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One service fits all? Insights on demand response dilemmas of differently equipped households in Germany

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ABSTRACT

Households equipped with flexible technologies, such as electric vehicles, can support the energy transition by shifting electricity consumption to times of high renewable supply and by preventing consumption peaks that cannot be covered by existing grid and generation infrastructure. Demand response services support households in performing these consumption shifts. Households ask for specifications of services that stand partly in contrast to each other. For instance, while electric vehicle owners tend to insist on retaining control over their charging, others prefer data-driven automation to minimize their active involvement. Recent studies exploring the acceptance of demand response services focused either solely on specific household groups (e.g. electric vehicle users) or on a broad representative sample without further differentiation. Complementarily to fill this gap, we examine differences in preferences for contrasting service designs between household groups. Specifically, we consider: (i) the type of flexible technology to which demand response is applied, and (ii) the adoption level, i.e., whether the households plan to, or currently own, a flexible technology.

In a vignette survey, we examine the preferences towards four contrasting service designs with German households that either own or have expressed interest in acquiring a flexible technology ($n = 962$). Our results show that the preferences do not fundamentally differ between the kind of flexible technology and adoption level. Generally, participants prefer automated demand response services with data sharing. The added value of realizing energy cost savings effectively and efficiently stands out as the main driver for the diffusion of demand response services, outweighing data privacy concerns. Contrary to our expectations, electric vehicle owners did not show a special need for control and households not yet owning flexible technologies did not express a need for little effort. We discuss the implications of our findings for demand response service providers and outline pathways of future research in this domain.

1. Introduction

Coordinated consumption shifts of flexible household technologies, such as electric vehicles (EV), heat pumps (HP), or battery storage systems (BSS), support a cost-efficient and secure decarbonization of the energy system. These technologies can be leveraged to consume energy during periods of high renewable supply and to prevent consumption peaks that exceed the capacity of existing energy infrastructure [1,2]. While households recognize the value of these consumption shifts, their limited time and other priorities often prevent them from actively implementing such changes in consumption. Demand response services (DRS) by service providers, such as variable electricity tariffs or energy management systems with direct load control, are emerging to facilitate the required consumption shifts [3,4]. Different specifications of the services exist to please the households' needs for participation in DRS [5,6]. Some popular but contrasting specifications create dilemmas for households and force them to decide between these contrasting options [7,8]. This paper reveals households' preferences on the most prominent demand response (DR) dilemmas in current literature.

Shifts in the operation of flexible technologies align with the households' needs as long as they do not violate their primary purpose (e.g., heating and mobility needs). This compatibility tends to differ between the kind of flexible technology and its adoption level. Specifically, studies with EV-owners report a strong need to stay in control of charging processes [9–11]. Comfort losses and a high operational effort

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Abbreviations

EV	electric vehicle
HP	heat pump
BSS	battery storage system
DR	demand response
DRS	demand response service
ANOVA	analyses of variance
SD	standard deviation

discourage households – especially if participation in DRS requires prior investments in flexible technologies [12,13]. While most studies focus on households with one specific flexible technology (e.g., [9–11,14,15]) or a broad representative sample without further differentiation into subgroups (e.g., [16–21]), we compare the preferences towards contrasting DRS designs between households with different flexible technologies and with different adoption levels. Our comparison demonstrates whether the household groups require fundamentally different DRS designs (e.g., variable electricity tariffs for current EV-owners and direct load control for late adopters) or if there is a general alignment in preferences, suggesting a 'one-size-fits-all' service approach. We summarize our research objective in the following research questions: How do households decide when confronted with dilemmas of contrasting attributes in DRS? In these dilemma situations, do households' choices of DRS attributes vary based on their current ownership of a flexible technology? And does it matter which kind of flexible technology they own?

Based on the literature, we specify the research questions and postulate three hypotheses that illustrate the prevalent design contrasts for specific household groups. We choose a simplified vignette study to investigate the hypotheses. The simple design with a limited set of attributes and binary attribute specifications allows to examine preferences of different household groups in one study and challenges the households to choose between contrasting DRS designs. We combine the advantages of the two most common research approaches for the acceptance of DRS design, qualitative studies describing contrasting design aspects more comprehensively (e.g., [9,13,15]) and choice experiments forcing the households to decide (e.g., [16,19,22,23]). Thereby, we find a balance with the vignettes: making them as descriptive as possible (especially for households interested in but not yet owning a flexible technology), while keeping them sufficiently abstract to involve different household groups (with different technologies) within a single study.

