



Original research article

Does solar interest extend to battery storage? Understanding shared and distinct motivators of adoption among German households

Stephanie Stumpf^{a,*}, Daniel Sloot^{a,b}, Wolf Fichtner^a^a Institute for Industrial Production, Karlsruhe Institute of Technology, Karlsruhe, Germany^b Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology, Karlsruhe, Germany

ARTICLE INFO

Keywords:

Value-Belief-Norm theory
Theory of Planned Behavior
Diffusion of innovations
Residential photovoltaics
Home battery storage
Theory triangulation

ABSTRACT

Household battery storage systems (BSSs) are increasingly installed alongside residential photovoltaics (PV), yet behavioral research on BSS adoption remains limited. This study investigates whether established frameworks explaining PV uptake extend to BSS adoption and whether households perceive the two technologies as distinct or interconnected. Using a proposed integrated framework combining insights from Diffusion of Innovations theory, Theory of Planned Behavior, and Value-Belief-Norm theory, we surveyed German households ($N = 371$) and compared non-adopters, PV adopters, and PV-BSS adopters on psychological determinants of adoption.

Despite PV being perceived as somewhat more visible, socially endorsed, and environmentally beneficial than BSSs, households did not appear to evaluate PV and BSS as entirely separate decisions. Compared to non-adopters, both adopter groups expressed more favorable beliefs about the technologies, with PV-BSS adopters perceiving the strongest benefits, lowest expense concerns, and reporting the highest personal innovativeness. Measurement model comparisons further indicated that PV- and BSS-specific beliefs were highly correlated, pointing to a unified decision-making structure. Structural equation modeling revealed that adoption intention was positively associated with personal norms to use renewable energy, perceived social approval, innovativeness, and perceived personal benefits, while expense concerns were related to lower intentions. Overall, our integrated model explained 42% of the variance in intention. Perceived control over installation was not significantly related to intention. These findings provide empirical support for a triangulated theoretical framework in the context of household energy technology adoption, underscoring the inclusion of norm activation processes into models of PV-BSS adoption and potentially other low-carbon technologies.

1. Introduction

Energy generated from photovoltaics (PV), including rooftop residential PV, is a central pillar of the sustainable energy transition in many countries. In recent years, interest in storing energy from residential PV in home battery storage systems has grown exponentially. This trend might have been triggered by structural factors, such as rising retail electricity prices, sharply decreasing costs of lithium-ion batteries, and reductions in feed-in tariffs [1,2], all of which provide economic opportunities for self-consumption. In Germany, the number of battery storage systems (BSSs) installed alongside residential PV has steadily increased over recent years. This uptake resulted in 80% of all new PV systems including a BSS in 2024, bringing the cumulative number of BSS installations to roughly 1.8 million nationwide [3]. The German context

is particularly relevant, as it represents a comparatively advanced diffusion context for residential PV and, increasingly, household battery storage, in which adoption has been shaped by a changing policy environment. Under the Renewable Energy Sources Act (EEG, [4]), residential PV was historically supported by high feed-in tariffs that declined over time and, together with high retail electricity prices, have increasingly shifted the economic rationale of residential PV toward self-consumption [5]. Beyond household-level benefits, residential battery storage can provide significant system-level benefits to local energy grids. BSSs can enable households to use solar energy generated at midday during evening hours, supporting demand-side flexibility. Such flexibility can contribute to aligning electricity consumption with fluctuating renewable supply and reducing grid stress during peak hours and in regions with high PV penetration [6]. These systems thus significantly

* Corresponding author at: Chair of Energy Economics, Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Hertzstraße 16, 76187, Karlsruhe, Germany.

E-mail address: stephanie.stumpf@kit.edu (S. Stumpf).

<https://doi.org/10.1016/j.erss.2026.104996>

Received 12 March 2026; Received in revised form 11 September 2026; Accepted 24 September 2026

Available online 8 October 2026

2214-6296/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

Open access funding enabled and organized by Projekt DEAL.

enhance both the effectiveness and efficiency of demand-side flexibility by reducing risks of congestion, reverse power flows, and the need for renewable curtailment [7]. Though this study focuses on household-level benefits and decision-making processes, these system-level benefits are important for understanding the socio-technical relevance of BSS adoption.

Despite the multiple technical and social functions battery storage systems might address, academic and policy discussions of the residential sector tend to focus primarily on solar adoption without storage, thereby neglecting potentially distinct drivers and barriers for the adoption of storage systems. Thus, while household decision-making and social acceptability for rooftop PV adoption have been extensively investigated [8–10], determinants of BSS adoption remain comparatively underexplored in spite of the technology's economic and technical relevance [11,12]. Given the frequent co-adoption of PV systems and BSSs, coupled with overlapping incentives and technical context, similar behavioral drivers of adoption might be expected. Yet, the two technologies differ in important aspects, such as purchasing costs and specific benefits they provide to the household. This puts into question whether their adoption can be treated as one, and empirical evidence suggesting that PV adoption insights might extend to BSSs is currently limited [11]. Previous studies of PV adoption have advanced theory by integrating motivations, drivers, and barriers from the theory of planned behavior [13], value belief norm theory [14], and diffusion of innovations theory [8,9,15–17]. However, a similarly comprehensive theoretical foundation has yet to emerge for battery storage (or coupled) adoption. Building on the well-established literature on PV adoption therefore provides a valuable basis to ground new empirical work on BSS within a mature conceptual framework and to explore whether comparable motivational mechanisms apply. Moreover, most existing studies on PV adoption focus on non-adopters only, trying to understand decision-making regarding future PV installations. Yet a growing stream of research systematically compares the two groups of adopters and non-adopters (see, e.g., [18–22] and a comprehensive review by Alipour et al. [16]). Initial evidence suggests potential variation across adopter groups regarding socio-demographic and motivational characteristics for PV-only and PV-BSS adopters, as shown by Alipour et al. [11]. Although their study did not explicitly test for differences between the groups, the descriptive patterns point to the value of further differentiating adopter types. However, studies comparing these groups with respect to psychological factors prevalent in established theories of PV adoption are scarce, which limits current theoretical understanding of BSS adoption. At the same time, adoption decision-making is highly contextual due to differences in energy systems, market structures, and policy incentives. Thus, it is essential to validate and refine theoretical developments within different contexts, such as adoption in Germany, whose advance diffusion context might serve as a model for other countries.

Building on these research gaps, the present study aims to advance understanding of household adoption of PV and BSS by empirically examining how established behavioral frameworks explaining photovoltaic adoption apply to battery storage adoption in the German context. Specifically, the study examines the following research questions:

1. Do households perceive PV and BSS technologies similarly or differently?
2. How do non-adopters, PV-only adopters, and PV with BSS adopters compare with respect to theory-based psychological determinants of adoption?
3. Does decision-making for PV and BSS reflect a shared structure or technology-specific structures, and how are motivational and belief structures related to adoption intention for the technologies individually and in combination?

In addressing these questions, the study develops and applies a

triangulated theoretical framework that integrates key behavioral theories frequently used in PV adoption research, thereby extending their empirical validation to BSS adoption. Our findings show that households evaluate PV and BSS through a largely shared belief structure rather than as fully separate technologies. This study thereby contributes to bridging the empirical and theoretical divide between photovoltaic and battery storage research and advances the development of more comprehensive models of household energy technology uptake that span different technologies.

In the remainder of this paper, we review the existing empirical literature on BSS adoption and develop our integrated conceptual model by reviewing existing empirical work on the integration of theories on sustainable behaviors and technology adoption, including PV adoption. Then, research methods involving survey participants and procedure, measures, and the analytical approach of group comparisons and structural equation modeling are presented. Next, we report study results before discussing implications, limitations, and suggestions for future work.

2. Literature review

2.1. Existing literature on PV and BSS adoption

In recent years, empirical work investigating the determinants of household decision-making in renewable energy technology adoption has advanced rapidly (for an overview, see [10,16,23,24]). The most prominently investigated technologies in this field are alternative-fuel vehicles [25,26], energy-efficient appliances [27–29], and residential PV systems. The adoption of PV systems in particular has been investigated from diverse perspectives, including economic, socio-psychological, and sociological research. Reviews and meta-analytic studies on PV and related household energy technologies have especially consolidated evidence on psychological and socio-technical determinants, which form the focus of the following sections. Behavioral-economic perspectives on rational choice, heuristics, and biases offer complementary insights into household energy decision-making, but fall outside the primary theoretical scope of the present study. Several meta-analyses have summarized the main drivers and barriers related to PV decision-making (PV in specific: [8,9], renewable energy technologies more broadly: [10,24]). Across these meta-analyses, the most impactful and consistent determinants of household PV adoption were found to be positive evaluations of PV, operationalized as attitudes or perceived benefits, and external economic factors, which show the largest pooled associations with individuals' intention to adopt. Moreover, subjective norms have a smaller but reliable positive effect. General motivations, such as environmental concern and innovativeness, also correlate with adoption intentions. In contrast, the influence of socio-demographic variables and perceived behavioral control is often weak or negligible, although existing barriers, such as roof suitability can reduce adoption intentions [8,9].

Despite this comprehensive literature on PV adoption, only a few studies have investigated determinants shaping the decision-making of battery storage systems. Existing empirical research across Germany, Australia, and the United States highlights how household and community characteristics, as well as economic and psychological motives, shape BSS adoption. In both Germany and Australia, discrete choice experiments demonstrate that upfront costs, anticipated savings on electricity bills, and a desire to achieve self-sufficiency and reduce reliance on electricity companies strongly influence the decision to adopt [30,31]. These findings are consistent with prior studies by Gähns et al. [32] and Ecker et al. [33], which show that beliefs about personal benefits, especially related to independence, can act as drivers of BSS adoption.

In a study among PV owners, Poier et al. [34] primarily examined the role of general personal values to distinguish between BSS adopters and non-adopters, finding that conservation (also referred to as

traditionalism) had a negative influence, while self-transcendence (altruism) had a positive effect on the adoption decision. Environmental concern, however, appeared to have no effect on the decision to purchase BSS. In a more recent study, Poier [35] emphasized both personality traits and perceived risk dimensions as key factors distinguishing battery adopters from non-adopters. Compared to PV-only adopters, battery adopters perceived lower financial risk and exhibited greater extraversion as well as emotional stability. These findings indicate that economic feasibility might constitute an adoption barrier, but individual characteristics and risk perceptions of potential adopters might be important next to objective cost structures. Brown [36], analyzing residential battery installations under California's Self-Generation Incentive Program (SGIP), examined adoption rates across over 1500 zip codes. Adoption was found to concentrate in communities that have higher household income and lower environmental justice concerns. These findings show that communal settings and structural access play a decisive role in determining where residential battery adoption accumulates. Besides financial factors, moral, social, and affective factors are important determinants of BSS adoption. In Australia, Alipour et al. [12], using a hybrid discrete choice and latent-variable model, found that energy autonomy was the strongest predictor of integrated PV–battery adoption, especially for non-adopters considering their first installation. McCarthy and Liu [37], surveying 557 Queensland homeowners, extended this finding by demonstrating that social and identity factors as well as technical and load-shifting interest exert significant influence on acceptance.

Recent research has also differentiated between different adopter groups. Alipour et al. [12] found that people who had already adopted a PV system stated that battery size was decisive in driving adoption, while those who had not adopted indicated that achieving autonomy was most important. In a separate study, McCarthy and Liu [38] found that households that already engage with PV exhibit stronger acceptance, fewer concerns, and are typically in a higher income group than non-adopters. Poier [35] further investigated differences between combined PV-BSS adopters and PV-only adopters, identifying that adopters of both technologies were typically younger, more extraverted, and less financially risk-averse than PV-only owners.

