes since AC energy consumption represents a substantial portion of the total appliance consumption for most households. Understanding these challenges is crucial for developing interventions and initiatives tailored to the unique needs of vulnerable populations.

Moreover, the potential reasons behind individuals' decisions to adopt decentralized HEMS to adjust their AC operation were investigated. Factors such as privacy concerns, reliance on traditional AC systems, environmental awareness, and discomfort perception will be examined to gain insights into the barriers to adoption and behavior adjustment. This study attempts to address the above issues through answering the following research questions:

1) Is there a significant relationship between AC and EV demand flexibility?
2) What are the disparities between adopting decentralized HEMS and the willingness to let HEMS adjust AC settings and EV charging behaviors?
3) What are AC and EV demand flexibility patterns, including time-shifting and load-reduction, across different income groups, homeownership, and racial backgrounds?
4) Is there a significant difference in the demand flexibility (including load-reduction and time-shifting) for AC settings among concentrated disadvantages?
5) What are the potential psychological factors for people not to adopt HEMS or to adjust AC schedule and load?

4. Methodology

4.1. Survey procedures

This study conducted an online survey (n = 1,196) among residents in California in 2021, utilizing an internet-based questionnaire distributed through Qualtrics Paid Panel Service, a widely recognized online data collection platform for researchers. Our comprehensive survey covered a diverse spectrum of essential domains, and it started by building the background knowledge of decentralized HEMS to let the participants know the differences between decentralized HEMS and traditional HEMS. This survey put a primary emphasis on gaining insights into individuals' inclinations regarding the adoption of decentralized HEMS and their intention to give the decentralized HEMS some level of control over the following appliances to improve their energy efficiency at home: 1) Automatically adjusting their heating or cooling temperature; 2) Automatically scheduling their EV charging time (assuming the participants own an EV).

Our investigation delved deeply into various facets of AC adjusting behaviors, including practices related to time-shifting and load reduction, and we closely examined their intricate relationships with psychological factors like privacy concerns, AC reliance, environmental concerns, and discomfort perception, which are elucidated in detail in the forthcoming section of this study.

4.2. Participants' demographics

The demographics of the surveyed population show a relatively even distribution among groups of people across gender, income level, homeownership status, race, and age. As shown in Table 1, it can be seen that the sample closely mirrors the national composition in several demographics, with minor differences. While the sample does show a good representation of the national demographics, there are some areas of over- or under-representation, particularly in homeownership and age groups.

For income levels, low-income households (LIHs) earn less than or equal to $50,000 annually, which constitutes 37.5 % of the sample. In contrast, those with medium-income households (MIHs) range from $50,001 to $99,999 yearly, comprising 29.1 %. High-income households (HIHs) earn $100,000 or more annually, representing 33.4 % of the demographic. Homeownership is prevalent among respondents, with 55.9 % identifying as homeowners and 44.1 % as renters. Within the renter category, 61.5 % are LIHs, whereas only 38.5 % are MIHs and HIHs. Regarding racial composition, the majority of respondents, 60.4 %, identify as White, while 39.6 % belong to non-white racial groups. Among the non-white demographic, individuals of Black and Latino descent, presented as people of color (POC), represent 21.1 %, while 78.9 % were of another race. Analysis by gender shows a near-even split, with 40.4 % of respondents identifying as male and 59.6 % as female. When examining the age distribution, a notable portion of the sample falls within the young adult category (18–37 years), comprising 36.4 %. Middle-aged individuals (38–61 years) comprise 38.1 % of the demographic, while the elderly (62 years and older) constitute 25.5 %. Additionally, nearly all participants reported owning an AC system, accounting for 99.9 % of the sample. This widespread AC ownership emphasizes the prevalence of cooling systems among the surveyed population, allowing for investigation of the dynamics of AC usage and flexibility in the context of HEMS.

4.3. Procedure of measurement key variables

In this study, we examine the influence of psychological factors on energy management behaviors, focusing on the following eight variables: "Intention to adopt Household Energy Management Systems (HEMS)", "Acceptance of Decentralized HEMS for controlling both air conditioning (AC) and electric vehicle (EV) energy usage to enhance energy efficiency","AC & EV adjusting behaviors for load-reduction and time-shifting", "Privacy concerns", "AC reliance", "Environmental concern," and "Discomfort perception". These variables were measured using a multi-item approach in our survey, which combined latent variables identified through factor analysis. Factor analysis is a statistical method used to elucidate relationships among observed and correlated variables by identifying a smaller set of unobserved variables, which was employed to identify the crucial variables for further analysis [41,42]. The key variables and their definitions are elaborated upon in the following sections.

The intention of adopting decentralized HEMS is a variable that measures individuals' readiness to embrace the concept of decentralized Household Energy Management Systems (HEMS). It is evaluated based on the response: "How likely are you to adopt HEMS? The decentralized HEMS will enable users to control their appliances and collect energy data from the appliance without sharing with others". This variable seeks to gauge individuals' level of interest and willingness to incorporate decentralized HEMS into their homes.

Acceptance for decentralized HEMS. This variable measures individuals' openness to granting HEMS a degree of control over their appliances to enhance home energy efficiency. It is evaluated based on the response to the question: "How likely are you to give this HEMS some control over the following appliance to improve your home's energy efficiency? You control this alternative HEMS, not utility companies or providers". Acceptance for decentralized HEMS assesses the degree to which individuals are willing to delegate certain control functions to adjust their AC operating and scheduling EV charging times. In addition, this study aims to clarify the disparities between the acceptance of AC and EV, shedding light on how individuals perceive the integration of HEMS into different aspects of their energy consumption and management routines. This variable is pivotal in understanding individuals' receptiveness to innovative and automated energy management solutions that empower them while promoting energy efficiency within their homes.

AC Time-shifting. This variable investigates occupants' willingness to adjust their AC operating schedule based on the question: "I am willing to set my A/C higher during peak hours and set the temperature back to normal_hour(s) later". Time-shifting refers to modifying electricity consumption patterns by raising the AC set temperature during peak hours and returning it to its typical setting after these peak hours have passed. This approach is designed to alleviate the stress on the grid during periods of high demand and encourage an eco-friendly approach to energy consumption. By assessing individuals' willingness to adapt their AC settings to off-peak hours, people can contribute to achieving a more equitable and efficient distribution of electrical energy.

AC Load-reduction. This variable examines occupants' willingness to modify their AC operation, as indicated by their response to the question: "I am willing to set my A/C_degree higher than the normal setting during peak hours". AC load reduction involves individuals' willingness to raise the temperature setting of their air conditioning units by a specified number of degrees above the usual setting during peak hours. This deliberate adjustment aims to curtail electricity consumption at times of high demand. By assessing individuals' willingness to implement AC load reduction strategies, we gain insights into their contribution to reducing the strain on the electrical grid during peak periods.

Table 1
Descriptive statistics of the demographics.

Demographics	Frequency (%)		Demographics	Frequency (%)	
	Within Sample	National		Within Sample	National
Income			**Homeownership**		
LIH (<$50,000/year)	37.5 %	36.5 %	Homeowners	55.9 %	65.4 %
MIH ($50,001-$99,999/year)	29.1 %	29.5 %	Renters	44.1 %	34.6 %
HIH (>$100,000/year)	33.4 %	34.0 %	**EV Ownership**		
			EV Owners	16.7 %	N/A
Race			Non- EV Owners	83.3 %	N/A
White	60.4 %	60.9 %	**Age**		
Non-white	39.6 %	39.1 %	Young Adult (18–37)	36.4 %	32.5 %
Gender			Middle Age (38–61)	38.1 %	38.9 %
Male	40.4 %	49.6 %	Elderly (62 +)	25.5 %	28.6 %
Female	59.6 %	50.4 %			

EV Time-shifting. Time-shifting involves adjusting electricity consumption by shifting the timing of EV charging to periods occurring after peak hours, typically between 5 pm and 8 pm. We collected respondents' opinions based on the question: "I am willing not to charge my EV during peak hours, instead, charge it__hour(s) later". This strategy aims to reduce the strain on the grid during high-demand periods and promote more sustainable energy usage. By rescheduling EV charging to off-peak hours, individuals can contribute to a more balanced and efficient distribution of electrical energy while potentially benefiting from cost savings and environmental advantages.

EV Load-reduction. Load reduction is a crucial strategy for managing electricity consumption. It involves adjusting electrical usage by decreasing the amount of EV charging that occurs during peak hours. By reducing the demand for electricity during these high-demand periods, load reduction helps to alleviate stress on the grid. It ensures a more stable and efficient distribution of electrical power. This contributes to grid reliability and can result in cost savings and reduced environmental impact, making it a valuable approach for individuals and utilities seeking to optimize energy usage. This variable was measured based on the question: "I am willing not to charge my EV fully (100 %) during peak hours, instead, charge it__%".