In the vignette study, participants are asked to state their preferences based on a short description of a situation. In each situation, four variables are implemented in a way that the contrasting attributes of DRS vary between situations. Thus, each situation contains one positively specified attribute, leading to a total of four DRS designs (for details see Section 3). The hypothetical setting is made tangible for participants with a descriptive reference to familiar dilemmas and technologies. We recruited participants ($n = 962$) from Germany who either own or have expressed interest in purchasing a flexible technology, aiming to compare their preferences. This specific sample is more suitable to respond to the vignettes than a representative sample because the ownership of flexible technologies is a technical prerequisite for participating in DRS [12,24]. Since DRS are hardly offered in Germany (apart from field experiments with variable electricity tariffs and a curtailment product offered by German distribution system operators), operating flexible technologies is the most relevant experience for assessing the consequences of shifting their operation. Thereby, our paper extends the existing literature by examining the preferences of different household groups towards contrasting DRS designs by presenting dilemmas.

The following section (Section 2) reviews the relevant literature on key dilemmas and introduces the tested hypotheses on DRS. Section 3 presents the experimental design, the collected data, and the methods of the present study, while Section 4 outlines the results of the statistical analyses. Finally, Section 5 discusses the results and their implications.

2. Literature review and hypotheses

The range of discussed DRS in the literature indicates a lacking consensus on their design. For instance, variable electricity tariffs (e.g., [18,25,26]) and energy management systems with direct load control (e.g., [7,13,17]) are two frequently mentioned examples with a contrasting design, which target different needs of the households. While variable electricity tariffs empower households to shift their consumption by themselves, energy management systems automate the shifts and reduce the effort for households. To create a targeted design for a broad adoption of DRS, scholars and service providers need to understand which needs drive DRS adoption. Since the needs are likely to differ between households, we also explore their heterogeneity. For instance, research shows that some households dislike frequent disruptions while others dislike rare but extreme events [7].

2.1. Common study designs for testing the DRS adoption

Present DRS studies differ not only in the examined methodological design but also in the abstraction level of the design and the targeted household groups (see Table 1). Regarding the abstraction level, focus groups (e.g., [13]), interviews (e.g., [15]), and mixed-method studies (e.g., [9]) revealed (mainly) qualitative drivers on a higher abstraction level (e.g., maintaining control, reducing operational effort, mitigating risks). At the same time, choice experiments (e.g., [16,19,22,23]) explored the value of specific design features leading to less abstraction. The latter assessed, for instance, the timing of the consumption shift (e.g., point in time, frequency, and duration, [16,19]), its relevant interactions (e.g., advance notifications, right to opt-out, data sharing, [22,23]), additional services (e.g., technical support, device monitoring, smart home services, [23,27]) and monetary aspects (e.g., compensation and fees, [17,18]). The associated value of the specific features is partly hard to assess in a generalizable fashion since it varies over time depending on the participants' socio-temporal conditions [28]. While qualitative studies describe contrasting DRS design aspects more comprehensively, the comparative approach of choice experiments reveals preferences between DRS designs. Acknowledging the strengths and limitations of both approaches, we choose a simplified vignette study, which forces participants to decide between contrasting DRS designs after their comprehensive description.

Regarding the targeted household groups, present DRS studies focus either on early adopters of specific flexible technologies, such as EV-owners (e.g., [9–11,14,15]) whose experience prequalifies them for more valid judgment on shifting the particular technology, or a representative sample (e.g., [16–21]), also capturing the perspectives of potential future adopters. Combining both advantages, we follow the approach of Delmonte et al. [15] to involve households who own or are interested in acquiring flexible technologies. Combined with the decision for a simplified vignette study, this allows to involve (prospective) owners of different flexible technologies in one study and compare their preferences while achieving valid responses.

2.2. Acceptance of control loss, operational effort, and other requirements for DRS

Table 1 displays the heterogeneity of service attributes that are identified as drivers for the adoption of DRS. Financial benefits and means to retain control over consumption are key drivers in many studies. In some of them, both are reported as important (e.g., [19,22]). In others, financial benefits overrule means to retain control (e.g.,

Table 1
Literature overview w.r.t. to method and sample, tested DRS service attributes, main determinants for the adoption of DRS and other outcomes; sorted by method (i.e., qualitative studies, choice experiments, surveys separated by a horizontal double line) and sample (i.e., households (=HH) with or without flexible technologies separated by a horizontal bold line); grey cells mark the tested attributes; among them, the dark grey cells highlight the ones that are confirmed as drivers of DRS adoption.