Overall, the existing evidence underscores that household decision-making around battery storage is best understood as the outcome of numerous economic, psychological, and social factors. Many of these factors align closely with the conceptual dimensions emphasized in research on PV adoption. Consequently, these findings provide a valuable empirical foundation for linking battery storage adoption to the theoretical frameworks that have been most influential in explaining photovoltaic adoption behavior.

2.2. Theory triangulation and conceptual model

Building on the theoretical foundations that have been most frequently applied to explain household PV adoption, this section develops a conceptual framework for analyzing household decision-making regarding PV and BSS. Among the various theories used to understand household decision-making for installing PV systems, three theories have repeatedly provided successful explanations for adoption, namely the diffusion of innovations theory (DOI) [15], the theory of planned behavior (TPB) [13], and the value belief-norm theory (VBN) [8,9,14,16,17,39]. These theories cover different strands of explanation, as PV-BSS adoption can be understood as a multi-faceted decision context [40]. It may reflect a rational consumer choice involving an evaluation of tangible costs and benefits, a pro-environmental behavior grounded in moral obligations and value-based motivations, or a response influenced by the diffusion process of novel technologies. These perspectives do not necessarily represent competing explanations but may address different levels of decision-making that operate concurrently. Specifically, the TPB captures deliberative and intention-based evaluations through attitudes, subjective norms, and perceived

behavioral control [13], whereas VBN theory extends this perspective by accounting for internalized moral norms and value-driven motivations that are particularly salient in environmentally consequential decisions [14]. DOI complements both approaches by introducing an innovation-oriented perspective that emphasizes how perceptions of technological novelty, compatibility, and observability influence adoption propensity [15]. Prior integrative applications in the residential energy context further support this theoretical combination, demonstrating that these frameworks can be meaningfully combined to explain household investment behavior (e.g., [17,40]). Taken together, integrating these perspectives enables a more comprehensive understanding of household PV-BSS adoption by accounting for the interplay between rational evaluation, normative commitment, and innovation-related adoption processes.

From an innovation diffusion perspective, DOI theory emphasizes that the uptake of an innovation depends not only on the technology's characteristics, but also on the characteristics of the adopter, such as a person's general tendency to try new technologies or behaviors. On the other hand, the TPB adopts a framework for rational decision-making and assumes that a person's behavior is primarily determined by their intention to behave in a certain way, which in turn is driven by the three factors of attitude, subjective norms, and the perceived ability to perform the behavior under consideration. In contrast, VBN theory mainly emphasizes personal norms, understood as feelings of moral obligation, as the main determinant of environmental behavior, such as adopting PV. Empirical studies have shown that these theories contribute to understanding decision-making processes for or against installing PV systems more in a complementary way than as competing theories [17], suggesting value in combining them to understand adoption behavior holistically. To address this heterogeneity of determinants across the two technologies, we triangulate these three behavioral theories, building on the integrative model of PV adoption proposed by Wolske et al. [17]. More recent research has produced additional evidence on the integration of these three theories. Thus, we reviewed existing evidence of pro-environmental behavior and technology acceptance beyond PV that integrates two or all of the theories. This allows us to clarify well-supported cross-theory paths and to identify underexplored links between constructs from different theoretical perspectives.

A substantial stream of research shows that combining VBN's moral-normative pathway with TPB's socio-cognitive predictors improves the explanatory power for sustainable behaviors [41,42]. A meta-analytic review concluded that models integrating rational choice elements with personal moral norms perform better than single-theory specifications [43]. Within this integration, personal norm frequently emerges as a mediator or parallel driver of intention alongside TPB constructs. A recent meta-analysis reports that subjective norm exerts indirect effects via personal norm, which mediate the effect of subjective norms on intention [44]. Primary studies similarly indicate that social normative pressures can activate feelings of moral obligation, with subjective norms positively predicting personal norms as well as ascription of responsibility (AR) [45]. Evidence on cross-links to other TPB components is mixed. Han et al. [46] suggest that attitude impacts personal norms in the context of eco-behavior among hotel guests, but across most studies integrating VBN and TPB, personal norms and attitude typically operate as independent antecedents of intention. Overall, the most consistently supported relationship indicates that personal norms might act as a mediator between subjective norm and intention, while personal norms and attitude tend to operate as independent, additive determinants of intention.

Complementing the findings connecting TPB and VBN, studies integrating DOI and TPB emphasize the role of an individual's innovativeness in shaping evaluations of the technology considered. Across multiple domains, including sustainable consumption, energy, mobility, and digital services, empirical studies show that consumer innovativeness is positively associated with attitudes toward the focal technology

and, in some cases, with stated adoption intentions [e.g. 47–55]. Several contributions further indicate that innovativeness positively impacts perceived usefulness, perceived ease of use, and perceived personal as well as environmental benefits, thereby strengthening beliefs and intentions across domains [e.g. 51,52,56,57]. Some studies have reported innovativeness exhibits a direct positive effect on intention [58,59]. In addition, Vu et al. [55] show that Innovativeness acts as a moderator between attitudinal evaluations and intention in the context of rooftop PV adoption in Vietnam.

With respect to perceived behavioral control, research on sustainable energy behavior suggests that innovativeness is positively related to perceived control [40,57]. With regard to subjective norms and DOI, a meta-analysis by Schulte et al. [9] shows that both subjective norms and innovativeness have a significant positive effect on perceived benefits of PV systems. Moreover, the authors indicate that subjective norms may influence the intention to adopt PV indirectly through increasing perceived benefits of adoption, rather than directly. Consistent with this account, primary evidence in a household PV context shows that perceived benefits are positively related to attitude and intention [60]. Findings for observability (another DOI variable) are mixed across settings. In an education-technology context, observability is not significantly associated with attitude [61], whereas studies in household energy domains show that observability relates positively to attitude for green appliances in South Africa [62] and to both attitude and intention for household PV in Malaysia [60].

Direct empirical links between DOI and VBN are scarce. Beyond the integrative approach by Wolske et al. [17], we did not identify studies that explicitly connect VBN variables to DOI attributes within a single empirical model. However, a study by Sloot et al. [57] examined participation in demand response programs in an integrated model of personal motivations, beliefs, and norms. One of the personal motivations measured was innovation-seeking self-identity, which was measured in a similar way to innovativeness. Their study showed an indirect effect of innovation-seeking self-identity on intention to participate via personal norm.

In summary, the most consistently supported cross-theory relationships are: (i) social influence shaping moral obligation, with personal norm mediating the effect of subjective norm on intention [44,45], (ii) consumer innovativeness being associated with more favorable attitudes and beliefs (e.g., perceived benefits of the adopting technology) and, in several studies, directly with intentions [47–49,51,52,56,58,59], and (iii) subjective norms associated with higher perceived benefits and, consequently, stronger intentions through belief-based pathways in the context of PV adoption [9,60]. In contrast, DOI–VBN connections remain underexplored within our domain. Building on the integrated model examined by Wolske et al. [17] and the literature discussed above, we propose an adapted integrated model for the context of PV and BSS adoption. In line with the TPB, our integrated model assumes that intention to adopt an energy technology is significantly impacted by attitudes, subjective norm, and PBC. In this context, attitudes are described as various facets of beliefs regarding the technologies. These beliefs may be influenced by subjective norms and observability of the technology, as perceived approval or adoption by relevant others can provide social information about the benefits of the technology, which, in turn, depend on the individual's innovativeness, as described within the DOI. In addition, personal norm is included in the model as a predictor of intention in accordance with VBN theory, while subjective norm directly affects personal norm. Furthermore, our integrated model suggests that ascription of responsibility, awareness of consequences and biospheric values act as key antecedents of personal norm. The interrelationships between these constructs follow the original casual chain of the VBN theory, with the exception that we exclude the New Ecological Paradigm (NEP) construct as an intermediate predictor to maintain model parsimony, given its close conceptual and empirical overlap with awareness-of-consequences beliefs already represented in the model [63].

Thus, following the reviewed evidence on theoretical integration, we make three substantial adjustments to the Wolske et al. [17] model: First, we include the indirect effect of subjective norm on intention via personal norm. Second, we add a path from subjective norm to attitudinal evaluations, which is aligned with the meta-analysis by Schulte et al. [9]. Third, we do not include the factor of social curiosity in our integrated model, as it has not been examined further in the literature, and instead focus on the main outcome of adoption intention. Our integrated conceptual model is shown in Fig. 1.

3. Materials and methods

3.1. Participants and procedure

In order to test our conceptual model, we conducted an online survey among German homeowners that was distributed via a commercial online panel between August and September 2022.¹ The sample was representative of the German population regarding gender and age. Compared to the overall German population, the respondents in our sample had a slightly smaller number of household members. Complete responses included those participants who passed an attention-check item and whose completion time was above one-third of the sample median completion time, which was 15.4 min. The final sample included 371 respondents (see Table 1 for general sample composition).² Within the final sample, 17.0% already had installed a PV system and 8.4% also had a battery storage system.

Overall, the survey comprised sociodemographic as well as building characteristics and questions about renewable technologies already installed, before assessing variables corresponding to the three theories of DOI, TBP, and VBN. While some of the measures captured general individual characteristics or motivations (e.g., values), others were specific to the targeted technology (e.g., beliefs about advantages of BSS). These variables were asked separately for both technologies, PV systems as well as battery storage systems.

3.2. Survey measures

Since our integrated model is based on Wolske et al. [17], most items relating to PV systems were used from this study, and the corresponding items referring to BSS were adapted accordingly (unless otherwise specified in the following). For any additional variables that were not used by Wolske et al., such as further VBN variables, we consistently employed previously used measures, as indicated below. Lastly, all measures were translated into German. Unless otherwise specified, we employed a five-point Likert scale ranging from “strongly disagree” (1) to “strongly agree” (5). A complete list of the English translations of the items used can be found in the Supplementary materials.

3.2.1. General characteristics

Since only *biospheric values* had a considerable significant impact on intention in the integrated model by Wolske et al. [17], we only measured biospheric values within our model. The value scales are based on Schwartz [67] and Stern et al. [68], of which we used a

¹ Respondents were recruited through *GapFish* (a *CINT Group Company*), an ISO 20252-certified online access panel provider. According to the provider's panel documentation, GapFish applies panel-level quality controls including double opt-in registration, automated verification procedures, manual participant review, duplicate checks and identity validation, and individual risk scoring. Respondent incentives were administered by the panel provider and may vary across panel sources, including monetary, points-based, or donation-based incentives.

² We originally conducted the survey using a sample that also included tenants, but we only used the sub-sample of homeowners for our study, as they were the group relevant to our research question.

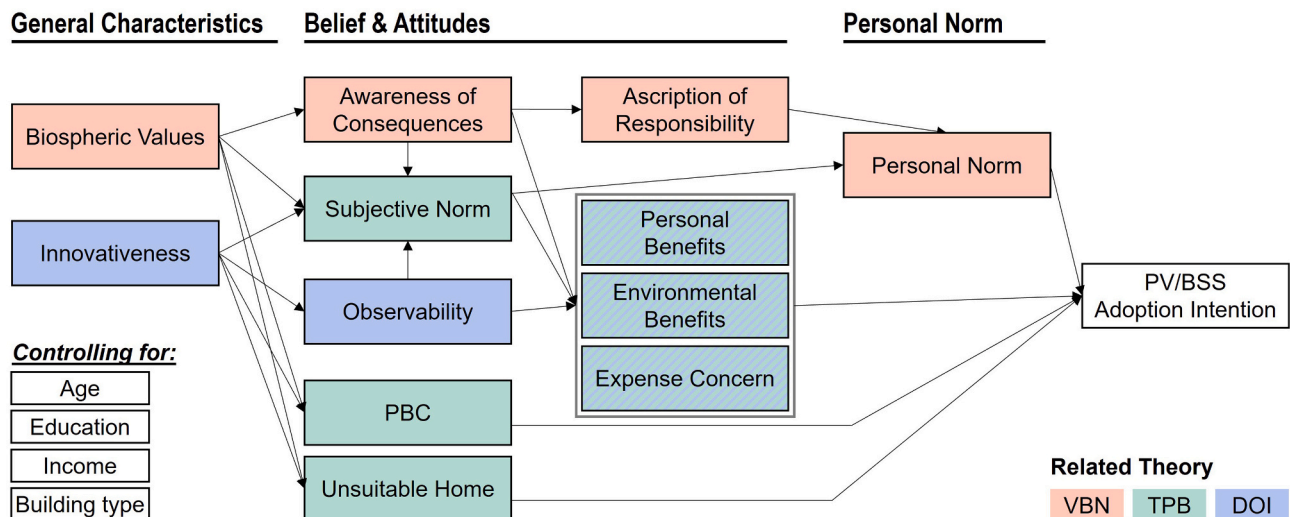


Fig. 1. Integrated conceptual model on PV and BSS adoption (arrows are only shown for the effect on the most proximate outcome, see A4 in the Supplementary materials for a full list of the indirect paths).