Privacy concerns. This study incorporated the concept of "privacy concerns" as a crucial dimension in its research framework. To assess this perception, participants were asked questions about their views on the privacy and sensitivity of their AC usage data. This indicator was measured based on the factor analysis (Table 2). It averaged the score of the three questions regarding their agreement and disagreement, including statements such as "I consider the electricity usage data of my AC as private and sensitive", "I am concerned that my utility company can infer when someone is at home and other lifestyle information from my AC's electricity usage data", "I consider the temperature setting data of my AC as private and sensitive", and "I am concerned that my utility company can infer when someone is at home and other lifestyle information from my AC's temperature setting data". These inquiries were crafted to delve into how individuals perceive their AC-related data as confidential and sensitive. By scrutinizing participants' responses to these statements, the study sought to uncover insights regarding privacy concerns related to AC data and the potential ramifications for data sharing and decision-making concerning AC.

AC reliance. This variable represents how much individuals rely on AC for comfort and well-being during the summer season. Based on the factor analysis result (Table 2), it is derived as the average score from three questions: "I find I cannot relax or work well if my house is not cool enough in the summer", "I have trouble falling asleep at night in the summer without an AC on", and "My need for being cool in the summer is higher than ordinary people". Understanding this variable provides valuable insights into the significance of AC in respondents' lives and its potential influence on their energy consumption patterns and cooling preferences.

Environmental concern is a multifaceted perspective that reflects an individual's apprehensions about the consequences of energy use. This indicator was measured by respondents' agreement or disagreement with the following statements. Firstly, it encompasses a broader awareness of the overall impacts by the statement "I am concerned about the overall impacts on the environment due to energy use"; secondly, this concern extends to specific worries about carbon emissions resulting from energy use, with individuals recognizing the role of carbon emissions in contributing to environmental challenges by the statement of "I am concerned about carbon emissions due to energy use"; lastly, a key component of environmental concern is the apprehension about the contribution of energy use to climate change was assessed by the statement of "I am concerned about climate change due to energy use". Averaging the score of the three variables based on factor analysis (Table 2), these concerns form a comprehensive outlook on the environmental repercussions of energy consumption.

Discomfort perception. This variable evaluates individuals' perceptions of the potential discomfort of reducing electricity consumption during peak hours. It is assessed based on their responses to the statement: "Reducing electricity consumption during peak hours will cause the experience of physical discomforts". Discomfort perception reflects participants' beliefs about the inconvenience or discomfort they anticipate when conserving electricity during high-demand periods. This variable provides valuable insights into how individuals perceive the trade-off between energy conservation and personal comfort. Understanding discomfort perception is crucial for designing strategies that balance energy efficiency goals with occupants' comfort and well-being, ultimately contributing to more effective and user-friendly energy management solutions.

Table 2
Factor analysis results of crucial variables.

Variables	*Mean*	*S.D.*	*Factor Loading*
Privacy concerns: (Please tell us if you agree or disagree with the following statements relating to AC usage and privacy?)			
Cronbach's α = 0.88; Composite Mean = 3.32			
AC's electricity usage data is private and sensitive	3.31	1.10	0.88
Concern of utility company can infer when someone is at home and other lifestyle information from my AC electricity usage data	3.35	1.11	0.87
Consider the AC temperature setting data as private and sensitive	3.26	1.15	0.85
Concern of utility company can infer when someone is at home and other lifestyle information from my AC's temperature setting data	3.37	1.11	0.84
AC reliance: (Please tell us if you agree or disagree with the following statements on AC usage)			
Cronbach's α = 0.78; Composite Mean = 3.42			
Cannot relax or work well if my house is not cool enough in the summer	3.70	1.06	0.84
Have trouble falling asleep at night in the summer without an AC on	3.47	1.21	0.84
The need to be cool in the summer is higher than in ordinary people	3.08	1.23	0.83
Environmental concern: (The agreement with the following views on the environmental impacts of energy use)			
Cronbach's α = 0.92; Composite Mean = 3.94			
Overall impacts on the environment	3.95	1.03	0.93
Carbon emissions	3.91	1.04	0.94
Climate change	3.94	1.09	0.92

5. Results and discussion

5.1. Relationship and disparities between AC and EV demand flexibility

To answer our first research question, two Ordinary Least Squares (OLS) regression models were used to investigate the association between the temporal adjustment of air conditioning usage during peak hours and EV charging behaviors, including time-shifting and load-reduction behaviors.

The results of the first regression model, as presented in Table 3,

Table 3
Results of OLS regression models for AC and EV time-shifting behavior.

Independent variables	Dependent variable: AC Time-shifting		
	Standardized Coeff. (Beta)	*Std. Error*	*F*
EV Time-shifting	0.429***	0.027	$F(1,1198) = 270.328$***

Note: All models are controlled for the effects of gender, ethnicity, and income.
$*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

reveal a strong and statistically significant relationship between the flexibility in EV charging times and the willingness to modify AC operation schedules ($B = 0.429$; $p < 0.001$). This finding underscores the tendency for individuals who demonstrate adaptability in their EV charging routines also to be open to making time-based adjustments in their air conditioning usage. Furthermore, the statistical significance of our model is evident ($F (1,1198) = 270.328$, $p < 0.001$), with the high F-statistic indicating that the independent variable significantly predicts the dependent variable. This robust model suggests that efforts to promote the shift of energy consumption to off-peak hours should consider broader behavioral patterns and emphasize the interconnected nature of energy utilization across different domains.

The analysis results of the second regression model are shown in Table 4. Our findings reveal a significant relationship between individuals' intentions to manage their energy consumption during peak hours through adjustments in their AC setting temperature and EV charging load ($B = 0.189$; $p < 0.001$). Specifically, the results show that individuals who are more willing to raise the temperature setting of their AC units during peak hours to reduce energy load are also more likely to reduce their EV charging load at these times. Furthermore, an increase in individuals' readiness to adjust their AC temperature settings is associated with a greater willingness to modify their EV charging habits, favoring less charging during peak hours. This relationship is significant and highlights the potential for integrated demand response strategies that address multiple facets of household energy management.

We further investigated the disparities in letting HEMS adjust AC settings and EV charging behaviors within our survey sample. As shown in Fig. 1, the analysis of respondents' willingness to permit HEMS to adjust AC and schedule EV charging demonstrates notable trends. The statistical descriptive results of these two variables show varying levels of willingness across the survey sample. Regarding AC adjustment, 38.10 % of respondents express a likelihood. In comparison, 15.30 % indicate a high probability of allowing HEMS to adjust their EC settings, suggesting a considerable openness to technology-mediated energy management strategies.

In contrast, for EV scheduling, a lower proportion of respondents express a likelihood (27.10 %) or significantly likelihood (17.80 %) to permit HEMS control over their EV charging schedule. This suggests that respondents are more willing to allow AC control over EV control by HEMS. A substantial portion of respondents remained neutral towards both AC adjusting (23.90 %) and EV scheduling (32.30 %), indicating a degree of ambivalence towards allowing control over these energy-related decisions to automated systems. The statistically significant Chi-square result ($\chi2$ (16, 1200) = 983.60; $p < 0.001$) highlights the strong association between respondents' attitudes towards AC adjusting and EV scheduling, indicating the interconnectedness of these preferences within the broader context of HEMS adoption.

5.2. Willingness to adopt HEMS, disparities of AC & EV demand flexibility patterns across demographics

This section delves into comparing AC and EV demand flexibility patterns across different demographics. AC, being a ubiquitous household appliance, significantly influences energy consumption behaviors. Understanding how various demographic factors impact the willingness and ability to adjust AC usage is crucial for adopting HEMS and overall energy efficiency. The subsequent sections will analyze survey findings, focusing on income, homeownership, and race demographics individually, to uncover nuanced insights into the interaction between these factors and compare the results of EV and AC demand flexibility patterns to explore the association.

5.2.1. Income

The analysis of AC and EV demand flexibility patterns concerning load-reduction across different income levels are evaluated (Fig. 2) based on the survey question regarding their "willingness to set their A/C_degree higher than the normal setting during peak hours" and "willingness of not to charge their EV fully (100 %) during peak hours, instead, charge it_%". Crosstabulation demonstrates varying willingness to increase the AC temperature during peak hours across income groups. Notably, a statistically significant association is observed (χ^2 (10, 1200) = 19.28; $p < 0.05$), emphasizing the relevance of income in influencing attitudes towards AC load reduction flexibility. Examining the percentage distribution shown in Fig. 2(a), higher proportions of LIH exhibit an inability to adjust, with 14.7 % of LIH respondents expressing no willingness to increase the temperature, compared to 12.1 % in MIH and 10.4 % in HIH. Conversely, a shift is observed as income increases, with HIH displaying a higher percentage of respondents willing to increase their thermostat temperature by 4 degrees and 5 degrees higher than average during peak hours. At 5 degrees, only 13.4 % of the LIH group reported willingness to increase this quantity, while 18.9 % of the HIH group exhibited willingness to increase this quantity.