Source	Method	Sample	Control of shifts	Effort of perform-ing shifts	Data sharing	Cost savings	Other attri-butes	Other determinants & outcomes
9	Mixed method	EV-owners (n=24-1428)	Reduced charging power					Participants driven by uncertainty & anxiety, and constrained by external factors (e.g., access to charging stations)
15	Semi-struc-tured inter-views	EV-owners or with purchase intension (n=60)	Third-party control	User-mana-ged charging		Financial incentive		Preferences towards user-managed charging due to control
14	Online nudge experi-ment	EV-owners (n=164)	State of charge buffer			Financial incentive	Social or enviro-nmental benefits	No change for social & environmantal benefits
13	Field trial with focus groups	HH with white goods (n=18-72)	Third-party control	Conven-ience, user interface				Financial incentives for initial user interaction
10	Choice exper-iment	EV-owners or with purchase intension (n=1470)	Third-party control		Degree of data sharing	Financial incentive	Share of renew-able consump tion	More driven by financial than environmental benefits
11	Choice exper-iment	EV-owners (n=611)	Min. range, timing of charging			Financial incentive	Access to board com-puter	Even without financial incentives, high acceptance rates
22	Choice exper-iment	HHs (10 percent with EVs, 50 percent with HPs, n=556)	Number of inter-ventions, prolongation of charging, override, notification			Financial incentive		Financial benefits for HP DR, overriding options for EV DR
19	Choice exper-iment	HHs (n=1034)	Frequency, duration, time period of inter-ventions			Financial incentive		
16	Choice exper-iment	HHs (n=918)	Third party control, time period of interventions		Degree of data sharing	Financial incentive	Heating or electri-city	
17	Choice exper-iment	HHs (n=160)		Ease of effort		Financial incentive	Environ mental or system benefits	Other determinants: environmental or system benefits
18	Choice exper-iment	HHs (n=160)		Degree of automa-tion			Granula-rity of variable tariffs & price spreads	Need for simple tariffs, increased acceptance in case of practical experience
23	Choice exper-iment	HHs (n=985)	Response time		Degree of data sharing	Financial incentive	Smart home features	
21	Survey	HHs (n=653)	Retain control	Conven-ience	Data security, data privacy	Financial incentive	Environ mental benefits	Other determinants: technical safety, data privacy
20	Survey	HHs (n=835)				Financial incentive	Smart techno-logies, actions for energy saving	Limited familiarity with smart grid technologies

[14,15]), or vice versa (e.g., [10,11,16]). Yilmaz et al. [22] explain this discrepancy with the involved flexible technologies. Other studies identify convenience, comfort, and simple information (e.g., [17,18,21]) or data privacy (e.g., [10,23]) as more important than financial benefits. Duetschke et al. [18] underline that the acceptance increases with the DRS experience level. This distinction may explain differences between studies with non-experienced and experienced participants.

The need for control over consumption, operational effort, level of data sharing, and energy cost savings are reoccurring attributes of DRS in the literature, whose specifications influence each other. Still, their importance for the adoption of DRS is hardly compared to each other within one study. Our study tackles this gap in the literature based on the following insights on the attributes, the role of flexible technology, and experiences with them from the literature.

DRS need to be designed in a way that the secondary purpose of the flexible technology, participating in DRS, does not impede its primary purpose (e.g., providing heat or mobility). The compatibility between both purposes depends on how households use flexible technologies. For instance, for most households, the usage of EVs is an integrated part of their daily routine, which depends on socio-temporal configurations [4,28]. Since charging is restricted to plugin times and the households rely on their EV for performing their daily activities, households tend to charge immediately after arrival and in larger quantities to cover their mobility needs [9,15,29]. Relying on public charging or having an inflexible daily schedule reinforces this charging practice [28]. For instance, when operating an HP, most households request that the temperature stays within a specific acceptable range, especially during the colder season [30]. In contrast to EVs and HPs, the primary purpose of BSSs is to provide flexibility, and therefore they are inherently compatible with DRS. Comparing the three flexible technologies, a special sensitivity to participation in DRS may apply for EV-owners because EV use is closely linked to households' daily routine [9,31]. This is in line with research showing that compatibility of an EV with household needs predicts EV purchase intention [33]. Given the strong interlinkages with their daily routine, a more substantial reluctance towards control loss is assumed for electricity-only (e.g., EVs) than heating technologies (e.g., HP) [26]. Households consider the right to opt-out of a DRS more important for EVs than for HPs [11,22]. Research shows similar service features that drive EV-owners' decisions for DRS, such as (i) an ensured minimum state of charge [10,11] and (ii) an immediate charge button [31]. This highlights the special sensitivity of EV-owners towards losing control over consumption shifts.