Table 1
Sample composition.

Socio-demographic variable	N	%	German population (%) ^b
Gender			
Female	189	50.9	50.7
Male	182	49.1	49.3
Age			
18–34 years	135	36.8	36.6
35–44 years	44	12.0	12.9
45–54 years	61	16.6	13.3
55–64 years	54	14.7	15.6
65 years or above	73	19.9	21.6
Monthly net income ^a			
Less than 1000 €	125	33.7	35.4
1000 €–1500 €	48	12.9	14.2
1500 €–2500 €	104	28.0	27.0
2500 €–3500 €	47	12.7	13.6
3500 € or more	47	12.7	9.8
Size of the household			
Single	43	11.6	20.6
Two-person	129	34.8	33.2
Three-person	68	18.8	17.6
Four-person or more	90	35.4	28.6

^a We asked for personal, not household income. Also, the reference for the overall German population refers to the year 2024, as there is no German data for individual net income in 2022.

^b Sources: [64–66].

shortened version similar to Steg et al. [69]. The scale captured items on the significance of protecting the environment, preventing pollution, and unity with nature as guiding principles. Values were measured on a 7-point Likert scale ranging from “opposed to my values” to “extremely important”. Innovativeness, a general characteristic from DOI describing the extent to which individuals seek out innovative and new products, was captured by a three-item-scale.

3.2.2. Beliefs, attitudes, and norms

As an extension of the integrated model by Wolske et al. [17], we further measured respondents' *awareness of consequences*. Items were adopted from earlier studies in which VBN was tested in the context of energy behavior [70,71], with minor modifications made. Thus, our final scale comprised three items, focusing on positive consequences of environmental protection and renewable energy for human health and quality of life. In the same way, we also measured ascription of responsibility with three items in line with Steg et al. [72]. These assessed

the extent to which individuals feel jointly responsible for energy problems and global warming. Moreover, we measured subjective norms as expectations that peers approve of installing PV and BSS [13]. In addition, as a key element of DOI is external social influences on adoption, we measured observability of the technologies with six yes/no questions indicating the extent to which PV and BSS were observed in the neighborhood or among peers. Three items referred to PV and three items referred to BSS. For the technology-specific analyses, we created separate PV and BSS observability indices by summing the three binary items for each technology and adding 1 to the resulting sum score, yielding indices ranging from 1 to 4. For analyses using the combined observability measure, all six binary items were summed and likewise shifted by adding 1, following the measurement approach by Wolske et al. [17] and resulting in an index ranging from 1 to 7. Unlike the other multi-point Likert-type constructs, this variable therefore represents a binary-item sum score and was treated as an observed index rather than as a latent construct in the SEM. Another key TPB element measured was PBC, which describes the perception of the subjective ease or difficulty of installing PV or BSS [13]. As for installing household technologies, the perception of the suitability of one's home for PV and BSS might be one facet of PBC. Thus, we additionally measured the factor *unsuitable home*, using a three-item-scale of perceived suitability for PV and BSS. Lastly, beliefs and attitudes toward the technologies integrate variables that overlap between TPB and DOI. Therefore, we measured beliefs about personal benefits, which capture the perceived advantages of both PV and BSS. These include protection against rising electricity costs or financial savings as well as protection against power outages. In addition, environmental benefits were measured, which cover the effectiveness of the technologies in tackling environmental challenges, as well as cost concerns, which assess the perceived affordability of PV and BSSs. Finally, as part of the VBN, personal norm was measured using three items that assess the extent to which people feel morally obliged to act on energy issues.

3.2.3. Household constraints

In addition to the predictors described, we included a number of socio-demographic and household characteristics that may affect a household's intention to adopt PV or BSS. Constraints that were included in the final SEM are income, education, age, and building type. For building type, we controlled whether or not it was a single-family home.

3.2.4. Adoption intention

Finally, adoption intention for installing PV and BSS was measured

using three items for each technology (“I intend to talk to an installation company for photovoltaic systems/battery storage in the next six months”, “I will be talking to an installation company for photovoltaic systems/battery storage in the next six months”, “I am interested in talking to an installation company for photovoltaic/battery storage systems”).

3.3. Analytic approach

To answer our research questions, we used a combination of statistical methods. First, in order to understand whether households perceive PV and BSS similarly or differently, we compared the endorsement of technology-specific beliefs between both technologies using (two-tailed) paired-samples *t*-tests. To do so, *p*-values were adjusted for multiple comparisons using Holm–Bonferroni correction [73]. These analyses were conducted in the full sample, comprising both adopters and non-adopters. In a next descriptive step, we analyzed if general characteristics, beliefs, attitudes, and norms differed between the households in our sample that had no technologies installed, only a PV system, or an integrated system with PV and BSS. Therefore, we compared the mean differences of all predictors using ANOVA or Welch's ANOVA, depending on the normality of the data and homogeneity of variances [74]. To account for multiple testing across the various omnibus group comparisons, *p*-values were again adjusted using the Holm–Bonferroni method. These analyses were also conducted in the full sample in order to obtain a descriptive comparison between the groups.

We examined our last research question in two parts, namely whether decision-making for PV and BSS is reflected by a shared structure or technology-specific structures, and how motivational and belief structures relate to adoption intention. First, we specified and compared two measurement models with identical items to examine the adequacy of the segregation of both technologies for respective factors of decision-making. In the first technology-specific model, the latent variables of subjective norm, personal benefits, environmental benefits, expense concerns, and PBC were constructed separately for each technology, such that each latent variable was measured exclusively by indicators referring to the respective technology (e.g., *PBC over PV* measured by items such as “Purchasing a photovoltaic system is entirely up to me,” and *PBC over BSS* by the corresponding item “Purchasing a battery storage system is entirely up to me”). In the alternative, shared-construct model, the same indicators for both technologies were specified to load onto common latent factors, implying that evaluations of both technologies reflect a unified decision-making structure. For each measurement model, a Confirmatory Factor Analysis (CFA) was performed in order to compare the latent structure, using the R package *lavaan* [75]. In all of our modeling steps, we addressed missing data using full information maximum likelihood estimation, which tends to produce less biased results than listwise deletion while maintaining statistical power [76]. Finally, we applied Structural Equation Modeling (SEM) to analyze how the various factors influence PV and BSS adoption intention, according to our conceptual model. Given that adoption intention was the outcome variable, this analysis was limited to households that had not yet adopted either technology. Direct, indirect, and total effects were estimated using nonparametric bootstrapping with 10,000 samples.

4. Results

4.1. Comparison of perceptions between PV and BSS

In order to examine the extent to which the decision-making process for purchasing battery storage systems differs from that for purchasing PV systems, we first compared participants' mean scores of PV and BSS-specific constructs. The results of the paired *t*-test, presented in Table 2, indicated significant differences between the two technologies for about half of the factors. PV systems were perceived as more visible within

participants' neighborhoods and social circles, with this difference showing a moderate effect size. The subjective norm toward PV was also more pronounced compared to BSS, but with a small effect. In addition, PV systems were viewed as slightly more environmentally friendly than BSS. On the other hand, the perceived personal benefits of both technologies and their perceived expense concerns did not show any significant differences. Also, the perceived behavioral control with regard to installing BSS was similar to that of PV.

4.2. Comparison of adopters and non-adopters

In order to understand the differences among groups of non-adopters, PV-only adopters, and PV-BSS adopters, we used a combination of mean difference methods, including ANOVA with Tukey's HSD post-hoc test and Welch's ANOVA with Games Howell post hoc. Fig. 2 shows the mean values and significance levels of the post-hoc tests of the various predictors for the different adopter groups. Mean comparisons show a consistent pattern across most variables, with the lowest mean scores among non-adopters, followed by higher values (signifying more favorable ratings) for PV adopters, and the highest for PV-BSS adopters (expense concerns, which were negatively framed, followed the opposite direction).

ANOVA results revealed significant effects of the adopter status on PV observability ($F(2,362) = 28.97, p < 0.001$), subjective norms about PV ($F(2,362) = 18.89, p < 0.001$), personal benefits of PV ($F(2,346) = 9.15, p < 0.001$), expense concerns regarding PV ($F(2,362) = 17.49, p < 0.001$) as well as BSS ($F(2,362) = 13.95, p < 0.001$), and PBC regarding BSS ($F(2, 362) = 6.51, p = 0.007$). Post-hoc Tukey tests indicated that PV observability and subjective norms about PV were significantly higher among both PV adopters and PV-BSS adopters compared to non-adopters ($p < 0.001$), with no difference between the two adopter groups. Personal benefits of PV were significantly higher for PV-BSS adopters compared to non-adopters ($p < 0.001$), but not compared to PV adopters ($p = 0.074$). Expense concerns (PV and BSS) were significantly lower for PV-BSS adopters compared to non-adopters ($p < 0.001$). PV-adopters also reported lower PV-related expense concerns than non-adopters ($p < 0.001$). Finally, PBC regarding BSS was higher for PV-BSS adopters than for non-adopters ($p = 0.002$), with no difference between the adopter groups ($p = 0.176$).

Welch's ANOVA found significant effects on innovativeness ($F(2, 47.58) = 12.92, p < 0.001$), awareness of consequences ($F(2, 49.77) = 7.11, p = 0.006$), ascription of responsibility ($F(2, 47.39) = 9.20, p = 0.002$), BSS observability ($F(2, 45.26) = 30.28, p < 0.001$), personal norms ($F(2, 50.06) = 10.14, p = 0.001$), personal benefits of BSS ($F(2, 51.70) = 15.15, p < 0.001$), subjective norms about BSS ($F(2, 51.78) = 15.49, p < 0.001$), environmental benefits of PV ($F(2, 51.56) = 14.15, p < 0.001$), environmental benefits of BSS ($F(2, 50.82) = 16.88, p < 0.001$), and PBC regarding PV ($F(2, 51.69) = 11.73, p < 0.001$). Games-Howell post-hoc comparisons showed that PV-BSS adopters reported significantly higher awareness of consequences ($p = 0.013$), responsibility ($p = 0.001$), personal norms ($p < 0.009$), personal benefits of BSS ($p < 0.001$), subjective norms about BSS ($p < 0.001$), environmental benefits (PV and BSS; $p < 0.001$), and PBC regarding PV ($p < 0.001$) than non-adopters. They also demonstrated greater innovativeness as well as BSS observability than both non-adopters and PV adopters. In addition, perceived environmental benefits of BSS were significantly higher for PV-BSS adopters compared to PV-only-adopters ($p = 0.003$). Interestingly, PV adopters perceived their homes less suitable compared to non-adopters ($p = 0.029$). No significant differences were found between PV adopters and PV-BSS adopters for the remaining variables. In summary, findings showed significant differences for the majority of predictors, most consistently between non-adopters and PV-BSS adopters. Exact overall ANOVA results, effect sizes, and 95% confidence intervals are reported in Table 3. Given the small and unequal adopter-group sizes, a sensitivity analysis using the harmonic mean of the group sizes indicated that the omnibus tests had 80% power to detect

Table 2Comparison of means between PV- and storage-specific beliefs ($N = 371$).