For EV load-reduction (Fig. 2 (b)), LIHs show a pronounced decrease in willingness to charge beyond the 0–10 % range, followed by a variable yet noticeable openness to charging within the 31–70 % range, beyond which their willingness again wanes. MIHs display a similar pattern, with a marked decline after the initial 10 %, a modest increase in willingness around 31–40 % and 51–60 % charge levels, and then a general, albeit fluctuating, downward trend. HIHs exhibit a trend similar to MIHs but with a slightly higher propensity to charge between 61–70 % and 81–90 % compared to the other groups. While the Chi-square results were not statistically significant (χ^2 (22, 1196) = 24.05; $p = 0.344$), insights can still be obtained from the distribution disparities. In sum, while there is a general trend across all groups towards a willingness to charge up to a certain percentage, with a notable reluctance for the lowest and highest charging brackets, a middle ground seems preferable, as evidenced by the higher percentage of participants across all income levels open to charging between 31–70 %.

Overall, the analysis indicates that LIHs are generally less willing to adjust their load-reduction behaviors for both AC and EV than MIHs and HIHs. However, it is worth noting that HIHs are more likely to set their AC temperature higher by 4 degrees or more for AC load reduction. Conversely, they are less likely to decrease their EV charging load, as the results indicate a higher percentage of HIHs that will still charge their EV at a higher percentage of energy load.

Analyzing the time-shifting flexibility of ACs and EVs concerning income groups provides valuable insights into households' willingness to adjust AC settings for various durations after peak hours and their EV charging schedules. Regarding the descriptive statistics results of AC time-shifting, the relationship between income and the flexibility to increase AC for a certain amount of time is statistically significant ($\chi2$ (12, 1200) = 23.52; $p < 0.05$). A discernible trend is observed (Fig. 3 (a)), with higher percentages of LIH expressing reluctance to adjust their AC settings showing 15.1 % of the group compared to 12.4 % and 11.7 % of the MIH and HIH groups respectively. As income level increases, there is a shift towards a greater willingness to wait for extended periods before resetting the temperature back to normal. In the bracket for waiting 4 h to return temperature to normal, 17.6 % of the HIH group reported this level of willingness. In contrast, only 12.0 % of the LIH group reported the same level of willingness. Increasing the duration to 5 h, willingness across all groups dramatically decreases, with 4.8 %,

Table 4
Results of OLS regression models for AC and EV load-reduction behavior.

Independent variables	Dependent variable: AC Load-reduction		
	Standardized Coeff. (Beta)	*Std. Error*	*F*
EV Load-reduction	0.189***	0.014	F (1,1198) = 44.196***

Note: All models are controlled for the effects of gender, ethnicity, and income.
**p < 0.05, ** p < 0.01, ***p < 0.001.*

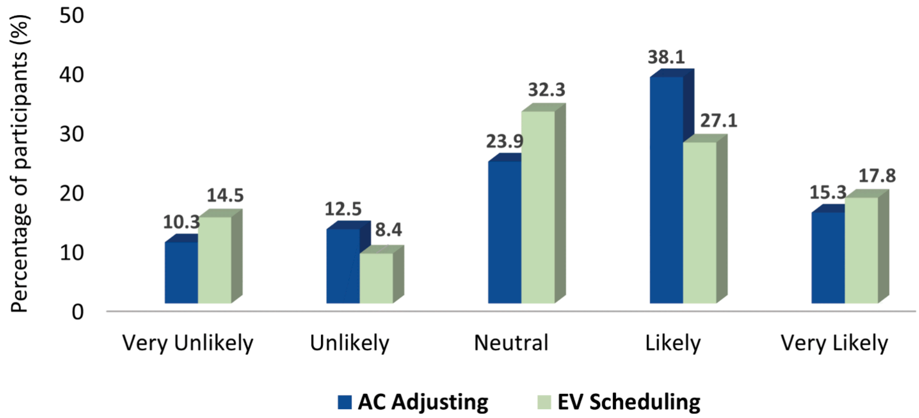

Fig. 1. Disparities of letting HEMS adjust AC settings and EV charging behaviors within the entire survey sample.

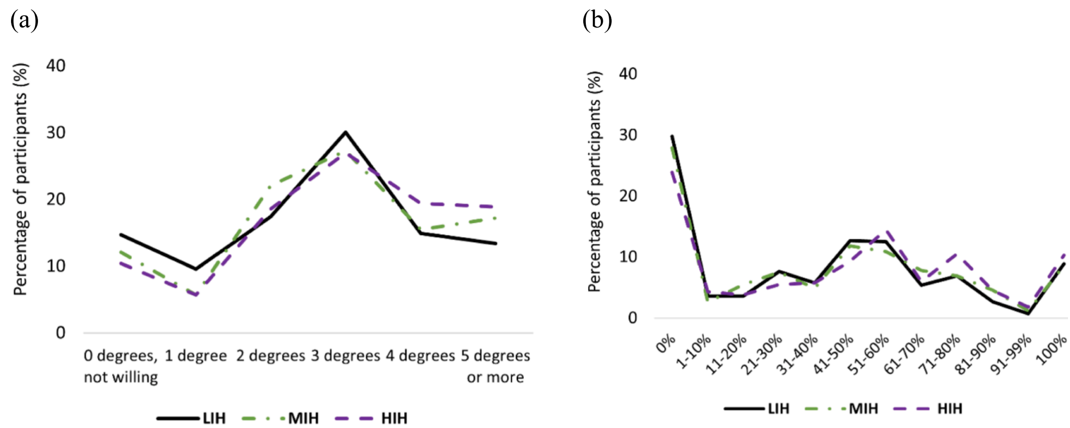

Fig. 2. Demand flexibility in load-reduction across income levels for (a) AC and (b) EV.

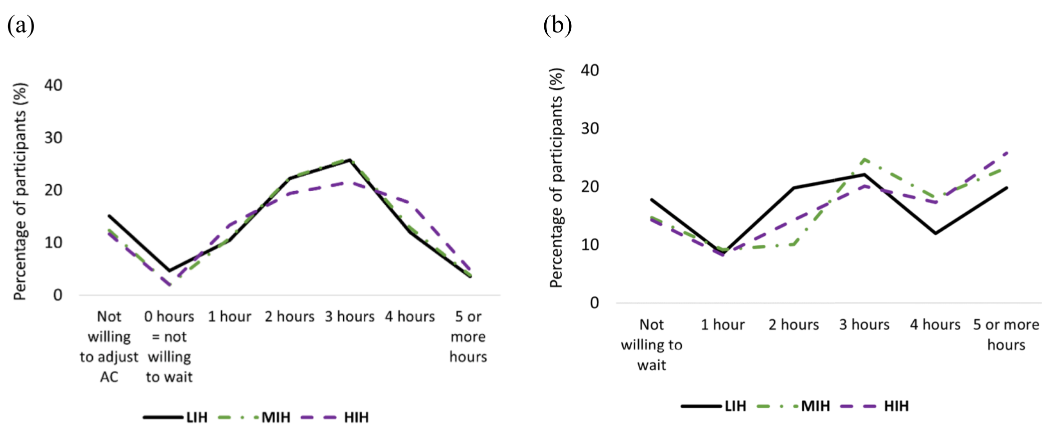

Fig. 3. Demand flexibility in time-shifting across income levels for (a) AC and (b) EV.

3.8 %, and 3.6 % of the HIH, MIH, and LIH groups, respectively.

The analysis results for time-shifting of EV charging behaviors, as shown in Fig. 3 (b), reveal that LIHs have the highest proportion of individuals unwilling to delay charging their EVs, with 17.8 % of LIHs expressing this sentiment. This is slightly higher than the 14.7 % of MIHs and 14.3 % of HIHs who prefer not to wait. On the other end of the spectrum, HIHs demonstrate greater openness to postponing their EV charging for extended durations, with 25.8 % willing to delay charging by five or more hours beyond peak times, a willingness that surpasses that of MIHs (23.3 %) and LIHs (19.8 %). The Chi-square results support this analysis with a statistically significant result (χ^2 (10, 1196) = 25.89; $p < 0.01$). These findings suggest that LIHs are generally less flexible in adjusting their EV charging schedules.

Regardless of AC or EV demand flexibility in time-shifting, our findings reveal that LIHs are less likely to adjust their schedules for both AC operation and EV charging. This suggests that tailored interventions must address specific income-related barriers and enhance overall demand response effectiveness.

5.2.2. Homeownership

Investigating load-reduction flexibility concerning homeownership status reveals distinct patterns in the willingness to increase AC temperature during peak hours among homeowners and renters. However, this difference is statistically nonsignificant (χ^2 (5, 1200) = 10.69; p = 0.058). Within the homeowner group, as shown in Fig. 4 (a), there is a higher willingness to adjust AC temperature during peak hours, with 14 % of renters showing no desire to shift, while only 10.9 % of homeowners reported the same level of unwillingness. When focusing on the more significant degree shift of 5 or more degrees, 18 % of homeowners reported this level of flexibility, while only 14.4 % of renters reported the same level of flexibility. These findings indicate that homeownership may influence load reduction flexibility within peak hours.