Owning a flexible technology is not only a technical prerequisite for DRS but also demonstrates openness towards technological innovations, which increases the likelihood of participating in DRS. One could state that technology openness leads to a higher acceptance of the downsides of innovations in early adopters compared to households with less or no technology openness. Parrish et al. [7] explain that a socio-technical differentiation of households (e.g., technology adoption) explains the usage likelihood of DRS better than socio-demographic variables. Put differently, the access and ability to use a flexible technology influence the intention to use a DRS more than, for instance, income or age. Abrahamse and Steg [31] support that socio-demographics explain the household's overall energy usage well but not whether households can change their energy consumption. The latter is better explained by socio-psychological values, such as social norms, environmental awareness, and openness towards innovations [12].

In particular, the literature recognizes differences in the acceptance of DRS based on the adoption level of corresponding technologies. For instance, a higher acceptance of shifting energy consumption is recognized for households owning generation technologies [32], EVs [22], and smart home devices [20]. For greater participation in DRS beyond the early adopters of flexible technologies, the need for enabling technologies that ease participation is emphasized [17].

Easing the participation of prospective owners of flexible technologies and safeguarding the control need of EV-owners are two key requirements for participation in DRS. While their importance is especially prevalent for specific household groups, they are also generally more important than other aspects [15,30]. While investments in flexible technologies are driven by their economic viability, participation in DRS depends on the corresponding effort and compatibility with the households' habits and comfort [12]. In field experiments examining variable electricity tariffs, households reported that the effort of monitoring the tariffs exceeded its financial benefit [13,33,34]. In some cases, even households with a high level of motivation showed fatigue effects after executing consumption shifts manually for a while [34,35].

Automated, data-driven consumption shifts (also called direct load control) reduce the effort for consumers [35,36]. This service specification creates two other dilemmas. Firstly, households fear that the automated shifts are incompatible with their routines and that they will lose control over their consumption [13,35]. In surveys, households asked for financial compensation for their electricity consumption being controlled in general [30] or for having less favorable DR conditions (e.g., the electricity consumption being controlled over long periods of time) [19]. At the same time, field experiments showed that the reservations towards automated consumption shifts diminished after a period of familiarizing with it [35,37] - underlining the importance of distinguishing between current and prospective owners of flexible technologies.

Secondly, calculating and determining the automated consumption shifts requires sharing sensitive consumption data with the service provider [37]. Surveys demonstrated that households are only willing to share their data if they receive financial compensation [23,27]. Inconsistencies in determining the compensation level were identified when short-term rewards of data sharing (e.g., an efficient realization of energy cost savings) were traded against its long-term risks (e.g., perceived surveillance of daily routines by the service provider). This can be explained by a lack of information for the household about the consequences and biases towards short-term rewards [38,39].

Requests for high compensations in surveys or drop-outs in field experiments indicate that staying in control of consumption and limiting the operational effort are basic requirements for participating in DRS [35]. These requirements need to be fulfilled before households shift their energy consumption for electricity cost savings. Based on the reviewed literature, safeguarding data privacy (i.e., no data sharing) tends not to be one of the basic requirements.

2.3. Summary and hypotheses

Summarizing households' needs for participating in a specific DRS, one can state that how the DRS is designed seems to be tantamount to the objective it aims to achieve. Based on previous research, we chose the following four attributes of DRS because they seem to influence household participation in DRS: control of consumption shifts, the effort of performing the shift, consumption data sharing (i.e., sharing more consumption data than with other DRS), and electricity cost savings. Combined with the households' two most prevalent, distinctive characteristics, the kind of flexible technology and its adoption level, we conclude the following three hypotheses for our study:

H1. "Consumption control and limited effort as basic DR requirements": Participants are less likely to use a DRS that violates the need for control of the electricity consumption and the operational effort than a DRS that violates the objective of saving electricity costs and data privacy.