	Mean PV	Mean BS	95% CI		T	p-Value (two-tailed)	d (z)
			Lower	Upper			
Personal Benefits	4.16	4.14	−0.036	0.086	0.806	0.783	0.043
Expense Concern	3.72	3.74	−0.086	0.034	−0.858	0.783	−0.044
Environmental Benefits	3.82	3.65	0.111	0.231	5.594	<0.001	0.290
Observability ^a	2.64	1.82	0.703	0.941	13.564	<0.001	0.704
Subjective Norm	3.73	3.62	0.035	0.183	2.909	0.015	0.151
Perceived Behavioral Control	3.48	3.53	−0.110	0.000	−1.949	0.156	−0.101

Notes. 95% CIs are unadjusted; p values are Holm-adjusted to control for family-wise error rate across the six trait comparisons ($\alpha = 0.05$). d (z) displays Cohen's d for paired samples.

^a The scale for observability is 1–4 (others are 1–5).

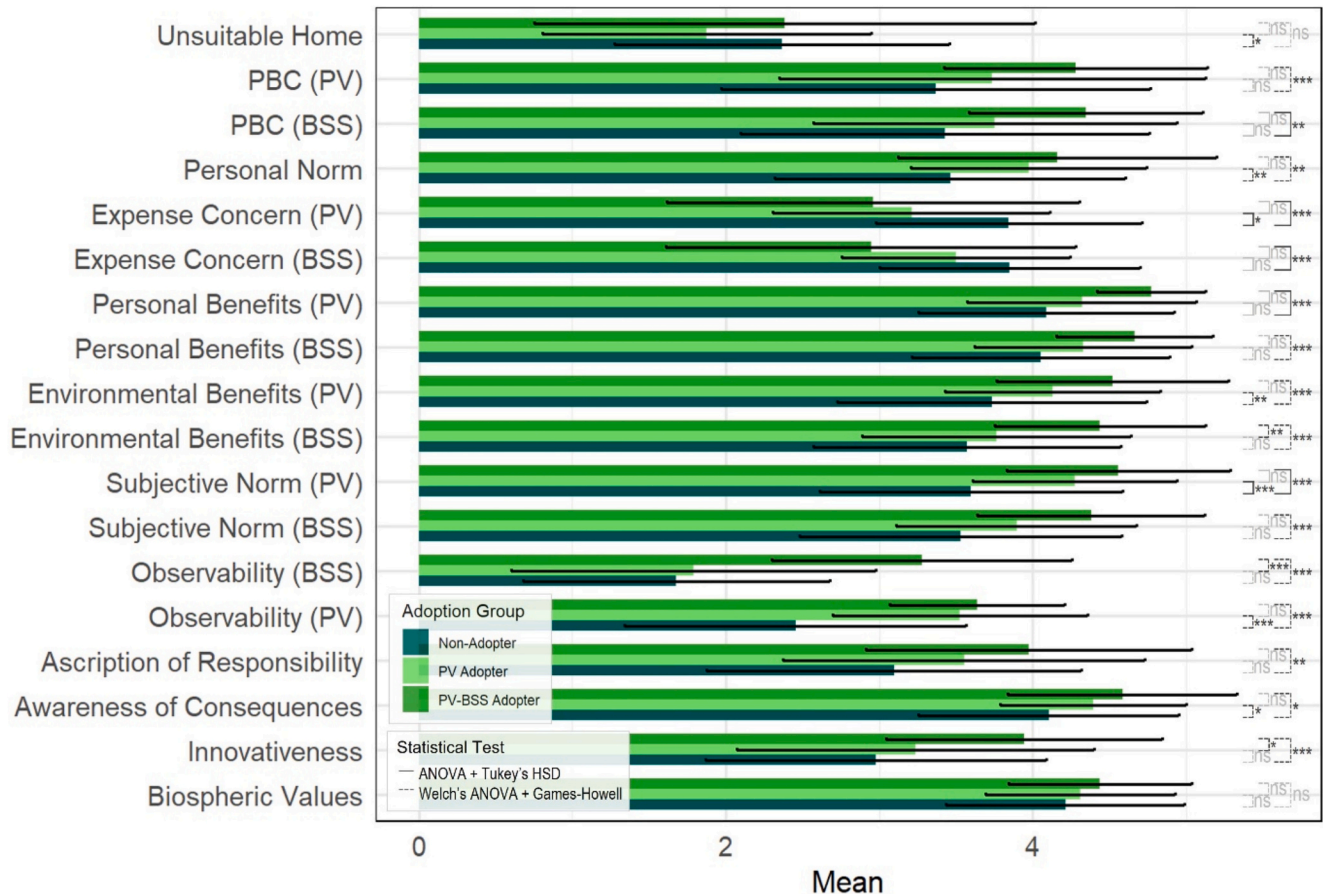


Fig. 2. Comparison of means across the different adopter groups (with standard deviation error bars).

effects of approximately Cohen's $f = 0.28$ or larger at $\alpha = 0.05$, corresponding to η^2 of approx. 0.07. Smaller group differences may therefore have remained undetected.

4.3. Comparing measurement models and measurement of validity and reliability

To further investigate the extent of overlap in the decision-making of PV and BSS, we compared a measurement model with separate latent factors of BSS- and PV-specific beliefs with a model specifying BSS and PV variables loading on combined latent factors. However, the model with separate factors of BSS- and PV-specific beliefs resulted in a non-positive definite covariance matrix, indicating estimation issues due to near-perfect correlations between beliefs about PV and BSS (see Supplementary materials). The inability of the model to converge indicates that the separate PV- and BSS-specific belief factors were empirically

non-distinguishable in our data, suggesting that households perceive PV and BSS adoption as interrelated rather than independent decisions.³ Therefore, the model with integrated technology-specific beliefs provides a more valid and theoretically sound representation of the data. This result indicates that participants may not differentiate strongly between the two technologies in terms of both their intention to adopt and determinants of intention, perceiving them as part of a unified construct rather than separate dimensions.

³ Due to the non-positive definite latent covariance matrix, the fit indices of the two models cannot be validly compared. Although the model with separate factors appeared to have better fit indices (e.g. χ^2 , CFI, RMSEA), these results cannot be interpreted due to the inadmissibility of the model. The CFA results of both models, including the diagnostic latent correlations from the separate-factors model are reported in the Supplementary materials.

Table 3
Full ANOVA results.

Construct	Test	F(df1, df2)	p-Value ^a	Effect size ^b	95% CI
Personal Norm	Welch ANOVA	10.14 (2, 50.06)	0.001	0.288	[0.113, 1]
Personal Benefits PV	One-way ANOVA	9.15 (2, 346)	<0.001	0.045	[0.014, 1]
Personal Benefits BSS	Welch ANOVA	15.15 (2, 51.7)	<0.001	0.369	[0.191, 1]
Environmental Benefits PV	Welch ANOVA	14.15 (2, 51.56)	<0.001	0.354	[0.176, 1]
Environmental Benefits BSS	Welch ANOVA	16.88 (2, 50.82)	<0.001	0.399	[0.219, 1]
Expense Concern PV	One-way ANOVA	17.49 (2, 362)	<0.001	0.083	[0.041, 1]
Expense Concern BSS	One-way ANOVA	13.95 (2, 362)	<0.001	0.066	[0.029, 1]
Ascription of Responsibility	Welch ANOVA	9.20 (2, 47.39)	0.002	0.28	[0.101, 1]
Awareness of Consequences	Welch ANOVA	7.11 (2, 49.77)	0.006	0.222	[0.061, 1]
Observability PV	One-way ANOVA	28.97 (2, 362)	<0.001	0.133	[0.081, 1]
Observability BSS	Welch ANOVA	30.28 (2, 45.26)	<0.001	0.572	[0.405, 1]
Subjective Norm PV	One-way ANOVA	18.89 (2, 362)	<0.001	0.089	[0.046, 1]
Subjective Norm BSS	Welch ANOVA	15.49 (2, 51.78)	<0.001	0.374	[0.196, 1]
Perceived Behavioral Control PV	Welch ANOVA	11.73 (2, 51.69)	<0.001	0.312	[0.137, 1]
Perceived Behavioral Control BSS	One-way ANOVA	6.51 (2, 362)	0.007	0.369	[0.191, 1]
Unsuitable Home	Welch ANOVA	3.49 (2, 44.1)	0.078	0.137	[0.004, 1]
Innovativeness	Welch ANOVA	12.92 (2, 47.58)	<0.001	0.352	[0.166, 1]
Biospheric Values	Welch ANOVA	1.73 (2, 50.07)	0.187	0.065	[0, 1]

Note. Tests compare non-adopters ($n = 308$), PV-only adopters ($n = 38$), and PV-BSS adopters ($n = 25$); six BSS-only cases with intended PV adoption were not included because they could not be assigned to one of the predefined comparison groups.

^a Reported p -values are Holm–Bonferroni-adjusted across the 17 omnibus group comparisons.

^b Omega squared (ω^2) is reported for standard one-way ANOVAs. For Welch ANOVAs, eta squared (η^2) and its 95% confidence interval were derived from the Welch F statistic.

Before running our integrated SEM, we evaluated the combined measurement model by analyzing the discriminant and convergent validity across five indices: factor loadings higher than 0.50 [77], Cronbach's alpha higher than 0.70 [78], the Composite Reliability above 0.70, average variance extracted (AVE) above 0.50 [77], and the Fornell–Larcker criterion to be met [79]. As shown in Table 4, all constructs met these criteria, providing support for the reliability and convergent as well as discriminant validity of the measurement model. Discriminant validity of the final unified measurement model using the Fornell–Larcker criterion is shown in Supplementary Table A2.3.

4.4. Structural equation model

The integrated structural model, explaining the intention to adopt a PV-BSS system using the combined factor structure established above showed an adequate model fit ($\chi^2 = 1318.2$, $df = 837$, $p < 0.001$; CFI =

Table 4
Validity testing of the integrated model.

Construct	Items	Factor loading	Cronbach's alpha	Composite reliability	AVE
Intention	INT1 INT2 INT3 INT4	0.962 0.892 0.944 0.851	0.95	0.952	0.834
Personal Norm	PN1 PN2 PN3	0.899 0.717 0.883	0.86	0.874	0.701
Personal Benefits	PB1 PB2 PB3 PB4	0.816 0.737 0.782 0.808	0.82	0.842	0.576
Environmental Benefits	EB1 EB2 EB3 EB4	0.842 0.870 0.841 0.797	0.90	0.904	0.702
Expense Concern	EC1 EC2 EC3	0.522 0.934 0.874	0.82	0.833	0.636
Ascription of Responsibility	AR1 AR2 AR3	0.857 0.893 0.888	0.91	0.911	0.774
Awareness of Consequences	AC1 AC2 AC3	0.826 0.732 0.817	0.83	0.835	0.628
Subjective Norm	SN1 SN2 SN3	0.779 0.885 0.731	0.84	0.842	0.642
Perceived Behavioral Control	PBC1 PBC2 PBC3	0.922 0.972 0.879	0.95	0.947	0.856
Unsuitable Home	UH1 UH2 UH3	0.859 0.646 0.856	0.82	0.834	0.629
Innovativeness	INN1 INN2 INN3	0.891 0.880 0.638	0.84	0.850	0.659
Biospheric Values	BIO1 BIO2 BIO3	0.846 0.877 0.778	0.87	0.873	0.697

CFI = 0.952, RMSEA = 0.045, SRMR = 0.044; $N = 308$.