Regarding the EV load reduction (Fig. 4 (b)), renters and homeowners exhibit a similar pattern of willingness across the different charging levels. Both renters and homeowners have the highest percentage of participants not willing to charge their EV during peak hours, with 28.3 % of renters and 26.5 % of homeowners. Our findings suggested that homeownership status does not significantly differ in willingness to participate in EV charging load shifting during peak hours (χ^2 (11, 1196) = 7.99; p = 0.714). Both renters and homeowners display a similar pattern of willingness across the charging percentages, with the slightest willingness at the lower charge levels and a higher willingness at moderate to complete charge levels.

The disparities in demand flexibility for load reduction between different homeownership statuses appear negligible, suggesting that attitudes toward load reduction, whether for AC or EV charging, are consistent regardless of homeownership. This uniformity implies that factors other than homeownership status may be more pivotal in influencing individuals' decisions to engage in load-shifting behaviors.

Looking at time-shifting flexibility across homeownership categories demonstrates the willingness of individuals to adjust AC settings and EV charging for different durations during peak hours. The results of AC time-shifting, despite the Chi-square test yielding a nonsignificant result (χ^2 (6, 1184) = 8.81; p = 0.185), suggest subtle distinctions in the aspects of AC adjustments between homeowners and renters. Referring to Fig. 5 (a), homeowners demonstrate a slightly higher willingness to adjust, with only 12.5 % of homeowners showing complete reluctance to shift AC demand, while 13.6 % of renters report complete reluctance. On the other end of the spectrum, analyzing the 4-hour and five or more-hour temperature increase duration, homeowners demonstrate a higher willingness with 15.1 % and 13.3 % of the homeowner group, respectively. When looking at the percentage of renters, there are only 13.3 % of renters at 4 h and 10.9 % of renters at five or more hours. At the higher durations, the percentage of renters to homeowners is lower within the survey population.

Similarly, regarding time-shifting for EV charging (Fig. 5 (b)), 16.9 % of renters are unwilling to postpone their EV charging until after peak hours, compared to 14.8 % of homeowners who express the same reluctance. Conversely, a more significant proportion of homeowners, 24.5 %, are willing to delay their charging by five or more hours, as opposed to 20.7 % of renters. Comprehensively, the disparities of demand flexibility in EV time-shifting for different homeownership statuses present subtle differences while statistically insignificant (χ^2 (5, 1196) = 5.94; p = 0.312).

The analysis of AC time-shifting indicates that homeowners exhibit a slightly higher willingness to adjust settings than renters, with nuanced distinctions in reluctance percentages observed across various duration intervals. Similarly, in EV charging time-shifting, homeowners display greater flexibility than renters, with a more significant proportion willing to postpone charging during peak hours. Although the Chi-square tests for load-reduction and time-shifting do not show significance, these nuances indicate a potential interaction with homeownership regarding demand flexibility, indicating the need for further investigation of the underlying dynamics of these observed trends.

5.2.3. Race

When investigating the flexibility in load-reduction concerning racial demographics reveals similar patterns between White and Non-white respondents in the willingness of individuals to increase AC temperature during peak hours, with a nonsignificant association (χ^2 (5, 1200) = 5.13; p = 0.40). The data suggests marginal variations in attitudes towards load reduction, with a slightly higher percentage of Non-white (13.9 %) than White (11.6 %) respondents who are not willing to increase AC temperature during peak hours. On the other hand, 17.5 % of White and 14.5 % of Non-white respondents report a willingness of 5 or more degrees (Fig. 6 (a)). The patterns of willingness as the degree amount increases are similar between White and Non-white groups. According to Fig. 6 (b), the flexibility in EV load-reduction also presented very similar results between White and Non-white respondents, with a nonsignificant association (χ^2 (11, 1196) = 11.87; p = 0.373).

Analyzing the flexibility in time-shifting across racial groups exposes slight variations in the willingness of individuals to adjust AC temperature settings for different durations during peak hours (Fig. 7 (a)). The Chi-square test results between White and non-white participants show a nonsignificant result (χ^2 (6, 1200) = 4.24; p = 0.644), indicating a limited association between racial demographics and AC time-shifting. The observed patterns closely resemble those identified in the AC load-reduction analysis, reinforcing the consistent nature of attitudes toward demand flexibility within the surveyed racial demographics. While the Chi-square test does not reach statistical significance, the trend alignment highlights the need for additional investigation to determine trends shaping time-shifting and load-reduction behaviors across racial groups and their potential implications for designing inclusive demand response initiatives.

Regarding the results of EV time-shifting, it is noteworthy that for a delay of less than four hours to charge the EVs, a higher percentage of non-white participants were willing to wait compared to white participants (Fig. 7 (b)). However, this trend fluctuates as the waiting time increases, with non-white participants reaching a peak willingness at

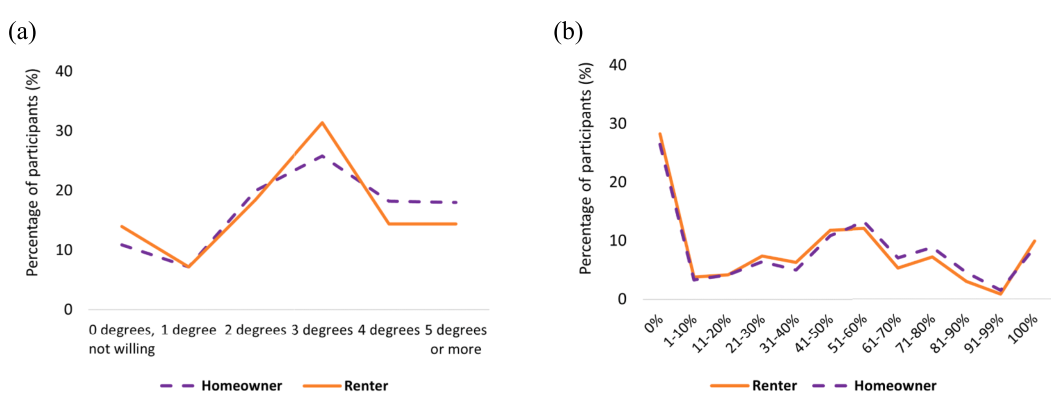

Fig. 4. Demand flexibility in load-reduction across homeownership status for (a) AC and (b) EV.

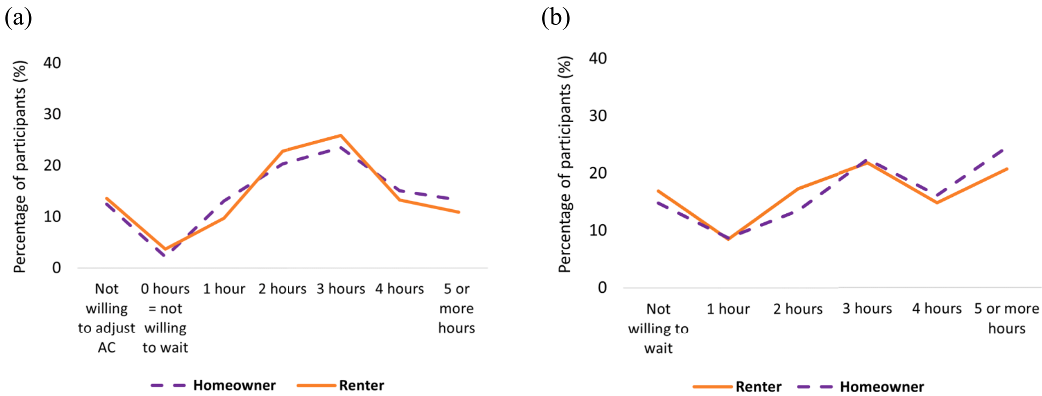

Fig. 5. Demand flexibility in time-shifting across homeownership status for (a) AC and (b) EV.

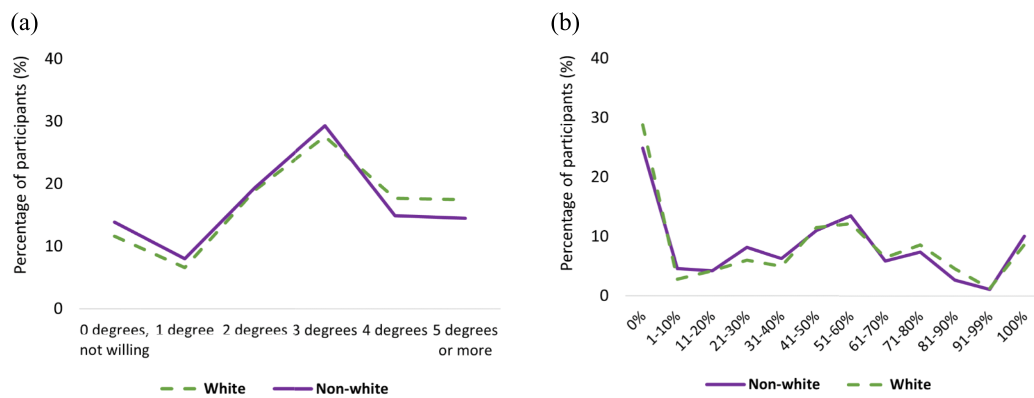

Fig. 6. Demand flexibility in load-reduction across racial backgrounds for (a) AC and (b) EV.