H2. "Need for consumption control of EV-owners": Participants with EVs are less likely to choose a DRS with low control than participants with other flexible technologies.

H3. "Need for effort limitation for interested householdshouseholds": Participants who do not yet own flexible technologies are less likely to choose a DRS with higher operational effort than participants who already own flexible technologies.

While Hypothesis 1 "consumption control and limited effort as basic DR requirements" does not differentiate between the household groups and involves all attributes, Hypothesis 2 "need for consumption control of EV-owners" and 3 "need for effort limitation for interested households" focus on specific groups and highlighted attributes.

In our study, a simplified vignette design based on the four highlighted service attributes and its carefully combined and described specifications convey the dilemmas of DRS coherently and meet the German participants' limited experience with DRS. While more complex vignette studies and choice experiments randomly combine 3 to 5 specifications of 3 to 5 DRS attributes with each other, we choose binary attribute specifications. The vignettes are embedded in a realistic and concrete context, which makes it easier for the participants to relate to and reveal their judgment – this applies especially for households that do not yet own a flexible technology [40]. At the same time, the vignettes' attributes are abstract enough to apply for households with different flexible technologies. A too specific contextualization is avoided to obtain generalizable results [41].

3. Materials and methods

The following section illustrates how we test the previously introduced hypotheses. In particular, we explain the experimental design (Section 3.1), the resulting data (Section 3.2), and the statistical methods applied to the data (Section 3.3). The study design including the hypotheses has been pre-registered and is available at https://aspredicted.org/blind.php?x=9Q3_3QG

3.1. Experimental design, survey, and measures

We conducted a vignette study in an online survey to test which of the four DRS attributes (control of consumption shifts, the effort of performing the shift, consumption data sharing, and electricity cost savings) are preferred by which household group based on their adoption level of different flexible technologies. The experiment targeted German households with some level of experience with flexible technologies. Thus, we surveyed households who reported in a pre-screening questionnaire that they own an HP, an EV, or a BSS (different flexible technologies) or considered purchasing one in the past half year (different adoption levels).

To implement the dilemmas based on the literature and the four outlined DRS specifications, we developed four different stylized DRS and included each DRS in a vignette. Each DRS was characterized by one negatively specified attribute, respectively. The other three attributes were framed positively. To have sufficient power for comparing the household groups, we decided to present all vignettes to each participant and limit the number of vignettes to four, the smallest sub-set of vignettes capturing dilemmas. The order of the services (each presented in a vignette) stayed the same for each participant, proceeding from the most to the least widespread DRS in Germany. In fact, it started with the DRS on losing control (similar to a curtailment product offered by German distribution system operators), followed by the one with high effort (i.e., performing the shifts by themselves; similar to the field experiments on variable electricity tariffs) and the DRS with data sharing. Lastly, the DRS having lower energy cost savings (as a consequence of minimizing control loss, effort and data sharing) was presented. The unified order ensures a logical flow from the participants' perspective [43]. After presenting one DRS, we assessed the DRS usage likelihood, the dependent variable, by asking participants how likely it is that they choose this DRS.

All four vignettes with the stylized DRS were introduced with a general explanation of DRS and a scenario of an electricity consumption shift from the evening to the night hours. This scenario was carefully chosen to create similar conditions for different flexible technologies owned, assuming that most participants are at home during these hours independent of their individual routines. The two specification levels for each attribute, the four stylized DRS, a short form of the introduction, and a text example of one DRS are illustrated in Fig. 1. The vignette text for the three other DRS is provided in Appendix F.

The technologies mentioned in the questionnaire were individually adjusted for those the participants owned or were interested in, which was asked beforehand. If multiple technologies were indicated in the pre-screening, the most prevalent one in the German population was displayed as a specific technology, ranking from HP and EV to BSS (see Figure Annex 1.).

We also collected socio-demographics (after the vignettes) and socio-psychological aspects (mainly before the vignettes, see in Table 2) in the survey to explain the likelihood of using each of the four DRS. The latter consists of items testing the attitude towards the four service specifications and other aspects from literature motivating DR participation, in particular, environmental awareness (e.g., [12,44]), technology openness (e.g., [23]), and social norms (e.g., [45]).[1] The implemented measures are presented in Table 2.