0.944, RMSEA = 0.043, SRMR = 0.056).⁴ Table 5 shows the standardized coefficients for the direct and total effects on adoption intention, and Table 6 shows the direct effects on the predictors of intention.⁵ In addition, the results for the two separate models explaining the intention to introduce PV as well as BSS are available in the Supplementary materials. Consistent with our conceptual model, personal norms showed a significant direct association with adoption intention. In contrast, PBC and the perception of an unsuitable home were not significantly related with intention. Among the behavioral beliefs, personal benefits were positively associated with intentions, whereas perceived expense concerns showed a strong negative association. However, there was no

⁴ In the process of analyzing the measurement model, 12 items were deleted to reduce the number of items per construct. This was done primarily because the original number of items was measured to account for the possibility of separate latent factors. In the integrated model, however, this number of items was adjusted to a more balanced number in order to ensure model parsimony and estimation feasibility.

⁵ Given the complexity of the model relative to the available sample size, smaller and nonsignificant paths should be interpreted cautiously. To better characterize estimation uncertainty, we report bootstrapped standard errors and confidence intervals in the Supplementary materials and additionally examined multicollinearity among the latent predictors of adoption intention using the model-implied latent factor correlation matrix. Variance inflation factor (VIF) values ranged from 1.0 to 4.4, indicating some shared variance among predictors but no severe multicollinearity. Replication with larger samples would nevertheless be valuable.

Table 5

Direct and total effects for integrated PV-BSS model on Adoption Intention (standardized coefficients).

Independent variable	Direct effect	Total effect
Biospheric Values	−0.100 ($p = 0.195$)	−0.010 ($p = 0.878$)
Innovativeness	0.158 ($p = 0.026$)	0.295 ($p < 0.001$)
Observability	0.123 ($p = 0.034$)	0.225 ($p < 0.001$)
Awareness of Consequences	0.022 ($p = 0.827$)	0.203 ($p = 0.004$)
Ascription of Responsibility	−0.005 ($p = 0.966$)	0.153 ($p = 0.031$)
Subjective Norm	0.104 ($p = 0.174$)	0.195 ($p = 0.009$)
Personal Norm	0.273 ($p = 0.036$)	0.273 ($p = 0.036$)
Environmental Benefits	−0.123 ($p = 0.161$)	−0.123 ($p = 0.161$)
Expense Concern	−0.257 ($p < 0.001$)	−0.257 ($p < 0.001$)
Personal Benefits	0.231 ($p = 0.005$)	0.231 ($p = 0.005$)
Perceived Behavioral Control	0.032 ($p = 0.576$)	0.032 ($p = 0.576$)
Unsuitable Home	0.068 ($p = 0.272$)	0.068 ($p = 0.272$)
<i>Household Constraints</i>		
Age	0.015 ($p = 0.815$)	−0.112 ($p = 0.048$)
Income	−0.008 ($p = 0.891$)	0.130 ($p = 0.040$)
Education	0.021 ($p = 0.679$)	0.057 ($p = 0.299$)
Building type	0.042 ($p = 0.401$)	0.097 ($p = 0.050$)
R ²	0.419	

CFI = 0.944, RMSEA = 0.043, SRMR = 0.056; $N = 308$.

Note. The slightly lower CFI relative to the measurement model reflects the additional constraints imposed in the structural model.

significant link found for environmental benefits. In addition, none of the household constraints showed a significant direct relationship with adoption intention.

With regard to the indirect effects, awareness of consequences and ascription of responsibility were positively related to adoption intention through personal norm, as suggested by VBN. Moreover, subjective norms toward PV and BSS showed a significant indirect relationship with intention via personal benefits, but not via personal norms. Next, the perceived observability of the technologies was indirectly associated with intention via subjective norms. Lastly, the general characteristic of innovativeness showed an indirect relationship with adoption intention through all the significant predictors, except personal benefits. There were no indirect effects of biospheric values on the intention to adopt PV and BSS. A full list of the indirect effects specified with bootstrapped confidence intervals can be found in the Supplementary materials.

5. Discussion

5.1. Summary of findings and theoretical implications

This study examines household decision-making for photovoltaic and battery storage adoption within an integrated behavioral framework that combines the diffusion of innovations theory, the theory of planned behavior, and the value-belief-norm theory. Three key findings

emerge. First, households largely perceive PV and BSS through a shared structure of decision-making factors. Specifically, the measurement model comparison revealed that beliefs about both technologies are highly correlated and best represented by a unified latent model, indicating that for households without a PV or BSS system, both technologies are viewed as elements of one unified adoption decision rather than as independent choices. The non-positive definite covariance matrix of the separate-factors model further supports this result, as it resulted from near-perfect correlations between the corresponding PV- and BSS-specific belief factors. This interpretation may be especially consistent with the German BSS market context, in which the use of battery storage systems is exclusively linked to the self-consumption of solar power [80] and not, for example, to back-up power supply, as might be the case in other countries. The findings are likely most applicable to contexts in which residential PV is already well established and battery storage is primarily embedded in self-consumption strategies. Where storage adoption is more strongly connected to other functions, such as resilience or back-up power, the structure of PV- and BSS-related beliefs may differ and should be examined empirically. Nevertheless, mean differences show that PV systems are generally regarded as more visible, socially endorsed, and environmentally beneficial than BSS, while personal benefits, perceived control, and expense concerns appear similar across both technologies. These results suggest that households view PV-BSS adoption as a technology bundle, but still differentiate between the technologies themselves in terms of their social recognition and environmental meaning.

Second, the comparison of adopter groups revealed that adopters of both technologies show general adoption-related characteristics to a greater extent as well as more favorable beliefs and attitudes compared to non-adopters, with slightly lower values among PV-only adopters compared to PV-BSS adopters. Thus, our analysis extends the work by Alipour et al. [11], which indicates descriptive differences in motivators between PV-only and combined PV and BSS adopters but does not permit groupwise statistical comparisons between adopter types. Differences are most pronounced between adopters and non-adopters, whereas differences between PV-only and PV-BSS were observed primarily for battery-specific beliefs, including perceived observability, environmental benefits, and expense concerns of BSS, as well as for individual innovativeness. This pattern suggests that the distinction between PV-only and combined adoption is less related to broad attitudinal or normative differences and more to BSS-specific evaluations and general openness to innovation.

Third, our structural model demonstrates that adoption intention for integrated PV-BSS systems is jointly associated with social, moral, and innovation-related determinants. Subjective and personal norms, innovativeness, and perceived personal benefits are the variables most strongly related to adoption intention, whereas expense concerns show a

Table 6

Direct effects on the predictors in the integrated model (standardized coefficients).

Independent variable	Dependent variable									
	Observability	PBC	Unsuit. home	AC	AR	Subj. norm	Env. benefits	Expense concern	Pers. benefits	Pers. norm
Innovativeness	0.348***	0.216**	−0.008	0.530***	0.184*	0.251**	0.062	−0.194*	0.010	0.137**
Biospheric Values		−0.008	−0.119			0.167*	−0.142*	0.128	0.013	0.180**
Awareness of Consequences (AC)					0.460***	0.149	0.608***	−0.193*	0.210*	0.213**
Observability						0.257***	−0.061	−0.092	0.055	0.029
Subjective Norm							0.283**	0.000	0.470***	0.063
Ascription of Responsibility (AR)										0.577***
R ²	0.184	0.187	0.015	0.280	0.348	0.286	0.467	0.171	0.354	0.771

CFI = 0.944, RMSEA = 0.043, SRMR = 0.056; $N = 308$.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

strong negative correlation. Surprisingly, for our sample, perceived behavioral control and the perception of how suitable one's home is, do not have a significant effect on adoption intention, pointing to a setting in which adoption is less constrained by perceived ability and more related to openness to technological novelty and beliefs about the technology. In Germany's mature PV market, willingness to extend systems with storage may thus depend increasingly on adopter orientation rather than on structural barriers. Moreover, our SEM results indicate that the relationship between environmental benefits and adoption intention is non-significant and negative. Consistent with this finding, Wolske et al. [17] found no significant direct or total effect of environmental benefits on PV adoption intention. This finding partially aligns with a broader body of mixed evidence, as Alipour et al. [16] found significant effects of perceived environmental benefits in only half of the ten studies considered in their vote-counting review of the PV adoption literature. More recent evidence from Germany further supports a differentiated interpretation. A study by Scheller et al. [81] on the adoption of low-carbon technologies in Germany suggests that perceived environmental benefits may be more closely linked to general technology attitudes than to adoption intention. Their findings indicate that while environmental benefits contribute to favorable evaluations of PV systems, others, especially financial, considerations are related to actual adoption intentions. In our study, environmental benefits may therefore have been less decisive for adoption intention, potentially because other considerations, such as financial or self-consumption benefits, were more salient. More broadly, this pattern may suggest that recognizing the environmental advantages of a technology is not sufficient to motivate adoption intentions. However, the strong association of personal norms with adoption intention in our findings indicate that environmental motivations still play a role, though operating through a more intrinsic moral motivational route rather than through technology-specific environmental benefit perceptions.

When compared to the integrative model developed by Wolske et al. [17] for the U.S., the present findings show several similar core pathways, particularly the positive effects of perceived benefits, subjective and personal norms, and innovativeness. Yet, there are also differences, especially with regard to the role of the perception of an unsuitable home and the relative weight of expense concerns and observability. The non-significant effect of perceived behavioral control also warrants closer theoretical consideration. Rather than indicating that control-related factors are irrelevant for PV and BSS adoption, the finding may reflect how perceived control is operationalized in this context. For instance, in their review of determinants of PV adoption, Alipour et al. [16] show that behavioral control has been represented in previous empirical studies by a range of specific feasibility conditions, including affordability, home ownership and building type, payback periods, available knowledge, and household income. A general measure of whether installation is perceived as being within one's control may not fully capture these distinct financial, structural, and informational constraints. This interpretation is also compatible with our finding that income and building type show overall associations with adoption intention. Some aspects of financial feasibility may also be reflected in our expense concerns construct, which showed a strong association with adoption intention. This may indicate that specific perceived financial constraints are more strongly correlated with behavioral intention than a general sense of control. Accordingly, future research should examine whether PBC is best conceptualized as a general perceived-control construct, a multidimensional set of (physical or perceived) constraints, or a combination of perceived and objective feasibility indicators in the context of residential energy technology adoption. In addition, Wolske et al. [17] found a significant indirect relationship between biospheric values and adoption interest in their integrated model, despite a nonsignificant direct relationship. However, the overall association with adoption intention in our model was close to zero and nonsignificant. The direct coefficient was negative but likewise nonsignificant and should therefore not be interpreted as evidence that

stronger biospheric values reduce adoption intention. Instead, the difference between the negative direct coefficient and the essentially null total association may reflect a cancellation pattern in which relationships operating through different pathways offset one another. Differences in the outcome constructs and adoption contexts may also contribute to the divergent findings. Given the statistical uncertainty of both estimates, however, this pattern should not be overinterpreted. Moreover, the stronger role of observability and expense concerns might underscore the contextual sensitivity in later stages of diffusion, although this could also be related to the fact that Wolske et al. [17] measured interest in PV as a dependent variable and not the intention to install the technology. Overall, we see a cross-contextual similarity that supports the robustness and generalizability of the triangulated theoretical structure.