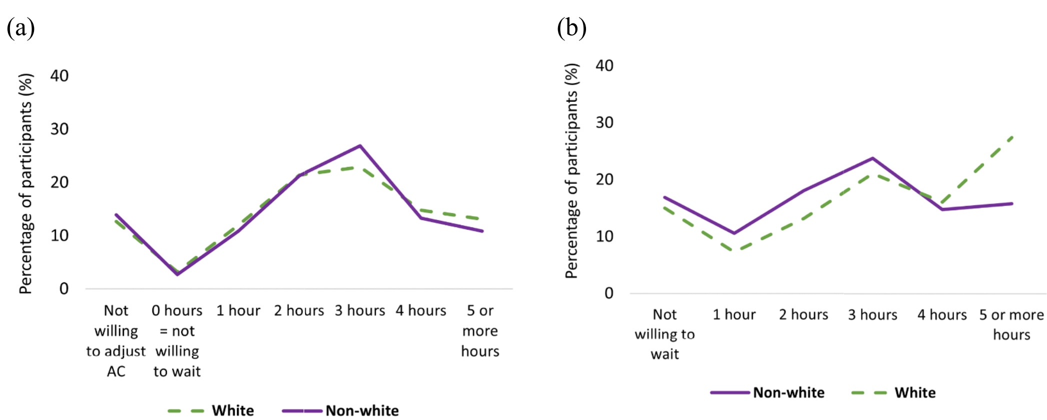

Fig. 7. Demand flexibility in time-shifting across racial backgrounds for (a) AC and (b) EV.

three hours, followed by a significant decline for delays exceeding four hours. In particular, white respondents (27.4 %) are more inclined to postpone charging after five or more hours than non-white participants (15.8 %). The Chi-square results, which reached statistical significance (χ^2 (5, 1196) = 26.97; $p < 0.001$), indicate the importance of exploring the relationship between racial background and EV charging behavior of time-shifting.

Compared to the AC time-shifting results, the disparities between different racial backgrounds in EV charging time-shifting are more pronounced. This suggests that while attitudes towards adjusting AC temperature settings during peak hours exhibit a consistent pattern across racial demographics, the willingness to modify charging behaviors for EVs may be influenced by a broader range of factors, including socio-economic considerations, access to charging infrastructure, and perhaps cultural perspectives on energy usage and sustainability.

5.3. Interaction of income, homeownership, and race in AC demand flexibility

5.3.1. Variations in willingness for AC load-reduction during peak hours

Since AC is currently a household appliance, accounting for the primary energy consumption, this study delved into a deeper investigation focused on the interaction of demographics and its impacts on AC demand flexibility. This section explores variations in the willingness to increase AC temperature settings during peak hours across different populations. The focus is on the interaction of income, home ownership, and race to examine outcomes for disadvantaged groups such as low-income renters or low-income POC. Two-way ANOVA was used to investigate the relationship between the dependent variable of AC load-reduction and the interaction of demographics. Our goal in exploring the estimated marginal means is to gain insight into the ways demographic factors converge to influence attitudes toward load reduction. This is based on the response to the survey question: "I am willing to set my A/C_°F higher than the normal setting during peak hours (e.g., 5–8p.m.)". This study aims to develop a comprehensive understanding of the multifaceted dynamics within distinct population subgroups. Such an approach offers a valuable perspective for tailoring demand response strategies to meet the needs of the specific population.

Firstly, the interaction between homeownership and income levels concerning the willingness to increase AC temperature during peak hours was analyzed. The results unveiled significant variations in AC load-reduction behaviors across different demographic subsets. Fig. 8 presents the mean value of degrees that individuals are willing to increase their AC temperature setting during peak hours. The results indicated distinctions in the reported willingness, with LIH homeowners displaying a mean of 3.7 °F, while MIH and HIH homeowners showed means of 3.9 °F each. With a specific focus on comparing low-income and high-income renters, the results demonstrate a significant difference in load reduction flexibility between these subgroups, indicating that high-income renters (4.1 °F) are more likely to increase their AC temperature setting than low-income renters (3.6 °F). These results are statistically significant ($F (5, 1183) = 2.66$; $p < 0.05$), emphasizing that the convergence of homeownership and income level plays a significant role in influencing attitudes towards AC load-reduction.

The interaction between income levels and racial groups regarding willingness to increase AC temperature during peak hours was analyzed. Our results indicated significant distinctions in load reduction behaviors across these diverse demographic subgroups. As shown in Fig. 9, the average degrees people are willing to increase within the White demographic are 3.7 °F, 3.9 °F, and 3.9 °F for LIH, MIH, and HIH respondents. While the White LIH respondents show a lower mean than White MIH and HIH respondents, it is not as low as the mean for Non-white LIH respondents of 3.5 °F, the lowest of all subgroups in this analysis. The ANOVA results show the statistical significance of this interaction ($F (5, 1199) = 3.89$; $p < 0.01$), indicating that the interplay between income levels and racial demographics significantly influences attitudes towards load reduction.

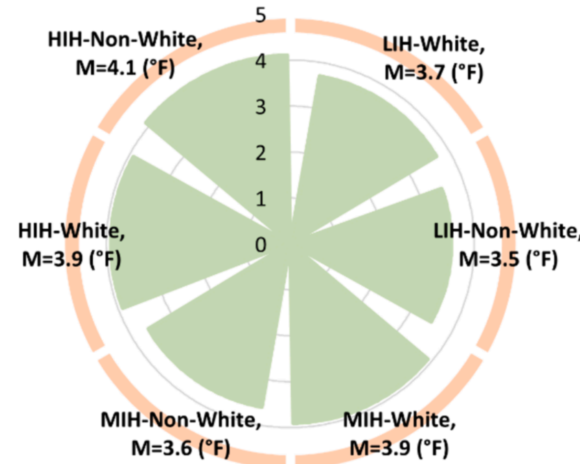

Fig. 9. Degree of willingness to increase AC temperature setting (°F) during peak hours by income level and racial background.

Thirdly, this study investigated the interaction between homeownership status and racial groups regarding the willingness to increase AC temperature during peak hours. Referring to Fig. 10, for the White group, both renters and homeowners exhibit the same degree value of 3.9 °F. There is no difference between the two subcategories within the White group. In the Non-white group, Renters have a lower degree value of 3.5 °F, while Homeowners have a higher value, equal to the degree of both subcategories in the White group, at 3.9 °F. The graph indicates that within the Non-white group, homeowners are willing to increase relatively higher setting temperature than renters. In contrast, among the White group, the temperature degree is consistent regardless of homeownership status. The ANOVA results indicated the significance of this interaction, with $F (3, 1183) = 4.55$; $p < 0.01$.

5.3.2. *Variations in willingness for AC time-shifting during peak hours*

Similar to section 5.3.1, the analysis in this section examined the variations in AC reset time across different populations by incorporating the interaction of different demographic variables, including income levels, homeownership status, and racial background. Employing the statistical analysis of ANOVA, the objective of this analysis is to observe the interplay between these specific demographic subgroups and attitudes towards resetting AC temperature during peak hours based on the question "I am willing to set my A/C higher during peak hours and set the temperature back to normal_hour(s) later" in our survey. This approach provides information on AC time-shifting attitudes for

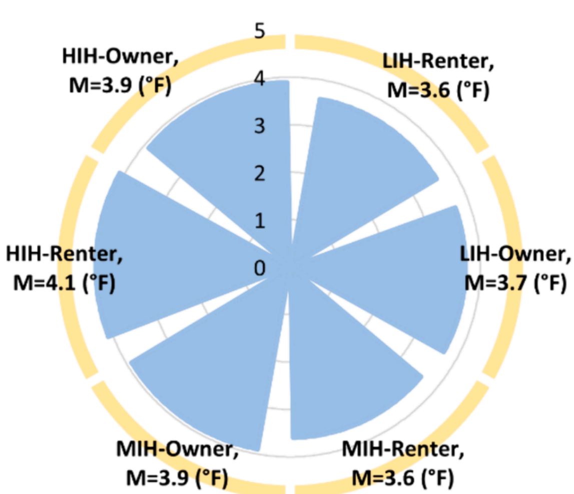

Fig. 8. Degree of willingness to increase AC temperature setting (°F) during peak hours by income level and homeownership status.

