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ORIGINAL PAPER

A survey on the user acceptance of PV battery storage systems

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Abstract
This study presents the results of an analysis of user acceptance of PV battery storage systems. A structural equation model is developed based on Davis' technology acceptance model (TAM). It is expanded by integrating elements of Ajzen's theory of planned behavior (TPB). The main factors influencing the acceptance of PV battery storage systems are evaluated and analyzed. Empirical findings indicate that survey participants' acceptance of PV battery storage systems is mainly influenced by their behavioral beliefs, perceived knowledge about battery storage systems, perceived ease of use, and perceived usefulness of PV battery storage systems. The results indicate a high degree of acceptance for PV battery storage systems.

Keywords Solar energy · Battery storage · User acceptance · Technology acceptance model (TAM) · Structural equation modeling (SEM)

1 Introduction

More than two million PV systems with a nominal capacity of 54 GW have been installed in Germany under the Renewable Energies Act since 2000 (Wirth 2021). While the costs for electricity generated by rooftop PV systems have declined drastically over time, the electricity prices for households were increasing (Kost et al. 2018). As the remuneration for PV feed-in was adapted to the decreasing system costs, self-consumption became increasingly attractive (Wirth 2021). Prices for lithium-ion batteries have decreased by more than 50% since 2013 and continue to decline (Figgener et al. 2018). Consequently, every second small-scale PV system has been installed with battery storage to increase self-consumption. However, battery storage systems started being installed in numbers before profitability was reached, and the buyers stated that they were aware of that (Figgener et al. 2018). Moreover, not all households install battery storage systems after profitability is reached, proving that there are other factors influencing adoption and acceptance. Different authors have evaluated the user acceptance of PV battery storage systems or asked for possible reasons for the installation of PV battery storage systems (Figgener et al. 2018, 2017; Gährs et al. 2015; Moshövel et al. 2015). However, to our knowledge, so far, the main factors influencing individuals' acceptance of PV battery systems have not been analyzed with the help of regression- or structural equation models (SEM). This article intends to fill this gap in the literature by examining factors that potentially influence the acceptance of PV battery systems.

This paper is structured as follows: In Sect. 2, the hypotheses are presented and the term acceptance is discussed. Sect. 3 describes the methodology and the empirical data used to evaluate our structural equation model. Sect. 4 shows exemplary results, including acceptance scores, quality measures, and the main effects of our SEM. In Sect. 4, the results and potential limitations of our work are discussed before conclusions are provided in Sect. 5.

2 Acceptance and hypotheses

2.1 Acceptance

There is no uniform, generally applicable definition of the term "acceptance" in the scientific literature (Quiring 2006). However, many authors consider two to three different dimensions of acceptance: the attitudinal dimension, the behavioral dimension, and sometimes the normative dimension (Schäfer Keppler 2013). The attitudinal dimension is