Our findings advance theoretical integration of adoption decision frameworks by further integrating previous empirical findings in the context of PV-BSS adoption. Specifically, beyond reproducing the core pathways in the integrated model by Wolske et al. [17], we integrated further cross-theory pathways. Building on the triangulated framework, our findings show that subjective norms are positively associated with perceived personal as well as environmental benefits. The corresponding indirect relationship with intention is consistent with the meta-analysis on PV adoption intention by Schulte et al. [9]. This evidence further suggests that normative approval may be linked indirectly to adoption intention through more favorable perceptions of technology benefits, in line with theorizing on informational influence [82]. However, our findings did not show a mediation of personal norms between subjective norms and intention, as suggested by the meta-analytic evidence by Helferich et al. [44]. The non-significant relationship between subjective and personal norms warrants further research, particularly since empirical evidence on this association remains scarce in the context of PV and BSS adoption. Existing meta-analyses, such as those by Li et al. [8] and Schulte et al. [9] did not incorporate personal norms. Against this background, our findings suggest that subjective and personal norms may represent distinct rather than sequential motivational pathways in the context of PV and BSS adoption. This interpretation also is consistent with the review-based framework proposed by Huijts et al. [83], which conceptualizes subjective and personal norms as adjacent determinants of sustainable energy technology acceptance. In addition, the non-significant association may also partly reflect the different levels of specificity of the measures, as subjective norms referred specifically to PV and BSS adoption whereas personal norms concerned energy-related behavior more broadly. Future research should therefore examine this relationship more directly across technologies and adoption contexts. Instead, in our sample, subjective norm is more strongly associated with belief formation. With regard to the cross-theory paths of innovativeness, we found direct links to subjective and personal norms, expense concerns and PBC, but not to environmental and perceived benefits. The positive association with perceived control accords with findings in residential energy upgrades reported by Klöckner [40]. Also, the direct links to subjective and personal norms extend the literature that typically connects innovativeness to attitudinal pathways [51,52,56]. Taken together, this suggests that in our context, innovation orientation operates less through technology-oriented beliefs about benefits and more through normative beliefs and negative beliefs about costs.

Overall, these findings demonstrate the explanatory value of combining DOI, TPB, and VBN perspectives. The weak role of perceived behavioral control further indicates that, under supportive institutional conditions, normative and attitudinal factors might dominate over perceptions of physical or financial constraint. The integrated framework therefore provides a coherent perspective for understanding household adoption of coupled technologies within mature energy markets. Notably, this study provides one of the first empirical tests of a triangulated DOI-TPB-VBN framework for integrated PV-BSS adoption. The results demonstrate that moral-normative factors remain influential alongside attitudinal and innovation-related considerations. While the

review by Alipour et al. [16] shows that moral and normative constructs are used infrequently in studies of PV or BSS uptake, our findings underscore their relevance and support the inclusion of moral activation processes into models of PV and potentially other low-carbon technology adoption.

5.2. Limitations and future research

While the study provides novel empirical evidence, several limitations have to be considered. First, despite the triangulation approach of three prominent theories, the analysis omitted certain further psychosocial variables identified as influential in prior meta-frameworks, such as environmental identity and environmental concern (see e.g. [84]). Including these constructs could improve the explanatory scope of future integrated models and contribute to a further theoretical integration. In addition, future research could assess objective feasibility constraints more directly, since the present study did not assess specific structural or ownership-related constraints, such as co-owner decision-making or required electrical modifications before adoption. These factors may be particularly relevant for households in multi-apartment buildings. Beyond objective feasibility barriers, the psychological perspective adopted in our study could be further enhanced by drawing more explicitly on microeconomic rational-choice approaches as well as research on heuristics and cognitive biases. This may offer additional insights into how households evaluate costs, benefits, and energy-related information when making adoption decisions [85,86].

Second, the sample size and limited representativeness restrict generalization beyond the studied population. The use of an online panel may have introduced selection bias, particularly if digitally engaged households were overrepresented relative to the broader German population. This limitation is especially relevant for the group comparison, as both adopter subgroups were small and the group sizes were highly unequal. Consequently, the analyses had limited sensitivity to smaller group differences, especially regarding comparisons between the two adopter subgroups. Significant differences may also be estimated imprecisely, while nonsignificant findings should not be interpreted as evidence of equivalence between groups. Accordingly, these comparisons should be regarded as exploratory and descriptive rather than as definitive evidence of adopter-group differences. Similarly, the SEM results should be interpreted in light of the complexity of the model relative to the available non-adopter sample size. Although model fit was acceptable and bootstrapped confidence intervals were used to assess uncertainty, smaller associations between variables may have been estimated with limited precision and should be examined in larger samples. Future replication with larger samples, including more balanced adopter samples and especially a larger group of BSS owners would strengthen the robustness of our findings. Future research with larger samples could also apply more comprehensive latent variable approaches that test measurement invariance and estimate latent mean differences next to structural relationships between technologies, rather than relying on conventional mean scores [87,88]. Such analyses would enable direct tests of latent mean and path differences while accounting for measurement error. As the diffusion of PV and BSS continues and larger samples become available, such analyses represent a promising avenue for future research. In addition, the timing of our data collection in August and September 2022 potentially limits generalizability of our findings, as Europe was experiencing exceptional energy market volatility following the escalation of the Russia–Ukraine conflict during that period. This specific temporal context may have increased the salience of energy prices and unusually heightened expense concerns, which should be considered when generalizing the findings to other periods.

Third, the cross-sectional correlational design precludes causal inference about the temporal ordering of attitudes, norms, and intentions. Relatedly, as we did not collect data on the timing of adoption among existing adopter groups, we cannot assess whether differences between adoption groups reflect pre-existing differences, post-adoption

experiences, or changing technological, market, and policy conditions at the time of adoption. The group comparisons should therefore be interpreted as descriptive rather than causal evidence. Future research should employ longitudinal panel designs to test causal mechanisms more rigorously, ideally observing actual adoption decisions beyond the formation of intentions. Comparative studies across national contexts could further reveal how institutional settings influence the relative strength of innovation-related and normative pathways. However, our findings highlight that understanding the diffusion of distributed energy technologies requires an integration of moral, social, and innovation perspectives.

Fourth, the self-report survey design represents a further limitation, as all constructs were measured using the same survey instrument and respondent source. Thus, the results may be affected by common method variance, which can inflate or otherwise bias observed associations between variables [89,90]. Future research could reduce this risk by combining self-reported perceptions with behavioral indicators, administrative data, or longitudinal designs.

Fifth, beyond the technology-specific beliefs and perceived benefits that we measured in parallel for comparability across PV and BSS, we did not include additional variables that might be motivators of the distinct features of these technologies, such as a desire for autonomy. As prior work indicates that autonomy and self-sufficiency can be decisive for BSS adoption, we included protection from future outages in the personal benefits scale as a conceptually related indicator. However, this does not entirely substitute for an explicit assessment of autonomy-related motives. Thus, future studies could include targeted items that reflect distinct attributes of storage and PV.

5.3. Practical implications and conclusions

From a practical standpoint, the high interdependence between PV and BSS evaluations suggests that communication and incentive schemes should address them as components of an integrated energy system. This is particularly relevant in the German context, where declining feed-in remuneration under the Renewable Energy Sources Act has increasingly shifted the economic rationale of residential PV from feeding electricity into the grid toward self-consumption. Because BSS can increase the share of self-generated electricity used within the household, PV and BSS may be perceived less as separate adoption decisions and more as complementary elements of a broader self-consumption strategy. Policies and communication strategies that not only emphasize the financial and practical value of integrating PV and BSS, but also connect this integrated system perspective to broader household benefits, such as autonomy, social visibility, and moral engagement, may be particularly effective. This implication also applies to BSS-specific installers and manufacturers, for whom communication should clarify the added value and system fit of the storage component within an integrated PV-based self-consumption strategy. Initiatives that increase the social salience of storage could further enhance observability and strengthen subjective norms around adoption, which is also consistent with past research [17,91]. In contrast to the findings by Wolske et al. [17], our findings do not indicate that focusing on the environmental benefits or targeting households with high biospheric values would influence adoption patterns of both PV or battery storage. This could be due to the advanced diffusion stage in the German market. Finally, the negative association of expense concerns with adoption intention within our sample underscores the value of policies that decrease upfront costs and reframe costs in terms of lifetime-returns. This is in line with past research that shows that perceived financial benefits and incentives are among the most consistent positive predictors of residential PV uptake [9,16]. In practice, a framing of PV that focuses on financial savings for households tends to be very effective in promoting technology uptake [92]. While Germany already offers financing instruments for residential renewable energy investments, including low-interest loan programs for PV and battery storage systems

[93], and average expense concerns among non-adopters in our sample were moderate rather than uniformly high, the strong association with adoption intention might suggest that existing financing instruments may not be equally visible, understandable, or perceived as accessible across households. Policy efforts could therefore place greater emphasis on communicating existing financing opportunities and their long-term economic benefits. Given the shared decision-making structure identified in our study, such information should present PV and BSS jointly and clearly outline the combined costs, financing options, and expected savings of integrated systems.

In conclusion, this study focused on household decision-making regarding battery storage adoption in relation to photovoltaic adoption. To this end, we tested a behavioral model of PV and battery storage adoption, based on triangulation of three behavioral theories. The results showed that households perceive PV and BSS through a largely unified decision-making structure, although a few technology-specific differences in household perceptions appear to be that PV is viewed as more visible, socially endorsed, and environmentally beneficial than BSS. Overall, personal and subjective norms, the households' innovativeness, as well as perceived personal benefits of PV and BSS drive adoption intention, while perceived expense concerns deter it.

CRediT authorship contribution statement

Stephanie Stumpf: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Daniel Sloat:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Wolf Fichtner:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ResearchRabbit after their literature review to identify further relevant literature. In addition, the authors used DeepL and ChatGPT to improve language and readability, as well as revision of the manuscript, and to enhance the structure and coherence of the argumentation throughout the paper. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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.

Acknowledgments

This work was supported by the German Federal Ministry for Economic Affairs and Energy within the framework of the project “En4U – Pathways of a decentralized energy system considering decisions of private and commercial actors under uncertainty”, grant number. 03EI1029.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.erss.2026.104996>.

Data availability

Data will be made available on request.