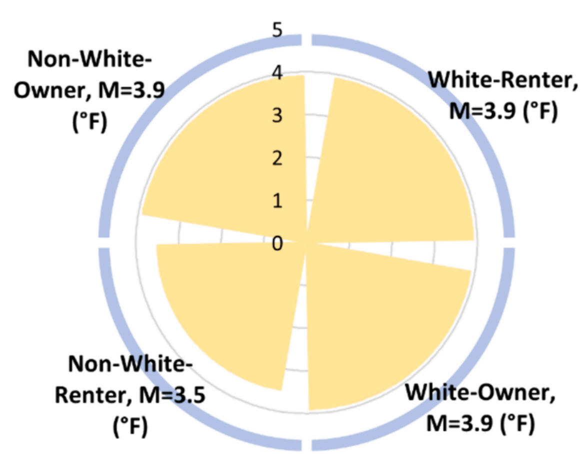

Fig. 10. Degree of willingness to increase AC temperature setting (°F) during peak hours by homeownership status and racial background.

specifically tailored strategies to accommodate the varying levels of flexibility within demographic intersections.

The interaction between homeownership and income levels regarding the willingness to set AC temperature higher during peak hours was investigated. As shown in Fig. 11, the results presented slight variations across different demographic subgroups. For LIHs, renters and homeowners report an equal willingness to delay returning their A/C to the typical setting by 4.2 h after peak hours. In MIHs, renters show a slightly higher willingness to delay (4.3 h) than homeowners (4.4 h). HIHs display a different pattern in that renters reported a willingness to delay returning to the typical A/C setting by 4.6 h, which is longer than any other group. Homeowners in the high-income bracket report a willingness to postpone by 4.4 h, which is consistent with the homeowners in the MIH group. Overall, the graph indicates that high-income renters are the most willing to delay returning their A/C to the typical temperature setting after peak hours. At the same time, there is generally less variation between renters and homeowners within the low and middle-income brackets. The ANOVA results, however, did not reach statistical significance ($F (5, 1183) = 1.56$; $p = 0.167$), suggesting that the interaction between homeownership and income levels may have a limited impact on the willingness to extend the duration of AC reset time during peak hours.

The data was segmented by income level and divided by racial background, comparing White and Non-white individuals. As shown in Fig. 12, in the LIH category, there is no variation between White and Non-white individuals, with both groups reporting a willingness to wait 4.1 h before returning their A/C to the typical setting. Among MIHs, White individuals report a slightly higher willingness to extend (4.5 h) than Non-white individuals (4.2 h). In the high-income segment, the pattern shifts; Non-white individuals are more willing to delay resetting their A/C temperature (4.6 h) than White individuals (4.4 h). The graph indicates that, overall, there is a variation in willingness to delay returning the A/C to standard settings after peak hours when comparing White and Non-white individuals across different income levels, with the most significant difference observed in the HIHs. The ANOVA result highlighted the statistical significance of this interaction ($F (5, 1199) = 2.29$; $p < 0.05$), indicating the interplay of income levels and racial demographics significantly influences attitudes towards extending the duration of AC reset time during peak hours.

The interaction between homeownership and racial groups concerning the willingness to increase AC temperature for a specific time during peak hours shows similar results from each subgroup (Fig. 13). For White individuals, renters reported a willingness to wait 4.3 h before resetting their A/C to the typical setting, while homeowners reported a slightly higher willingness, with an average of 4.4 h. Regarding Non-white individuals, renters indicated a willingness to extend reverting to the typical A/C setting for 4.2 h, slightly less than White renters. Non-white homeowners, however, show a willingness equal to that of White homeowners, averaging 4.4 h. The results suggested that homeownership appears to have a minor impact on the willingness to delay the return to standard A/C settings after peak hours, with homeowners across racial groups reporting a marginally higher willingness than renters. However, the differences are subtle and indicate that the interaction of racial background and homeownership status have limited influence on these decisions. This assertion is supported by the lack of statistical significance ($F (3, 1183) = 0.71$; $p = 0.548$).

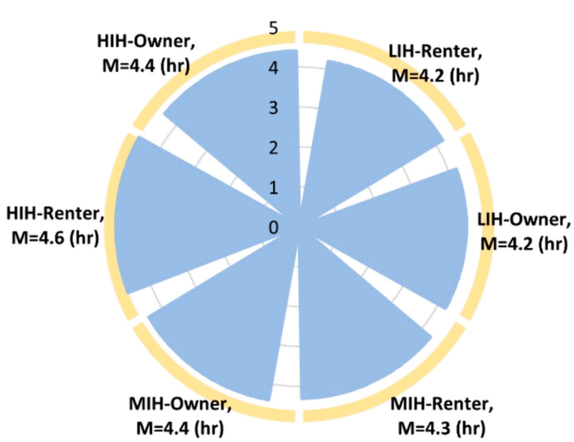

Fig. 11. Time of willingness to return AC temperature (hr) to the typical setting by income level and homeownership status.

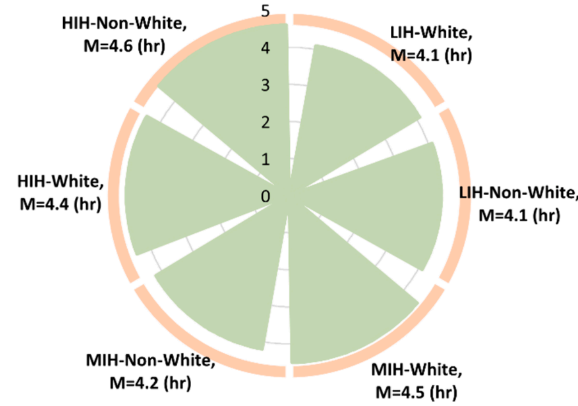

Fig. 12. Time of willingness to return AC temperature (hr) to the typical setting by income level and racial background.

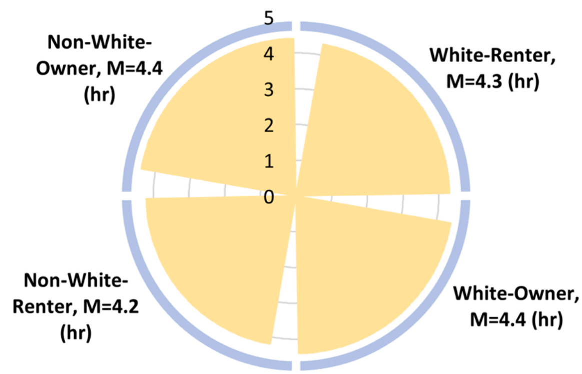

Fig. 13. Time of willingness to return AC temperature (hr) to the typical setting by homeownership status and racial background.

5.4. Potential psychological factors affected willingness to adopt HEMS

In the last section, this study shifts focus towards identifying potential psychological factors influencing individuals' intention to adopt HEMS for adjusting their AC schedule and temperature settings. The dependent variable under examination is the willingness to adopt HEMS, while four potentially influential variables—privacy concerns, AC reliance, environmental concern, and discomfort perception—will be explored. By examining the interplay between these variables, the research aims to discern patterns that shed light on the potential factors influencing adoption and behavioral adjustments. When analyzing continuous variables, it is beneficial to segment subjects into equal groups, such as by using quartiles, tertiles, or quintiles [43]. In this study, we applied two tertiles to divide the data for the three variables (privacy concern, AC reliance, and environmental concern) into three distinct levels: low, medium, and high. This categorization provides a nuanced approach for evaluating the ANOVA results, which in turn offers insights into the factors influencing individuals' decisions regarding energy management. Such insights are crucial for developing strategies to overcome barriers and promote the adoption of sustainable practices.

Regarding privacy concerns, the different levels of it were defined based on the average privacy score calculated through four questions regarding potential areas of concern among respondents' AC usage. From the average privacy concern score for AC usage, three groups were defined through two tertiles, sorting respondents into low concern, medium concern, and high concern. Average scores from 1.0 to 2.25 were assigned to low concern, 2.26 to 3.5 were assigned as medium concern, and 3.51 to 5.0 were categorized as high concern. The investigation of the influence of privacy concerns on the willingness to adopt HEMS shows discernible patterns within different privacy concern groups, as shown in Fig. 14. Notably, individuals with low privacy concerns exhibited the highest percentage of respondents very unlikely to adopt HEMS, with 11.1 % of low privacy concern respondents very unlikely to adopt, while medium concern had 7.8 % and high concern had 6.1 %. Additionally, the medium concern level group indicated the highest percentage of respondents at the neutral level (46.4 %), and the high concern level group demonstrated the highest percentages compared to the other two groups at both the likely (36.9 %) and very likely (20.1 %) willingness levels. The Chi-square test results indicated a significant association (χ^2 (8, 1200) = 61.39; $p < 0.001$), which suggests that there is a strong relationship between privacy concerns and the willingness to adopt HEMS.

The respondents' AC reliance and its impact on the willingness to adopt HEMS show patterns within different reliance levels. This study defines the three levels of AC reliance by categorizing the average AC reliance score determined by a series of questions inquiring about respondents' need for AC for daily life. These three levels were divided through two tertiles and were defined as low reliance (1.0 to 2.32), medium reliance (2.33 to 3.67), and high reliance (3.68 to 5.0).