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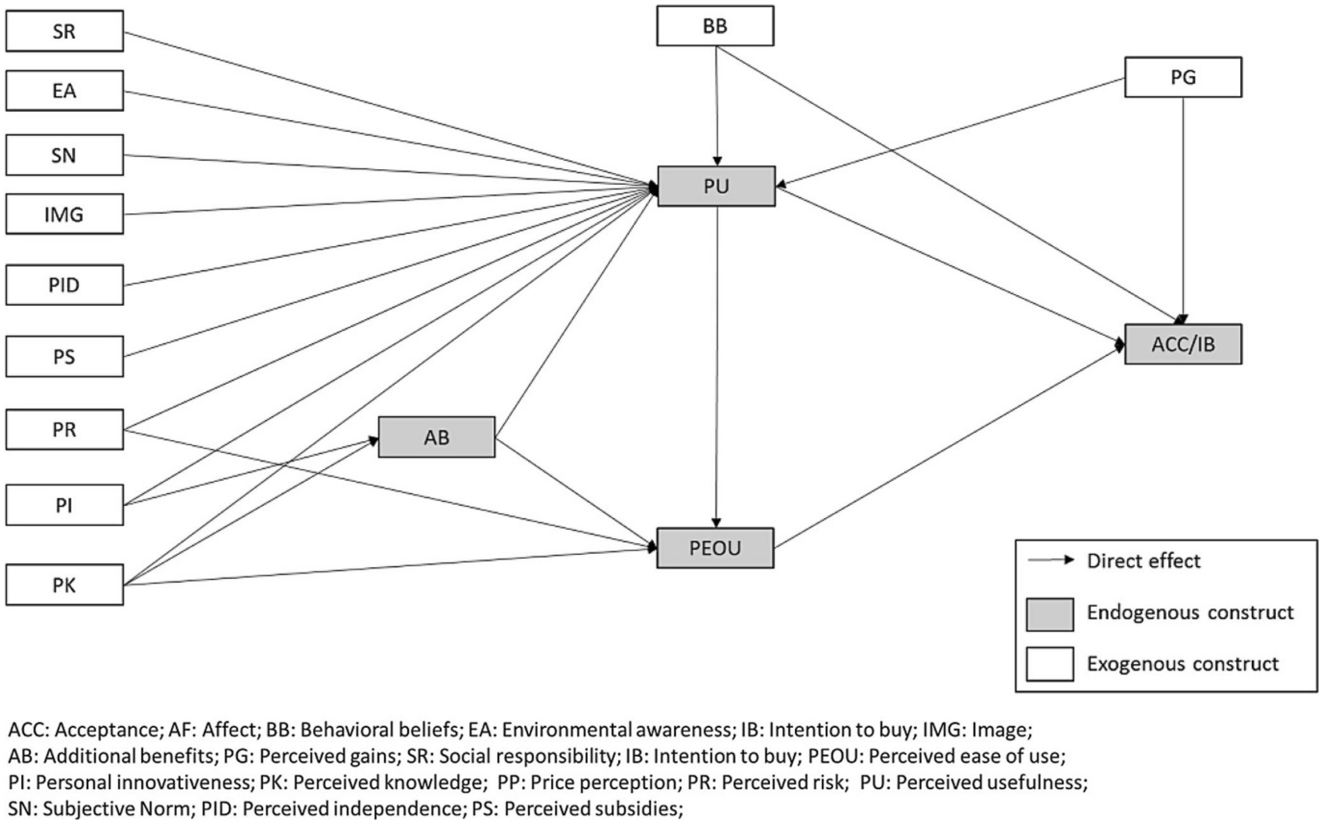

Fig. 1 Structural equation model

part of almost every definition of acceptance. It describes the attitude of a person or group of people toward a technology. This attitude-related dimension can also include an intention or a willingness for a certain behavior, but not the behavior itself (Lucke 1995). The behavioral dimension describes the active component of acceptance, which goes beyond the willingness for a certain behavior and accordingly includes an observable action Schweizer-Ries et al. 2010. However, an observable action is not a necessary prerequisite for acceptance, meaning that an action can occur but does not have to occur (Huijts et al. 2012). The normative dimension describes the assessment of a technology based on norms and values. These can be distinguished in individual and societal values. In literature, the normative dimension is often embedded in the attitudinal dimension of acceptance (Schäfer Keppler 2013). PV battery storage systems are a comparably new technology, which is not accessible to everyone. Consequently, actual usage is not sufficiently observable. As in Fazel (Fazel 2014) and Dudenhöffer (Dudenhöffer 2015), the intention to use is therefore considered instead.

2.2 Hypotheses

In understanding technology acceptance, some primary hypotheses have proven to be a reliable starting point to analyze human behavior. The technology acceptance model (TAM) by Davis (Davis 1989) posits that perceived usefulness (PU) and perceived ease of use (PEOU) are the main determinants of technology acceptance. Subsequently, Venkatesh and Davis (Venkatesh Davis 2000) and Venkatesh *et al.* (Venkatesh et al. 2003) turned to explicate further which variables are essential to understanding PU and PEOU. Our set of hypotheses builds upon these basic presuppositions and extends TAM and the theory of planned behavior (TPB) by Ajzen (Ajzen 1991) by technology-specific hypotheses. Fig. 1 depicts the entire set of hypotheses that we discuss in the following.

The diffusion literature has shown that personal affinity to new technologies is an essential variable in technology adoption processes (Rogers 2003). Therefore, we adopt the hypothesis that “personal innovativeness” will affect PU. Another classic premise from TBP (Ajzen 1991) is that “behavioral beliefs” affect PU and IB.