References

- [1] Harry Wirth, Fraunhofer ISE, Recent Facts about Photovoltaics in Germany, Download from, <https://www.pv-fakten.de/>, 2025 (Version update 18.08.2025).
- [2] BloombergNEF, Lithium-Ion Battery Pack Prices See Largest Drop Since 2017, Falling to \$115 per Kilowatt-Hour. <https://about.bnef.com/insights/commodities/lithium-ion-battery-pack-prices-see-largest-drop-since-2017-falling-to-115-per-kilowatt-hour-bloombergnef/>, 2024.
- [3] Bundesverband Solarwirtschaft e. V, Statistische Zahlen der deutschen Solarstrombranche (Speicher/Mobilität), 2025 (Berlin).
- [4] ACT, German Renewable Energies, Erneuerbare-Energien-Gesetz vom 21. Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 23 des Gesetzes vom 18. Dezember 2025 (BGBl. 2025 I Nr. 347) geändert worden ist. EEG 2023, 2023.
- [5] Bundesnetzagentur, A, Archivierte EEG-Ver-gü-tungs-sät-ze, 2026.
- [6] Daniel Sloat, Nico Lehmann, Armin Ardane, Wolf Fichtner, A behavioral science perspective on consumers' engagement with demand response programs, *Energy Res. Lett.* 4 (2023), <https://doi.org/10.46557/001c.38831>.
- [7] Rasmus Luthander, Joakim Widén, Joakim Munkhammar, David Lingfors, Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment, *Energy* 112 (2016) 221–231, <https://doi.org/10.1016/j.energy.2016.06.039>.
- [8] Wenjie Li, Jiaolan Zhu, Yongchang Li, Yaning Li, Zhikun Ding, Determinants of solar photovoltaic adoption intention among households: a meta-analysis, *Sustainability* 16 (2024) 8204, <https://doi.org/10.3390/su16188204>.
- [9] E. Schulte, F. Scheller, D. Sloat, T. Bruckner, A meta-analysis of residential PV adoption: the important role of perceived benefits, intentions and antecedents in solar energy acceptance, *Energy Res. Soc. Sci.* 84 (2022).
- [10] Philipp S. Eppe, Elena Niehoff, Casper Albers, Thijs Bouman, Sustainable energy technology adoption for a low-carbon future: a global meta-analysis of psychological determinants, *Energy Res. Soc. Sci.* 126 (2025) 104152, <https://doi.org/10.1016/j.erss.2025.104152>.
- [11] M. Alipour, E. Irannezhad, R.A. Stewart, O. Sahin, Exploring residential solar PV and battery energy storage adoption motivations and barriers in a mature PV market, *Renew. Energy* 190 (2022) 684–698.
- [12] Mohammad Alipour, Elnaz Irannezhad, Rodney A. Stewart, Oz Sahin, Factors driving battery and solar purchase decision of residents: a behavioural choice experiment using a hybrid discrete choice and latent variable model, *Adv. Sustain. Syst.* (2025) e00370, <https://doi.org/10.1002/adsu.202500370>.
- [13] Icek Ajzen, The theory of planned behavior, *Organ. Behav. Hum. Decis. Process.* 50 (1991) 179–211, [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T).
- [14] Paul C. Stern, Thomas Dietz, Troy Abel, Gregory A. Guagnano, Linda Kalof, A value-belief-norm theory of support for social movements: the case of environmentalism, *Hum. Ecol. Rev.* (1999) 81–97.
- [15] Everett M. Rogers, Diffusion of Innovations, Fifth edition, Free Press, New York London Toronto Sydney, 2003.
- [16] M. Alipour, H. Salim, R.A. Stewart, O. Sahin, Predictors, taxonomy of predictors, and correlations of predictors with the decision behaviour of residential solar photovoltaics adoption: a review, *Renew. Sustain. Energy Rev.* 123 (2020).
- [17] Kimberly S. Wolske, Paul C. Stern, Thomas Dietz, Explaining interest in adopting residential solar photovoltaic systems in the United States: toward an integration of behavioral theories, *Energy Res. Soc. Sci.* 25 (2017) 134–151, <https://doi.org/10.1016/j.erss.2016.12.023>.
- [18] N. Balta-Ozkan, J. Yildirim, P.M. Connor, I. Truckell, P. Hart, Energy transition at local level: analyzing the role of peer effects and socio-economic factors on UK solar photovoltaic deployment, *Energy Policy* 148 (2021).
- [19] Johannes Rode, Alexander Weber, Does localized imitation drive technology adoption? A case study on rooftop photovoltaic systems in Germany, *J. Environ. Econ. Manag.* 78 (2016) 38–48, <https://doi.org/10.1016/j.jeem.2016.02.001>.
- [20] Calvin Lee Kwan, Influence of local environmental, social, economic and political variables on the spatial distribution of residential solar PV arrays across the United States, *Energy Policy* 47 (2012) 332–344, <https://doi.org/10.1016/j.enpol.2012.04.074>.
- [21] Genevieve Simpson, Julian Clifton, Testing diffusion of innovations theory with data: financial incentives, early adopters, and distributed solar energy in Australia, *Energy Res. Soc. Sci.* 29 (2017) 12–22, <https://doi.org/10.1016/j.erss.2017.04.005>.
- [22] Véronique Vasseur, René Kemp, The adoption of PV in the Netherlands: a statistical analysis of adoption factors, *Renew. Sustain. Energy Rev.* 41 (2015) 483–494, <https://doi.org/10.1016/j.rser.2014.08.020>.
- [23] Bastien Girod, Sebastian Mayer, Florian Nägele, Economic versus belief-based models: shedding light on the adoption of novel green technologies, *Energy Policy* 101 (2017) 415–426, <https://doi.org/10.1016/j.enpol.2016.09.065>.
- [24] Alessandro Milani, Federica Dessi, Marino Bonaiuto, A meta-analysis on the drivers and barriers to the social acceptance of renewable and sustainable energy technologies, *Energy Res. Soc. Sci.* 114 (2024) 103624, <https://doi.org/10.1016/j.erss.2024.103624>.
- [25] A. Priessner, R. Sposato, N. Hampl, Predictors of electric vehicle adoption: an analysis of potential electric vehicle drivers in Austria, *Energy Policy* 122 (2018) 701–714.
- [26] Anika Linzenich, Katrin Arning, Dominik Bongartz, Alexander Mitsos, Martina Ziefle, What fuels the adoption of alternative fuels? Examining preferences of German car drivers for fuel innovations, *Appl. Energy* 249 (2019) 222–236, <https://doi.org/10.1016/j.apenergy.2019.04.041>.
- [27] Megan McMichael, David Shipworth, The value of social networks in the diffusion of energy-efficiency innovations in UK households, *Energy Policy* 53 (2013) 159–168, <https://doi.org/10.1016/j.enpol.2012.10.039>.

- [28] Guo Si-dai, Lu Cheng-Peng, Li Hang, Zhu Ning, Influence mechanism of energy efficiency label on consumers' purchasing behavior of energy-saving household appliances, *Front. Psychol.* 12 (2021) 711854, <https://doi.org/10.3389/fpsyg.2021.711854>.
- [29] Ya Li, Abu Bakkar Siddik, Mohammad Masukujjaman, Xiujian Wei, Bridging green gaps: the buying intention of energy efficient home appliances and moderation of green self-identity, *Appl. Sci.* 11 (2021) 9878, <https://doi.org/10.3390/app11219878>.
- [30] Scott Agnew, Paul Dargusch, Consumer preferences for household-level battery energy storage, *Renew. Sustain. Energy Rev.* 75 (2017) 609–617, <https://doi.org/10.1016/j.rser.2016.11.030>.
- [31] Bernhard J. Kalkbrenner, Residential vs. community battery storage systems – consumer preferences in Germany, *Energy Policy* 129 (2019) 1355–1363, <https://doi.org/10.1016/j.enpol.2019.03.041>.
- [32] Swantje Gährs, Katrin Mehler, Mark Bost, Bernd Hirschl, Acceptance of ancillary services and willingness to invest in PV-storage-systems, *Energy Procedia* 73 (2015) 29–36, <https://doi.org/10.1016/j.egypro.2015.07.554>.
- [33] Franz Ecker, Hans Spada, Ulf J.J. Hahnel, Independence without control: autarky outperforms autonomy benefits in the adoption of private energy storage systems, *Energy Policy* 122 (2018) 214–228, <https://doi.org/10.1016/j.enpol.2018.07.028>.
- [34] Stefan Poier, Anna Maria Nikodemka-Wolowik, Michał Suchanek, How HIGHER-personal values affect the purchase of electricity storage—evidence from the German photovoltaic market, *J. Consum. Behav.* 21 (2022) 909–926, <https://doi.org/10.1002/cb.2048>.
- [35] S. Poier, A matter of risk? Investigating the battery purchase decision in the German photovoltaics market, *Energy* 275 (2023), <https://doi.org/10.1016/j.energy.2023.127463>.
- [36] David P. Brown, Socioeconomic and demographic disparities in residential battery storage adoption: evidence from California, *Energy Policy* 164 (2022) 112877, <https://doi.org/10.1016/j.enpol.2022.112877>.
- [37] Breda McCarthy, Hongbo Liu, It starts at home: consumer acceptance of battery storage and response to prosumer models, 2023, <https://doi.org/10.21203/rs.3.rs-2993839/v1>.
- [38] Breda McCarthy, Hongbo Liu, Power to regional households: consumer attitudes towards electricity-saving, the solar rebound and the determinants of rooftop solar adoption, *Aust. J. Environ. Manag.* 29 (2022) 405–424, <https://doi.org/10.1080/14486563.2022.2140212>.
- [39] Stefan Poier, Towards a psychology of solar energy: analyzing the effects of the Big Five personality traits on household solar energy adoption in Germany, *Energy Res. Soc. Sci.* 77 (2021) 102087, <https://doi.org/10.1016/j.erss.2021.102087>.
- [40] Christian A. Klöckner, Psychological determinants of intentions to upgrade the energy standards of privately-owned buildings: results from a Norwegian survey, *Int. J. Sustain. Build. Technol. Urban Dev.* 5 (2014) 222–229, <https://doi.org/10.1080/2093761X.2014.954652>.
- [41] Heesup Han, Travelers' pro-environmental behavior in a green lodging context: converging value-belief-norm theory and the theory of planned behavior, *Tour. Manag.* 47 (2015) 164–177, <https://doi.org/10.1016/j.tourman.2014.09.014>.
- [42] Shaul Oreg, Tally Katz-Gerro, Predicting proenvironmental behavior cross-nationally: values, the theory of planned behavior, and value-belief-norm theory, *Environ. Behav.* 38 (2006) 462–483, <https://doi.org/10.1177/0013916505286012>.
- [43] Rama Mohana R. Turaga, Richard B. Howarth, Mark E. Borsuk, Pro-environmental behavior: rational choice meets moral motivation, *Ann. N. Y. Acad. Sci.* 1185 (2010) 211–224, <https://doi.org/10.1111/j.1749-6632.2009.05163.x>.
- [44] Marvin Helfferich, John Thøgersen, Magnus Bergquist, Direct and mediated impacts of social norms on pro-environmental behavior, *Glob. Environ. Chang.* 80 (2023) 102680, <https://doi.org/10.1016/j.gloenvcha.2023.102680>.
- [45] W.H. Loo, Paul H.P. Yeow, Yuen Yee Yen, Antecedents of the responsible acquisition of computers behaviour: integrating the theory of planned behaviour with the value-belief-norm theory and the habits variable, in: Tai Ming Wut (Ed.), *PLOS ONE* 18, 2023, <https://doi.org/10.1371/journal.pone.0286022> (e0286022).
- [46] Heesup Han, Myoung Jae Lee, Wansoo Kim, Promoting towel reuse behaviour in guests: a water conservation management and environmental policy in the hotel industry, *Bus. Strateg. Environ.* 27 (2018) 1302–1312, <https://doi.org/10.1002/bse.2179>.
- [47] Pi-Chuan Sun, Hsueh-Mei Wang, Hsien-Long Huang, Chien-Wei Ho, Consumer attitude and purchase intention toward rooftop photovoltaic installation: the roles of personal trait, psychological benefit, and government incentives, *Energy Environ.* 31 (2020) 21–39, <https://doi.org/10.1177/0958305X17754278>.
- [48] Saqib Ali, Habib Ullah, Minhas Akbar, Waheed Akhtar, Hasan Zahid, Determinants of consumer intentions to purchase energy-saving household products in Pakistan, *Sustainability* 11 (2019) 1462, <https://doi.org/10.3390/su11051462>.
- [49] Philipp Feisthauer, Monika Hartmann, Jan Börner, Behavioral factors driving farmers' intentions to adopt spot spraying for sustainable weed control, *J. Environ. Manage.* 353 (2024) 120218, <https://doi.org/10.1016/j.jenvman.2024.120218>.
- [50] Ke Lu, Chunmei Shi, Why do travelers discontinue using integrated ride-hailing platforms? The role of perceived value and perceived risk, *Hum. Soc. Sci. Commun.* 12 (2025) 344, <https://doi.org/10.1057/s41599-025-04683-5>.
- [51] Dissakoon Chonsalasin, Thanapong Champahom, Natcha Limpasirisuwan, Sajjakaj Jomnonkwa, Vatanavongs Ratanavara, Urban-rural differences in electric vehicle adoption intentions: integrated TAM, TPB, UTAUT with environmental identity, *Civ. Eng. J.* 11 (2025) 1891–1923, <https://doi.org/10.28991/CEJ-2025-011-05-010>.
- [52] Branka Rodić, Vladimir Stevanović, Aleksandra Labus, Dragana Kljajić, Marija Trajkov, Adoption intention of an IoT based healthcare technologies in rehabilitation process, *Int. J. Hum. Comput. Interact.* 40 (2024) 2873–2886, <https://doi.org/10.1080/10447318.2023.2175160>.
- [53] Samar Rahi, Mazuri Abd Ghani, Aamir Rashid, Rizwana Rasheed, Foreseeing the future of robotics in service sector: unveiling factors influence individual behavior to adopt services robots, *Foresight* 27 (2025) 770–788, <https://doi.org/10.1108/FS-05-2024-0111>.
- [54] Sushant Kumar Vishnoi, Smriti Mathur, Vaishali Agarwal, Naveen Virmani, Sandeep Jagtap, What drives Generation Z to choose green apparel? Unraveling the impact of environmental knowledge, altruism and perceived innovativeness, *Int. J. Sustain. Eng.* 18 (2025) 2473986, <https://doi.org/10.1080/19397038.2025.2473986>.
- [55] Tuan Duong Vu, Thi My Nguyen Nguyen, Phuong Thao Vu, Exploring young customers' purchasing intention for solar appliances in an emerging market: evidence from structural equation modeling approach, *Int. J. Energy Sect. Manag.* 19 (2025) 795–819, <https://doi.org/10.1108/IJESM-07-2024-0031>.
- [56] Dan Cudjoe, Bangzhu Zhu, Hong Wang, The role of incentive policies and personal innovativeness in consumers' carbon footprint tracking apps adoption in China, *J. Retail. Consum. Serv.* 79 (2024) 103861, <https://doi.org/10.1016/j.jretconser.2024.103861>.
- [57] Daniel Sloot, Nico Lehmann, Armin Ardane, Explaining and promoting participation in demand response programs: the role of rational and moral motivations among German energy consumers, *Energy Res. Soc. Sci.* 84 (2022) 102431, <https://doi.org/10.1016/j.erss.2021.102431>.
- [58] Hashita Joyram, Kannan Govindan, Robin Nunkoo, Development of a novel psychological model to predict the eco-block building adoption in Mauritius, *Cleaner Responsible Consumption* 12 (2024) 100172, <https://doi.org/10.1016/j.clrc.2024.100172>.
- [59] Tran Thi Thu Thuy, Nguyen Thi Thanh Thao, Vo Thi Thu Thuy, Su Thi Oanh Hoa, Tran Thi Diem Nga, Bridging human behavior and environmental norms: a cross-disciplinary approach to sustainable tourism in Vietnam, *Sustainability* 17 (2025) 4496, <https://doi.org/10.3390/su17104496>.
- [60] Syed Shah Alam, Maisarah Ahmad, Abdullah Sanusi Othman, Zullina Bt Hussain Shaari, Mohammad Masukujjaman, Factors affecting photovoltaic solar technology usage intention among households in Malaysia: model integration and empirical validation, *Sustainability* 13 (2021) 1773, <https://doi.org/10.3390/su13041773>.
- [61] Musabah Al Breiki, Abdullah Al Abri, Abdul Mutalib Al Moosawi, Adnan Alburaiki, Investigating science teachers' intention to adopt virtual reality through the integration of diffusion of innovation theory and theory of planned behaviour: the moderating role of perceived skills readiness, *Educ. Inf. Technol.* 28 (2023) 6165–6187, <https://doi.org/10.1007/s10639-022-11367-z>.
- [62] Nombulelo Dilotsolthe, Helen Inseeng Duh, Drivers of middle-class consumers' green appliance attitude and purchase behavior: a multi-theory application, *Soc. Mark. Q.* 27 (2021) 150–171, <https://doi.org/10.1177/15245004211013737>.
- [63] Paul C. Stern, Thomas Dietz, Gregory A. Guagnano, The new ecological paradigm in social-psychological context, *Environ. Behav.* 27 (1995) 723–743, <https://doi.org/10.1177/0013916595276001>.
- [64] Statistisches Bundesamt (Destatis), Statistischer Bericht - Mikrozensus - Haushalte und Familien 2022 (Endergebnis) (version Neuerstellung des Statistischen Berichts aufgrund geänderter Datenbasis. Die Hochrechnung erfolgt auf Basis des Zensus 2022. Ausführliche Hinweise finden Sie in den Informationen zur Statistik.), 2024.
- [65] Statistisches Bundesamt (Destatis), Statistischer Bericht - Mikrozensus - Arbeitsmarkt 2022 (Endergebnis) (version Neuerstellung des Statistischen Berichts aufgrund geänderter Datenbasis. Die Hochrechnung erfolgt auf Basis des Zensus 2022. Ausführliche Hinweise finden Sie in den Informationen zur Statistik.), 2024.
- [66] Statistisches Bundesamt (Destatis), Statistischer Bericht - Mikrozensus - Bevölkerung nach Migrationshintergrund - Erstergebnisse 2024, 2025.
- [67] Shalom H. Schwartz, Universals in the content and structure of values: theoretical advances and empirical tests in 20 countries, in: *Advances in Experimental Social Psychology*, Advances in Experimental Social Psychology, vol. 25, Elsevier, 1992, pp. 1–65, [https://doi.org/10.1016/S0065-2601\(08\)60281-6](https://doi.org/10.1016/S0065-2601(08)60281-6).
- [68] Paul C. Stern, Thomas Dietz, Gregory A. Guagnano, A brief inventory of values, *Educ. Psychol. Meas.* 58 (1998) 984–1001.
- [69] Linda Steg, Goda Perlaviciute, Ellen van der Werf, Judith Lurvink, The significance of hedonic values for environmentally relevant attitudes, preferences, and actions, *Environ. Behav.* 46 (2014) 163–192, <https://doi.org/10.1177/0013916512454730>.
- [70] Ferdinando Fornara, Piermarco Pattitoni, Marina Mura, Elisabetta Strazzera, Predicting intention to improve household energy efficiency: the role of value-belief-norm theory, normative and informational influence, and specific attitude, *J. Environ. Psychol.* 45 (2016) 1–10, <https://doi.org/10.1016/j.jenvp.2015.11.001>.
- [71] Abdullah Al Mamun, Naeem Hayat, Muhammad Mohiuddin, Anas A. Salameh, Mohd Helmi Ali, Noor Raihani Zainol, Modelling the significance of value-belief-norm theory in predicting workplace energy conservation behaviour, *Front. Energy Res.* 10 (2022) 940595, <https://doi.org/10.3389/fenrg.2022.940595>.
- [72] Linda Steg, Lieke Dreijerink, Wolkje Abrahamse, Factors influencing the acceptability of energy policies: a test of VBN theory, *J. Environ. Psychol.* 25 (2005) 415–425, <https://doi.org/10.1016/j.jenvp.2005.08.003>.
- [73] Sture Holm, A simple sequentially rejective multiple test procedure, *Scand. J. Stat.* 6 (1979) 65–70 ([Board of the Foundation of the Scandinavian Journal of Statistics, Wiley]: JSTOR).
- [74] Hae-Young Kim, Analysis of variance (ANOVA) comparing means of more than two groups, *Restor. Dent. Endod.* 39 (2014) 74, <https://doi.org/10.5395/rde.2014.39.1.74>.