Individuals with low reliance exhibit a higher percentage of respondents who are very unlikely (11.3 %) and unlikely (9.9 %) than the other groups (Fig. 15). In contrast, individuals with high AC reliance present a more dispersed pattern, with slightly elevated percentages of the group reporting likely (33.9 %) and very likely (17.3 %) to adopt HEMS compared to the other two groups. The Chi-square test results indicate a statistically significant association (χ^2 (8, 1200) = 20.91; $p < 0.01$), demonstrating there exists influence from AC reliance on willingness to adopt HEMS. These findings suggest that individuals with lower AC reliance may be less likely to adopt HEMS, emphasizing the need for specific communication and outreach strategies to address respondents' particular concerns and preferences.

The investigation regarding the influence of respondents' environmental concern levels on their willingness to adopt HEMS highlights distinct patterns within the concern groups. Environmental concern levels were determined by calculating the average level through a series of questions. These averages were divided into three groups: low concern, medium concern, and high concern, through two tertiles. Respondents with an environmental concern score between 1.0 and 2.32

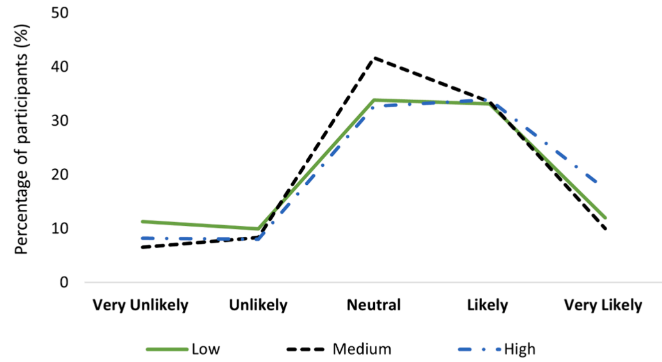

Fig. 15. Distribution of participants' willingness to adopt HEMS across different levels of AC reliance.

were assigned to the low-concern group. Scores between 2.33 and 3.67 were assigned to medium concern, and scores between 3.68 and 5.0 were assigned to high concern.

According to Fig. 16, the group with high environmental concern demonstrated the lowest percentage of respondents with very unlikely (5.8 %) and unlikely (6.8 %) adoption of HEMS, while in the likely bracket, the high environmental concern group has the highest percentage of respondents with 38.4 %. In comparison, medium concern had 23.1 % and low concern had 27.3 %. In the very likely bracket, the percentage of respondents from the great concern and low concern groups were similar, with 15 % of the high concern group and 15.9 % of the low concern group reporting very likely to adopt and showing similar adoption behaviors. The Chi-square test results underscore a statistically significant association between environmental concern and HEMS adoption (χ^2 (8, 1200) = 60.59; $p < 0.001$). This suggests that individuals with higher environmental concerns may be more inclined to adopt energy management technologies, indicating the potential for targeted initiatives to appeal to environmental values and behaviors.

The analysis of discomfort perception levels and the impact on respondents' willingness to adopt HEMS shows influence within different discomfort perception groups. This study divided the discomfort perception into three groups based on respondents' perceptions of discomfort associated with reducing electricity consumption during peak hours. Those who answered "strongly disagree" and "disagree" were classified into the low discomfort group, signifying a minimal discomfort association with peak-hour electricity reduction. Respondents who answered "neutral" were placed in the medium discomfort group, and those who answered "agree" or "strongly agree" were assigned to the high discomfort perception group. This stratification enables efficient examination of how varying levels of discomfort influence attitudes towards HEMS adoption.

In Fig. 17, Examining the very unlikely bracket, 10.6 % of the low

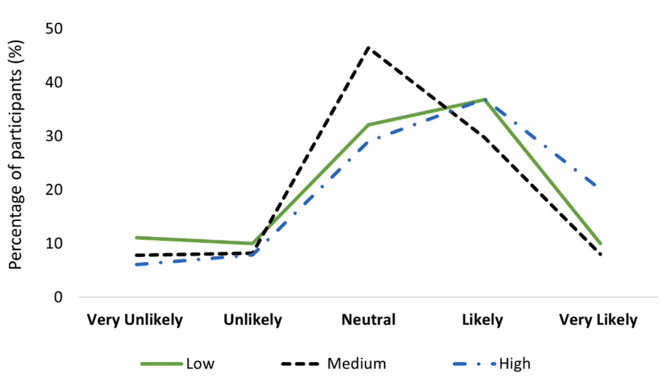

Fig. 14. Distribution of participants' willingness to adopt HEMS across different levels of privacy concern.

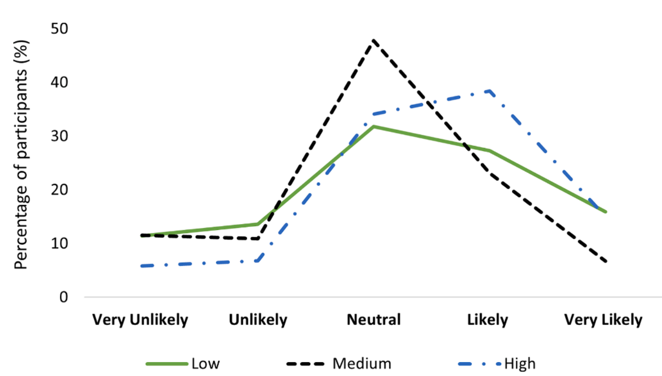

Fig. 16. Distribution of participants' willingness to adopt HEMS across different levels of environmental concern.

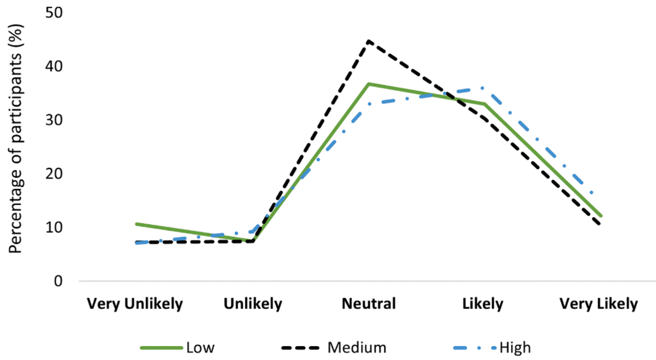

Fig. 17. Distribution of participants' willingness to adopt HEMS across different levels of discomfort perception.

discomfort perception group report being very unlikely to adopt HEMS, while only 7.1 % of the high discomfort perception group report being very unlikely to adopt. Conversely, the "likely" and "very likely" willingness brackets demonstrate similar behaviors across all three perception groups. In the "likely" bracket, 36 % are in the high perception group, 30.3 % are in the medium perception group, and 33 % are in the low perception group. Moving into the very likely bracket, the willingness over all three groups decreases nearly equally, with 14.8 %, 10.4 %, and 12.2 % of the high, medium, and low perception groups, respectively. The Chi-square results indicate a statistically significant relationship (χ^2 (8, 1200) = 18.51; $p < 0.05$), although this represents the least significant factor among the potential reasons evaluated in this section. This discovery suggests that while discomfort perception plays a role in shaping attitudes toward HEMS adoption, its influence may be less pronounced than other factors evaluated.

Exploring potential reasons influencing individuals' hesitancy to adopt HEMS and adjust their AC schedule and temperature settings influences privacy concerns, AC reliance, environmental concerns, and discomfort perception. The crosstabulation analyses and four significant Chi-square results indicate patterns within each influencing factor, providing insight into the nature of adoption behaviors. Privacy and environmental concerns strongly correlate with HEMS's willingness to adopt. While discomfort perception also influences adoption, its impact appears less pronounced than the other three factors addressed.

6. Discussion and policy recommendations

We aim to enhance our understanding of energy management across various populations by uncovering synergies between AC and EV demand flexibility. Our exploration is discussed and underscored through several key insights:

- A novel analysis of the intention to adopt decentralized HEMS, integrating investigations into AC and EV, is presented. Interestingly, across the entire sample, the study revealed a greater receptiveness towards the automation of AC usage compared to the scheduling of EV charging. This finding suggests a potential perception of the immediate necessity of AC for comfort or a higher level of trust in the predictability of AC usage patterns, in contrast to the potentially more variable requirements associated with EV charging. It is speculated that individuals may have had prior positive experiences with automated AC systems, such as programmable thermostats, which have become common in many households. However, given that EVs are relatively newer technologies, greater awareness and understanding of EVs may have focused more on promoting their benefits.
- Regarding the disparities between AC and EV demand flexibility across income groups, it is worth noting that LIHs are generally less flexible in adjusting load-reduction behaviors for both AC and EVs compared to MIHs and HIHs. Conversely, HIHs are less likely to decrease EV charging load because they rely on EVs and are less concerned about electricity costs. These findings suggest complex economic, environmental, and lifestyle factors influencing load-reduction behaviors, necessitating tailored policy interventions. Specifically, LIHs may face challenges adjusting EV charging schedules due to unpredictable schedules or limited charging infrastructure, while HIHs exhibit greater flexibility. Moreover, previous studies [44,45] have found that HIHs typically have more financial resources, allowing them to invest in energy-efficient appliances, smart home technologies, and EVs, contributing to their greater adaptability in managing energy consumption.