Recent studies on the acceptance of PV systems have shown that social interaction plays an important role in the adoption process (Scheller et al. 2021; Balta-Ozkan et al. 2021). Therefore, we adopt the hypothesis that "social norms" and "image" will positively affect PU. On the other hand, we posit that "perceived gains" by electricity production and self-consumption and "perceived subsidies" will influence an individual's PU and IB.

Technologically, PV storage systems are similar to electric cars, where a central component for electricity storage is the battery. When it comes to technology, our hypotheses are therefore based on recent surveys of electric mobility (Fazel 2014; Fett et al. 2018). From these studies, we formulate the hypotheses that the higher the "perceived risk", the lower PU and PEOU. Likewise, PV storage systems are complex products, and therefore we posit that "perceived knowledge" will increase PU and PEOU. However, recent studies have also shown that the adopters of PV and electric vehicle adopters differ geographically, indicating differences in the adoption process of both technologies (van der Kam et al. 2018).

As PV storage systems may be associated with renewable energies and environmental issues are frequently mentioned in political debates on renewables, we further hypothesize that environmental awareness and social responsibility will positively affect PU. As previous surveys found various potential benefits of PV storage systems, such as grid relief or increased awareness of individual electricity usage (Figgener et al. 2018, 2017), we posit that such "additional benefits" will positively affect PU, PEOU, and ACC/IB. Likewise, studies pointed out that "perceived independence" from the common grid may be a factor influencing PU (Figgener et al. 2018; Hoffmann et al. 2018).

3 Methodology and data

3.1 Operationalization

The procedure for measuring and operationalizing the constructs follows the procedure described in Fazel (Fazel 2014) and Homburg and Giering (Homburg Giering 1998). As a first step, existing constructs were collected from TAM literature. Additionally, studies of user acceptance using SEM in the area of electric mobility and renewable energies were screened for suitable construct operationalizations. This was complemented by extensive research in the two standard works *Marketing Scales Handbook* and *Handbook of Marketing Scales*, in which numerous constructs used in the context of structural equation models are listed with the corresponding items (Fazel 2014; Bruner 2015; Haws et al. 2014). Suitable constructs were documented in the longlist, including all items and information on the specification of the measurement model (formative/reflective) and their source. From this collection of potential indicators, those relevant to our subject were identified. These were checked for their performance in the empirical studies. After removing the redundant indicators, the selected constructs and items were included in the shortlist. During the analysis of the SEM results, a test for discriminance validity (see Sect. 4) would ensure that the constructs could be distinguished from one another. Additionally, we added self-developed constructs and items based on surveys evaluating user acceptance of PV battery storage systems or asking adopters for reasons for their decision to install a PV battery storage system. The constructs in the shortlist and the associated items were transferred to the questionnaire to conduct a comprehensive pretest. Different persons checked the questionnaire for comprehensibility and completeness of the content and made suggestions for changes.

3.2 Structural equation modeling

The latent variables and their definitions are presented in Table 1 in the Appendix. In general, a measurement model for a latent variable can be specified as formative or reflective. In the case of reflective measurement models, the indicators are influenced by changes in the latent variable. Therefore a change in the construct value induces changes in all indicators (Herrmann et al. 2006). Indicators are highly correlated and interchangeable (Weiber Mühlhaus 2014). In contrast to this, for formative measurement models, the indicators influence the latent variable. Furthermore, the construct is entirely derived from its indicators. Formative measurement models only require a relationship between indicators and construct, not necessarily between the different indicators (Jarvis et al. 2003). A classic example of a formative construct is the Socio-Economic Status, measured by education, income, and occupational prestige (Jahn 2007; Urban Mayerl 2014). Choosing the correct measurement model is a difficult decision (Christophersen Grape 2009). Jarvis et al. (2003) provide practical guidelines to help with the choice.

Following (Homburg Klarmann 2006), we mainly use reflective constructs to represent the latent variables. However, for some latent variables, such as the construct "additional benefits", it is necessary to consider different aspects (e.g., a higher awareness of individual energy consumption, possibly relieving the distribution grid or the possibility to extend the economic lifespan of a PV system after the expiry of the feed-in tariff), which as a whole form the construct. Hence, these constructs are specified as formative. More details on the measurement models for all constructs are given in Table 2 in the Appendix. We chose a partial least squares structural equation model (PLS-SEM), as is recommended for model extensions and exploratory research (Hair et al. 2011). The validity of this approach is discussed in Sect. 4.