In the context of the increased electricity prices in 2022 and their impact on consumption behavior, we asked participants for the change of their electricity tariffs since the beginning of 2022, ranging from a strong increase (coded as 5), no change (coded as 3) to a strong decrease (coded as 1). If appropriate, we conducted Cronbach's α to examine the reliability of the implemented scales. All measures appear reliable (Cronbach's α >0.70; see Table 3).

3.2. Data and sample

The data were collected in Germany by a market research institute from March to June 2022. They cleaned the data and excluded participants based on the following criteria: (1) incomplete questionnaire, (2) participants answering the two implemented quality control questions incorrectly, and (3) participants who reported in a pre-screening questionnaire that they did not own and were not interested in purchasing a flexible technology. Of the resulting sample of 1116 participants, the ones who did not disclose their gender, home tenure, education, or income level were also excluded to ensure maximum power for the analyses. This reduced the sample to 962 participants. Testing the hypotheses, we arrive at the same pattern of results with the full ($n = 1116$) and the reduced sample ($n = 962$).

The data present a non-representative subset of the German population, who is already experienced with or has seriously thought about purchasing flexible technologies and, thereby, is likely to answer questions on DRS meaningfully and reliably. In contrast to the German population, the socio-demographic variables show that a higher share of this sub-sample owns their home, is older and more often represented by male individuals, and has a higher income and education level (Table 3). This is in line with recent findings in the literature [46,51].

The sample involves five household groups regarding their ownership of flexible technologies, including HP, EV, and BSS (Table 3): participants (1) owning more than one flexible technology (also called multiple owners in the following, 27 %), (2) owning only an HP (20 %), (3) owning only an EV (10 %), (4) owning only a BSS (5 %) and (5) having considered to purchase at least one of the mentioned flexible technologies in the last six months (37 %). An analysis of the statistical power shows that BSS owners cannot be separately evaluated in the following analyses due to their small sample size ($n = 52$). Most multiple owners own an EV and a BSS (31 %), followed by owning all three technologies (30 %), an EV and an HP (25 %), and an HP and a BSS (13

[1] For the control loss measurements with EV as the reference technology, we refer to the usage of electric vehicles and not the usage of the charging point, since a limited usage of the latter results ultimately in a limited usage of the electric vehicle.

%). Most participants indicated that they do not have experiences with digital services for optimizing their consumption yet (69 %) but are interested or very interested in them (63 %).

3.3. Statistical method

The hypotheses deal with differences in DRS preferences between their specifications (H1) and the household groups (H2 and H3). Exploratory analyses provide insights into why participants have chosen one DRS specification over the other. The following illustrates the statistical methods for the hypothesis testing and the exploratory analysis.

Whether households respond more sensitively towards violating the attributes of staying in control and limiting effort than the ones of electricity cost savings, and data sharing (H1) is tested with (non-parametric) Wilcoxon signed-rank tests including a Bonferroni correction (instead of paired *t*-tests because the differences in ratings, i.e. the dependent variable, were not normally distributed; but see [58]). It compares the DRS with the hypothetically prioritized specifications to the ones with hypothetically secondary specifications. Therefore, Hypothesis 1 is decomposed into four sub-hypotheses (Fig. 2): To be confirmed, DRS 1 with loss of control is expected to have a lower usage likelihood than DRS 3 with data sharing and DRS 4 with fewer energy cost savings. As for DRS 1, the same applies to DRS 2 with more effort. To detect differences in the usage likelihood between hypothetically prioritized or hypothetically secondary specifications, respectively, comparisons between DRS 1 and 2, as well as 3 and 4, are conducted as an exploratory analysis. The Bonferroni correction is applied to minimize the risk of α inflation.

Hypotheses 2 and 3 focus on the DRS preferences between the household groups for the DRS 1 with control loss and DRS 2 with more effort (Fig. 2). Therefore, we conducted (non-parametric) Kruskal-Wallis tests (as Shapiro-Wilk tests indicated that the dependent variables were again not normally distributed). To confirm Hypothesis 2, EV-owners should show a lower usage likelihood for DRS 1 than the other participants. For Hypothesis 3, prospective owners of flexible technologies (i.e. participants with a purchase intention only) should show a lower usage likelihood for DRS 2 than current owners of flexible technologies. As part of the exploratory analysis, Kruskal-Wallis tests were also conducted for DRS 3 and 4 to explore preferences among the household groups towards these DRS.