  Additionally, HIHs may have access to more comprehensive information and resources regarding energy management practices, enabling them to make more informed decisions about energy management strategies. Given these findings, targeted educational campaigns are essential for informing the public about energy management practices, especially vulnerable populations such as LIHs. These campaigns should emphasize available resources, offer practical conservation tips, and address common barriers. Moreover, targeted financial assistance and incentives can help overcome economic obstacles, enabling LIHs to adopt sustainable energy behaviors. Improving EV charging infrastructure in underserved communities can enhance the convenience of EV ownership for LIHs, facilitating their transition to cleaner transportation options.
- Our findings highlight nuanced distinctions between homeowners and renters in their willingness to adjust AC and EV charging settings, indicating greater flexibility among homeowners. Although Chi-square tests did not show significance, these findings suggest a potential interaction with homeownership regarding demand flexibility, warranting further investigation. The observed distinctions between homeowners and renters in their willingness to adjust AC and EV charging settings may stem from several factors. For instance, homeownership often signifies greater economic stability and control over one's living environment, leading homeowners to prioritize energy-saving behaviors and greater flexibility in adjusting settings. Additionally, homeowners typically have more control over their living space than renters, who may face restrictions imposed by landlords or lease agreements. Policymakers should empower renters by offering financial incentives and support for energy-efficient upgrades, such as subsidies for appliances, smart thermostats, and EV charging infrastructure in rental properties. Furthermore, exploring regulatory measures to bolster renters' rights and give them more control over energy usage in rental properties can contribute to a more sustainable future.
- Compared to the AC time-shifting results, the disparities between different racial backgrounds in EV charging time-shifting are more pronounced. This suggests that while attitudes towards adjusting AC temperature settings during peak hours exhibit a consistent pattern across racial demographics, the willingness to modify charging behaviors for EVs may be influenced by a broader range of factors, including socio-economic considerations, access to charging infrastructure, and perhaps cultural perspectives on energy usage and sustainability. These nuanced differences underscore the importance of considering multifaceted approaches to address demand flexibility and energy management initiatives, especially in emerging technologies like EVs. Understanding and addressing these disparities is crucial for designing equitable and inclusive strategies to promote sustainable energy practices among diverse communities.
- The investigation into factors influencing decentralized HEMS adoption unveils critical insights. Privacy concerns, AC reliance, environmental concerns, and discomfort perception all influence adoption willingness, with environmental and privacy concerns being the most significant. These findings emphasize the complex

interplay of factors shaping adoption and stress the need to consider multiple dimensions in promoting energy management technologies. While previous studies have made efforts to enhance privacy protection [46], there remains a lack of emphasis on investigating the relationship between HEMS adoption intention and individuals with varying degrees of privacy concerns. Surprising findings for privacy concerns reveal that higher levels of privacy concern are associated with increased willingness to adopt HEMS, challenging conventional assumptions. Conversely, individuals with lower privacy concerns show higher reluctance. This suggests a nuanced relationship between privacy perceptions and technology adoption. Addressing privacy concerns directly may be crucial for fostering broader acceptance of HEMS. These unexpected results emphasize the importance of reevaluating assumptions and conducting thorough research to inform policy in energy management and technology adoption. For instance, policy initiatives should prioritize transparency and reassurance regarding data privacy in HEMS implementation. Clear guidelines and regulations should be developed to safeguard user data and address privacy concerns directly. In addition, AC reliance also proved to be a significant factor, albeit to a lesser extent than privacy and environmental concerns. Individuals with lower reliance on AC were less likely to adopt HEMS, suggesting the need for tailored communication strategies to address concerns specific to AC usage patterns.

- The findings of this study suggest that individuals with higher levels of environmental concern may be more inclined to adopt energy management technologies as a means of reducing their environmental footprint and promoting sustainability. Further exploration of the underlying motivations and mechanisms driving this relationship could yield valuable insights for policymakers and practitioners seeking to promote sustainable energy consumption behaviors. For instance, targeted initiatives that emphasize the environmental benefits of HEMS adoption may resonate more strongly with individuals with heightened environmental consciousness. Additionally, highlighting the tangible environmental impact of energy management technologies through personalized feedback and educational campaigns could further incentivize adoption among environmentally conscious consumers.
- Lack of access to and familiarity with novel technologies are significant barriers to vulnerable populations' adoption of decentralized HEMS. Access to technology can be limited due to financial constraints or inadequate infrastructure in underserved communities [47,48]. Moreover, individuals from vulnerable populations may have limited exposure to or understanding of advanced technological systems, hindering their ability to navigate and utilize decentralized HEMS effectively. Additionally, disparities in digital literacy and access to training or educational resources may further exacerbate these barriers, creating additional challenges for adoption. The investigation provided in this study plays an essential role in identifying disparities of intention to adopt decentralized HEMS across various populations.

7. Conclusions

This study thoroughly explores intentions and barriers to adopting decentralized HEMS, explicitly emphasizing the justice dimension of demand flexibility. Through an innovative analysis examining HEMS adoption and demand flexibility in integrating AC and EV control, the research reveals significant socio-demographic disparities. Of particular note is the disparity in acceptance between allowing HEMS to adjust AC and EV settings; more individuals are willing to adjust their AC settings compared to their EV settings. This sheds light on the intricacies of energy management practices. The differential acceptance levels underscore the importance of considering the varied complexities and preferences surrounding energy usage in different contexts. It suggests that while individuals may be more open to relinquishing control over their AC systems to achieve energy efficiency, they may exhibit greater hesitancy regarding ceding control over their EV charging schedules. This disparity may be influenced by perceived convenience, comfort, or the importance of maintaining autonomy over vehicle usage patterns. It is essential to consider that individuals, particularly those from vulnerable populations, may have limited knowledge and understanding of EVs compared to more established technologies like AC systems. This lack of familiarity with EVs may contribute to the greater hesitancy in allowing HEMS to adjust EV settings.

On the other hand, implementing an energy management system to enhance energy efficiency or adjusting schedules for AC and EV usage can somewhat alleviate the energy burden. However, our findings suggest that vulnerable populations, such as low-income households, low-income renters, and people of color, may not consistently possess the flexibility or resources to shift their energy consumption patterns effectively. Factors such as limited income, housing circumstances, and constraints related to work schedules and daily routines may hinder their ability to participate in such programs. Consequently, these individuals may encounter difficulties fully benefiting from incentive programs, amplifying energy-related disparities, and exacerbating their energy burden.

The current study has specific limitations that could provide valuable directions for future research. Firstly, despite our thorough endeavors to match our sample with the demographic composition of California, it is essential to acknowledge the potential limitations regarding the generalizability to the broader population and the biases that may influence the interpretation of our findings. Future work should prioritize collecting data that accurately reflects the demographic composition of the study areas, thereby enhancing the applicability and relevance of research outcomes. Secondly, as this survey was conducted online, it may have created a gap in accessibility for specific underserved communities or individuals lacking internet access, potentially introducing bias. Nevertheless, it is worth noting that our statistical analysis has unveiled noteworthy relationships among the groups within our sample size. Thirdly, the study was conducted in California, where AC is prevalent, and the adoption rate of EVs is relatively higher in the U.S. However, it is important to recognize that these regional characteristics may limit the generalizability of our findings to areas with different climates and levels of EV adoption. Therefore, while our study provides valuable insights into the context of California, caution should be exercised when applying these findings to regions with diverse environmental and technological profiles. Future research could explore demand response behaviors in a more geographically diverse sample, encompassing regions with varying levels of AC penetration and EV adoption. Conducting comparative studies across different geographic contexts could lead to a more comprehensive understanding of the factors influencing demand response participation. Fourthly, since the proportion of EV owners is not as high as that of people who own AC units, some of the questions in our survey were asked based on the assumption that the respondent owned an EV. This may have resulted in certain deviations from the actual situation. Along with the gradual increase in EV adoption rates, our future work aims to conduct more extensive surveys with increased representation from EV owners across diverse demographics. Furthermore, incorporating qualitative research methods, such as interviews or focus groups, may provide deeper insights into the socio-cultural factors shaping energy consumption patterns and demand response preferences among various populations. These actions will enable us to gather more extensive data and insights into the perceptions and behaviors of EV owners, allowing for a thorough understanding of the factors influencing their decision-making processes and behaviors.

Understanding the intricate interplay among technical, psychological, and socio-economic factors is essential for developing policies and strategies prioritizing fairness and accessibility for all, regardless of socio-economic circumstances. Further research is needed to deepen our understanding of the underlying motivations driving individuals' attitudes toward adopting decentralized HEMS for AC and EV. This research will pave the way for more inclusive and effective strategies in promoting sustainable energy practices.

CRediT authorship contribution statement

Wei-An Chen: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Chien-fei Chen:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Stephanie Tomasik:** Writing – original draft, Investigation, Formal analysis, Data curation.

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.

Data availability

The data that has been used is confidential.

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