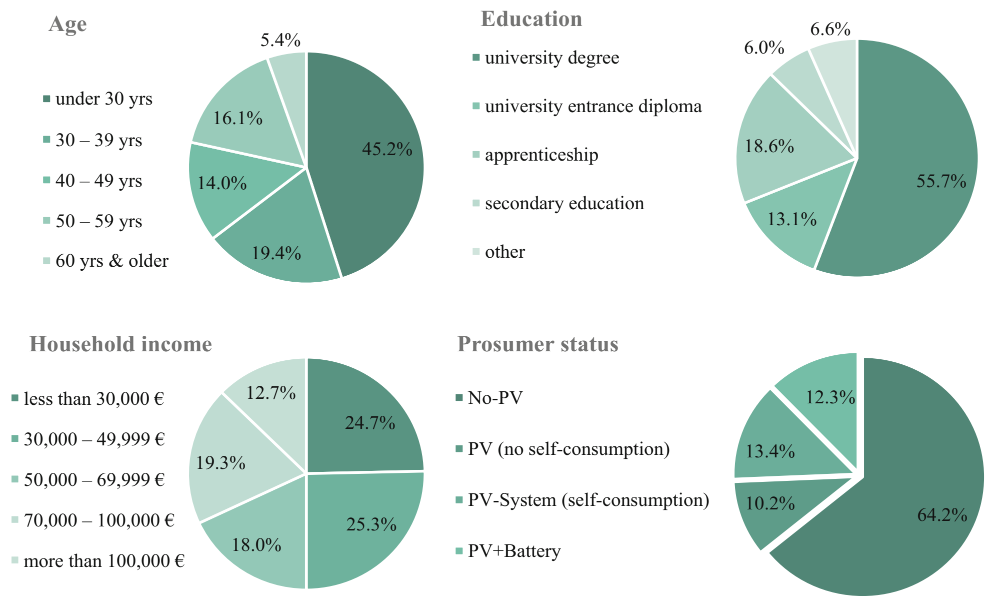

Fig. 2 Demographics and EV experience of the sample

3.3 Survey data

After pretesting, empirical data to validate the SEM was collected with an online survey between July and September 2019. Survey participants were recruited in various solar energy or electric mobility-related internet forums. Of the 301 respondents who started the survey, 208 completed it. Due to short answering times that raise doubts about whether questions were read thoroughly (faster than half the median response time), 15 responses were excluded (cf. Leiner 2013). Our sample is not representative of the German population. The share of respondents below 30 years (45.2%) is higher than in the German population, while the share of respondents who are 60 years and older (5.4%) is lower. Furthermore, women are underrepresented, as only 36.7% of survey participants are female. (Fig. 2).

Yearly household incomes also differ from the distribution of the German population: 37% of participants state an income ranging between 50,000 and 100,000 € and 18% above 100,000 €. Potenzial explanations are twofold: first, education levels are high, with 55.7% of the respondents having a university degree. Second, the share of people living in multi-person households is also very high (88.3%). Many respondents have experience with PV systems. More than one-third of respondents own PV systems. About one-fourth of the survey participants use self-generated solar energy, and 12.3% use battery storage systems to increase their self-consumption. Lots of similarities to other studies on the acceptance of innovative technologies (namely EV adoption and wireless charging for EVs) in Germany can be observed. In these studies, most participants also lived in multi-person households, were males, had a university degree and above-average incomes (Fett et al. 2018; Frenzel et al. 2015).

4 Evaluation

4.1 Acceptance

Fig. 3 shows the average scores of the latent variable acceptance and its indicators. A Likert scale ranging from 1 (“completely disagree”) to 5 (“completely agree”) was used for all indicators. Values of 4 and higher are regarded as consent (respectively called positive values), values of 2 and lower as dissent (respectively called negative values). About two-thirds consider PV battery storage systems to be “sensible and sustainable” and can imagine using one (scores of 4 and higher); 63% also state that they would like to use PV battery storage systems. The average values for these three indicators are all weakly positive, with values of 3.8 and 3.7. Almost half of the survey participants also believe that investing in a battery storage system has more advantages than disadvantages. Even though 43.2% state that they can imagine or have already invested in a PV battery storage system, the average value is only slightly positive with 3.2. An explanation for these values is that not everyone can benefit from self-consumption. Tenants and people living in apartments cannot invest in a PV battery storage system.