- [75] Yves Rosseel, Lavaan: an R package for structural equation modeling, *J. Stat. Softw.* 48 (2012) 1–36.
- [76] Craig K. Enders, Deborah L. Bandalos, The relative performance of full information maximum likelihood estimation for missing data in structural equation models, in: *Structural Equation Modeling* 8, Taylor & Francis, 2001, pp. 430–457.
- [77] Joseph F. Hair, William C. Black, Barry J. Babin, Rolph E. Anderson, *Multivariate Data Analysis*, Eighth edition, Cengage, Andover, Hampshire, 2019.
- [78] Alexandros Leontitis, Jenny Pagge, A simulation approach on Cronbach's alpha statistical significance, *Math. Comput. Simul.* 73 (2007) 336–340, <https://doi.org/10.1016/j.matcom.2006.08.001>.
- [79] Claes Fornell, David F. Larcker, Evaluating structural equation models with unobservable variables and measurement error, in: *Journal of Marketing Research* 18, Sage Publications Sage CA, Los Angeles, CA, 1981, pp. 39–50.
- [80] Jan Figgenger, Peter Stenzel, Kai-Philipp Kairies, Jochen Linßen, David Haberschus, Oliver Wessels, Georg Angenendt, Martin Robinus, Detlef Stolten, Dirk Uwe Sauer, The development of stationary battery storage systems in Germany – a market review, *J. Energy Storage* 29 (2020) 101153, <https://doi.org/10.1016/j.est.2019.101153>.
- [81] Fabian Scheller, Karyn Morrissey, Karsten Neuhoﬀ, Dogan Keles, Green or greedy: the relationship between perceived benefits and homeowners' intention to adopt residential low-carbon technologies, *Energy Res. Soc. Sci.* 108 (2024) 103388, <https://doi.org/10.1016/j.erss.2023.103388>.
- [82] Morton Deutsch, Harold B. Gerard, A study of normative and informational social influences upon individual judgment, *J. Abnorm. Soc. Psychol.* 51 (1955) 629–636, <https://doi.org/10.1037/h0046408>.
- [83] N.M.A. Huijts, E.J.E. Molin, L. Steg, Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework, *Renew. Sustain. Energy Rev.* 16 (2012) 525–531, <https://doi.org/10.1016/j.rser.2011.08.018>.
- [84] Ellen Van Der Werff, Linda Steg, The psychology of participation and interest in smart energy systems: comparing the value-belief-norm theory and the value-identity-personal norm model, *Energy Res. Soc. Sci.* 22 (2016) 107–114, <https://doi.org/10.1016/j.erss.2016.08.022>.
- [85] Shahzeen Z. Attari, Michael L. DeKay, Cliff I. Davidson, Wändi Bruine De Bruin, Public perceptions of energy consumption and savings, *Proc. Natl. Acad. Sci.* 107 (2010) 16054–16059, <https://doi.org/10.1073/pnas.1001509107>.
- [86] Thomas Dietz, *Decisions for Sustainability: Facts and Values*, Cambridge University Press, 2023.
- [87] Gregory R. Hancock, Structural equation modeling methods of hypothesis testing of latent variable means, *Meas. Eval. Couns. Dev.* 30 (1997) 91–105, <https://doi.org/10.1080/07481756.1997.12068926>.
- [88] Todd D. Little, Mean and Covariance Structures (MACS) analyses of cross-cultural data: practical and theoretical issues, *Multivar. Behav. Res.* 32 (1997) 53–76, https://doi.org/10.1207/s15327906mbr3201_3.
- [89] Philip M. Podsakoff, Nathan P. Podsakoff, Larry J. Williams, Chengquan Huang, Junhui Yang, Common method bias: it's bad, it's complex, it's widespread, and it's not easy to fix, *Annu. Rev. Organ. Psych. Organ. Behav.* 11 (2024) 17–61, <https://doi.org/10.1146/annurev-orgpsych-110721-040030>.
- [90] Philip M. Podsakoff, Scott B. MacKenzie, Jeong-Yeon Lee, Nathan P. Podsakoff, Common method biases in behavioral research: a critical review of the literature and recommended remedies, *J. Appl. Psychol.* 88 (2003) 879–903, <https://doi.org/10.1037/0021-9010.88.5.879>.
- [91] Bryan Bollinger, Kenneth Gillingham, Peer effects in the diffusion of solar photovoltaic panels, *Mark. Sci.* 31 (2012) 900–912, <https://doi.org/10.1287/mksc.1120.0727>.
- [92] Dominik Bär, Stefan Feuerriegel, Ting Li, Markus Weinmann, Message framing to promote solar panels, *Nat. Commun.* 14 (2023) 7187, <https://doi.org/10.1038/s41467-023-42904-0>.
- [93] KfW Bankengruppe, KfW-Programm Erneuerbare Energien “Standard” -Merkblatt Kredit Nr. 270, 2025 (Frankfurt am Main).