A more detailed analysis shows that more than 60% of respondents living in their own detached house can imagine or have already invested in a PV battery storage system. Consequentially, their average value for this indicator is higher at 3.7. The resulting construct value for accep-

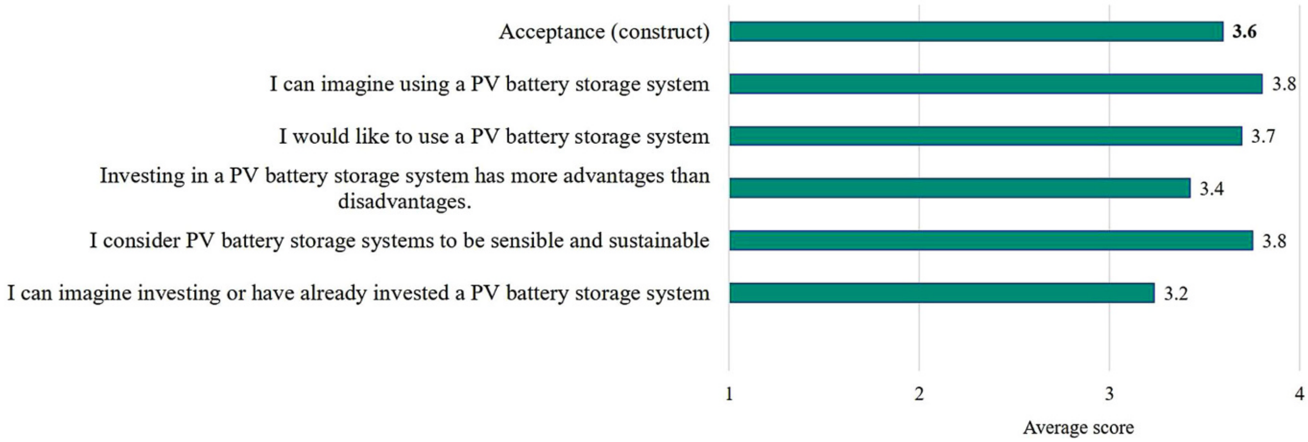

Fig. 3 Average values of the construct "acceptance"and its indicators

tance is 3.6. For most respondents, the average value of acceptance reaches positive values (3.5 and higher). As an additional question, survey participants were asked if they consider themselves supporters or adversaries of PV battery systems or to be neutral towards the technology. Only 2% of the respondents stated to be adversaries, and a majority declared to be supporters.

4.2 Quality criteria

All reflective measurement models are tested on reliability and validity. To assure indicator reliability, the factor loadings (≥ 0.4), the significance levels (t ≥ 1.6), and the item-to-total correlations (≥ 0.4) are analyzed (Hulland 1999; Huber et al. 2007; Zarantonello Pauwels-Delassus 2015). Construct reliability is tested by Cronbach's alpha (≥ 0.65), factor reliability (≥ 0.6), and average variance extracted (≥ 0.5) (DeVellis 2003; Bagozzi Yi 1988; Fornell Larcker 1981). If all constructs meet the required thresholds for average variance extracted and the factor reliability, then convergence validity is also given (Backhaus et al. 2016). The Fornell/Larcker-criterion is met for all constructs, ensuring discriminance validity (Fornell Larcker 1981). Formative measurement models do not require correlations between indicators. Consequently, the statistical quality assessment used for reflective measurement models cannot be applied (Backhaus et al. 2016). According to some authors, their validity and reliability cannot be tested at all (Homburg Klarmann 2006; Rossiter 2002). Nevertheless, we chose formative measurements for the three constructs shown in Table 2 in the Appendix. It would not have been possible to cover all necessary aspects of the constructs using reflective measurement models. Meta-analyses support the use of formative constructs. In the analyzed peer-reviewed articles, up to 35.2% of measurement models are erroneously specified as reflective (Jarvis et al. 2003; Fassott 2006; Eberl 2004). As statistical quality assessment is not possible, we follow the C-OAR-SE approach to assure content validity (Rossiter 2002). To verify the absence of critical levels of multicollinearity, additionally, the variance inflation factors (≤ 5) are analyzed (Hair et al. 2011).

The R^2-value for acceptance is 0.75 and considered substantial (Chin 1998). The predictive value Q^2 for acceptance is 0.51, so the model has predictive relevance (Fornell Bookstein 1982). These are excellent values indicating a good explanatory value of our model.

4.3 Main effects of PLS-SEM

Perceived gains (0.24), behavioral beliefs (0.40), perceived usefulness (0.43), perceived ease of use (0.35), and perceived knowledge (0.20) have significant positive total effects on acceptance of PV battery systems. On the other hand, perceived risk (–0.08) has a significant negative total effect on acceptance. However, only perceived gains (0.14), behavioral beliefs (0.26), perceived usefulness (0.43), and perceived ease of use (0.23) have significant direct effects on acceptance. Furthermore, the effects of perceived gains, behavioral beliefs, and perceived ease of use are amplified through indirect effects. Factors influencing endogenous constructs that influence acceptance should therefore be analyzed. All direct effects are listed in Table 3 in the Appendix, and significant effects are highlighted in Fig. 4.

While perceived knowledge (–0.27) has a strong negative impact, personal innovativeness (0.41) has a strong positive effect on additional benefits, which in turn has a significant positive effect on perceived ease of use (0.23). Perceived ease of use is also strongly influenced by perceived risk (–0.25) and perceived knowledge (0.48). Furthermore, perceived knowledge (0.11) and perceived ease of use (0.27) positively impact perceived usefulness.

In addition to the already mentioned endogenous constructs, perceived usefulness is also influenced by two exogenous constructs. Both perceived gains (0.22) and behav-

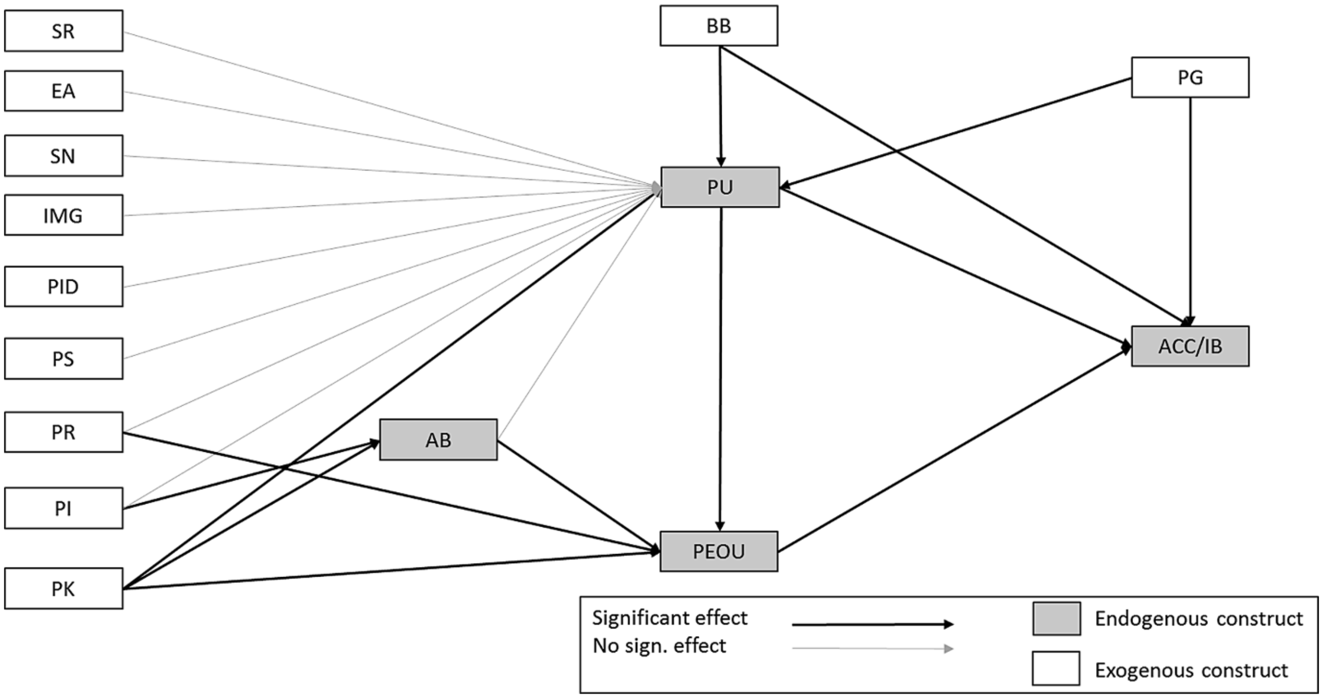

Fig. 4 Structural equation model, significant effects emphasized

ioral beliefs (0.34) have strongly significant positive effects on perceived usefulness.

5 Discussion and limitations

Our findings show that TAM provides a valuable framework to study the acceptance of PV battery systems. Perceived usefulness and perceived ease of use are among the variables with the highest explanatory values. Surprisingly, and somewhat in contrast to the literature on PV (Scheller et al. 2021; Balta-Ozkan et al. 2021), we could not detect peer effects on the decision to adopt PV in our sample. The low importance of peer effects may be related to the sample distribution that may be biased towards innovators and early adopters of technology, whose willingness to adopt generally depends less on the influence of others (Rogers 2003). The significant effect of personal innovativeness also underlines this observation. While perceived gains are important to understand the intention to buy, the variables measuring environmental awareness and social responsibility did not yield significant effects. Therefore, within our sample, motivations to buy PV storage systems appear more driven by self-interest than altruistic motives.

Our study is limited by using formative measurement models for some constructs (c.f. Sect. 4.2), whose reliability and validity cannot be assessed through statistical means. As discussed in Sect. 3.3, our sample is not representative of the German population. Personal experience with renewable energy sources increases acceptance (Agentur für Erneuerbare Energien e. V. 2016). With increasing numbers of installed battery storage systems, future studies should investigate if the personal experience with battery storage systems also affects the factors influencing their acceptance. The results presented in Sect. 4.1 show that acceptance for battery storage systems might differ between homeowners and tenants. It was not possible to perform a multigroup analysis comparing the two because the number of respondents of each group was lower than the necessary thresholds.

6 Conclusions and future work

Our research indicates that, in general, there is a high level of acceptance for battery storage systems. Our results suggest that acceptance for PV battery storage systems is highest among homeowners. However, even tenants or people living in apartments believe that PV battery storage systems are "sensible and sustainable", and a majority of them would like to use one.

Factors that might be important for the adoption of battery storage systems have been derived from the SEM. On the one hand, perceived knowledge about battery storage systems and behavioral beliefs (e.g., the possibility of contributing to energy transition) have a significant positive effect on acceptance. Perceived risks (e.g., doubts about lifetime), on the other hand, have a significant negative effect on acceptance. Therefore, campaigns informing people about battery storage systems and educating people about the current lifetime of batteries and existing warranties could increase acceptance and adoption. The perceived gains of battery storage systems (which mainly depend on the costs) also play an essential role. However, this factor improves by itself as battery prices continue declining.

Our results show that acceptance levels are different between homeowners and tenants. However, our sample size was insufficient to perform a multigroup analysis and analyze how the factors influencing acceptance for battery storage systems differ between the two groups. This could be addressed in future studies. PV battery storage systems can be economical particularly for PV users whose guaranteed feed-in tariffs are running out (Fett et al. 2017); our results also indicate that continued operation after feed-in tariffs influences the acceptance for battery storage systems. Future work could focus on surveying more PV owners who do not have battery storage systems yet. Their needs could then be analyzed in detail. Communication strategies for promoting PV battery storage systems could be developed based on the results of SEM and corresponding multigroup analysis.

Appendix

Table 1 Latent variables and their definitions

Latent variable	Definition
Personal innovativeness	The degree of interest in innovations and willingness to try innovative products (Rogers 2003)
Subjective norms	The degree of approval for the use of PV battery systems that a person perceives from his social environment (Fishbein Ajzen 1975)
Image	The degree to which the use of PV battery systems is perceived to enhance one's status in one's social system (Moore Benbasat 1991)
Environmental awareness	The degree to which a person's decisions are influenced by environmental concerns (Roberts 1995)
Behavioral beliefs	The degree to which a person believes that the use of PV battery systems will have positive effects (Ajzen 1991)
Perceived ease of use	The degree to which a person believes that using PV battery systems would be free of effort (Dudenhöffer 2015; Davis 1989)
Perceived usefulness	The degree to which a person believes that using PV battery systems would be useful (Dudenhöffer 2015; Davis 1989)
Perceived risk	The degree to which a person believes that using PV battery systems is safe (Fazel 2014)
Perceived knowledge	The degree to which a person believes to have a broad knowledge about PV battery systems (Dudenhöffer 2015)
Perceived independence	The degree to which a person believes that an installation will make her independent from the common electricity distribution system
Perceived subsidies	The degree to which a person believes that the purchase of a PV battery system is supported financially
Additional benefits	The degree to which an individual believes that a PV battery system has benefits encompassing financial gains and its usefulness
Perceived gains (PG)	The degree to which a person believes that a PV battery system will yield financial profits
Social responsibility (SR)	The degree to which an individual believes that costs and benefits of PV battery system should be distributed equally
Intention to buy (IB)	The degree to which a person is willing to buy a PV battery system

Table 2 Overview of measurement models

Latent variable	Composition	# of indicators	Source
Environmental awareness (EA)	Reflective	5	(Bruner 2015; Haws et al. 2014; Roberts 1995; Jansson 2011)
Subjective norms (SN)	Reflective	4	(Venkatesh Davis 2000; Venkatesh et al. 2003; Fishbein Ajzen 1975; Mathieson 1991)
Personal innovativeness (PI)	Reflective	6	(Fazel 2014; Parasuraman 2000)
Image (IMG)	Reflective	4	(Fazel 2014; Tornatzky Klein 1982)
Perceived independence (PID)	Reflective	4	(Figgener et al. 2018; Hoffmann et al. 2018)
Perceived risk (PR)	Reflective	5	(Figgener et al. 2018; Fazel 2014; Hoffmann et al. 2018; Bauer 1960; Cheng et al. 2006)
Perceived subsidies (PS)	Reflective	3	Self-developed
Perceived knowledge (PK)	Reflective	4	(Fazel 2014; Srinivasan Ratchford 1991)
Additional benefits (AB)	Formative	4	(Figgener et al. 2018)
Perceived gains (PG)	Reflective	5	(Figgener et al. 2018; Fazel 2014; Hoffmann et al. 2018; Moshövel et al. 2015)
Social responsibility (SR)	Formative	3	(Wiesehügel 2013; PV MAGAZINE 2014; Rutschmann 2019)
Behavioral beliefs (BB)	Formative	5	(Figgener et al. 2018; Hoffmann et al. 2018; Rentzing 2011)
Perceived usefulness (PU)	Reflective	4	(Davis 1989; Venkatesh Davis 2000; Ajzen 1991; Fishbein Ajzen 1975)
Perceived ease of use (PEOU)	Reflective	4	(Davis 1989; Venkatesh et al. 2003)
Acceptance/Intention to buy (IB)	Reflective	5	(Davis 1989; Venkatesh Davis 2000)

Table 3 Results of SEM Analysis

Factor	Target	Path coefficients	t	Hypothesis	f^2
PU	IB	0.432	6.207	Yes	0.244
PEOU	IB	0.234	5.558	Yes	0.150
PEOU	PU	0.265	4.712	Yes	0.123
EA	PU	–0.006	0.113	No	0.000
SN	PU	0.093	1.423	No	0.012
PI	PU	0.057	1.090	No	0.008
PI	AB	0.413	5.644	Yes	0.189
IMG	PU	0.010	0.172	No	0.000
PID	PU	0.010	0.174	No	0.000
PS	PU	0.053	0.868	No	0.006
PR	PU	0.014	0.252	No	0.000
PR	PEOU	–0.249	3.603	Yes	0.087
PK	PU	0.114	1.752	Yes	0.019
PK	PEOU	0.483	8.562	Yes	0.348
PK	AB	–0.266	2.993	Yes (opposite sign)	0.078
AB	PU	0.070	0.991	No	0.006
AB	PEOU	0.234	3.037	Yes	0.082
AB	IB	–0.042	0.780	No	0.003
PG	PU	0.218	2.278	Yes	0.054
PG	IB	0.142	2.497	Yes	0.036
SR	PU	–0.016	0.311	No	0.001
BB	PU	0.335	4.645	Yes	0.124
BB	IB	0.260	4.143	Yes	0.095

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