The hypotheses ask for comparisons between the DRS that reveal the importance of one attribute in relative terms, i.e., relative to the other three reversely specified attributes of the same DRS. The results do not explain whether the difference in usage likelihood results from the positively or negatively specified attributes of one service. Therefore, we additionally conduct one linear regression for all services to explore which attribute drives the difference in the usage likelihood between two services. Since the design of the stylized service vignettes makes the attributes correlate, we choose a ridge regression for the analysis. Its penalty term mitigates the impact of collinearity, such as demonstrated by [59–61]. The general psychological measurements in Table 2 are an additional source for explaining differences among the household groups.

As a further exploratory analysis, we conduct a linear hierarchical regression for the most popular DRS to understand the explanatory factors behind its usage likelihood. In TableAnnex 5, TableAnnex 6 and TableAnnex 7, the results of a linear hierarchical regression for the other three DRS can be found. In line with previous analyses and the explanatory variables in the literature, four hierarchical levels are applied:

- The attitude towards each of the four DRS specifications
- The adoption level of the different flexible technologies
- Other most common psychological aspects in literature or timely topics: environmental awareness, technology openness, social norm, energy price change
- Socio-demographics: Age, gender, tenure, education, income

The dependent variable for all analyses is the usage likelihood of the DRS rated on a 5-point Likert scale (ranging from 1 - fully disagree to 5 - fully agree). For validation, we also conducted all analyses with the ranked usage likelihood as dependent variable (ranging from 1 – most likely to be used to 4 – least likely to be used, see Appendix E).An analysis of the statistical power showed that the sample size is considered to be sufficient to identify even small effect sizes for all analyses.

4. Results

In the following, we present the results of the previously described statistical methods that were applied to test the hypotheses (Section 4.2). Then, we explain why the participants preferred one DRS specification over the other (Section 4.3). Beforehand, we introduce the descriptive statistics of (i) the psychological variables, including the attitude towards the DRS specification, and (ii) the usage likelihood for the four stylized DRS (Section 4.1).

4.1. Descriptive statistics

As the first step of the analysis, we examined the descriptive statistics of the psychological aspects (Table 4). The analysis shows that, on average, participants rated all variables high with means above the scale's midpoint. The importance of energy cost savings was rated highest (compared to the other variables). In contrast, the importance of data privacy is, on average, the lowest and its standard deviation (SD = 1.05) the highest (compared to the other variables), indicating different attitudes towards data privacy among respondents. However, the mean of the importance of data privacy is still high. Apart from the importance of data privacy (3), Spearman's correlation analyses show a positive correlation ($p < .01$) between variables associated with the DRS specifications and the psychological variables from the literature (5, 6, 7). The positive correlations indicate that a strong social norm, high environmental awareness, and high technology openness are associated with more tolerance towards the downsides of the DRS (e.g., the need to accept additional effort). However, the size of the correlations varies from weak (e.g., correlations between 5, 6, 7 and the importance of cost savings) to relatively strong (e.g., correlation between 6, 7 and acceptance of effort). Spearman correlations smaller than 0.10 can be considered negligible [62]. Descriptive statistics on these variables for each household group are provided in TableAnnex 1.

When examining the overall preference of households (i.e., usage likelihood of each DRS), we received the following descriptive results: DRS 3 with more data sharing is most likely to be used, followed by DRS 2 with more effort and DRS 1 with less control. Participants are least willing to compromise on cost savings, rating the usage likelihood of DRS 4 as the lowest (Fig. 3). If the participants are forced to decide *between* the DRS (i.e., rank them starting with the most preferred one), they respond consistently, ranking DRS 3 most often as the first choice and DRS 4 most often as the last choice (Fig. 4).

4.2. Hypotheses testing

The Wilcoxon signed-rank test supports only partially Hypothesis 1 *"consumption control and limited effort as basic DR requirements"*. We expected that DRS 1 with less control and DRS 2 with more effort are less preferred than the other two DRS (i.e., DRS 1 and 2 have a significantly lower usage likelihood compared to DRS 3 and DRS 4).. The results of the four comparisons (sub-hypotheses 1a-d) are illustrated in Tables 5 and 7. As expected, DRS 1 with less control had a significantly lower usage likelihood than DRS 3 with more consumption data sharing (a). In contrast, DRS 1 had a higher usage likelihood than DRS 4 with less cost savings (b), not confirming the hypothesis. The same applied to DRS 2 with more effort. DRS 2 showed a lower usage likelihood than DRS 3 (c)

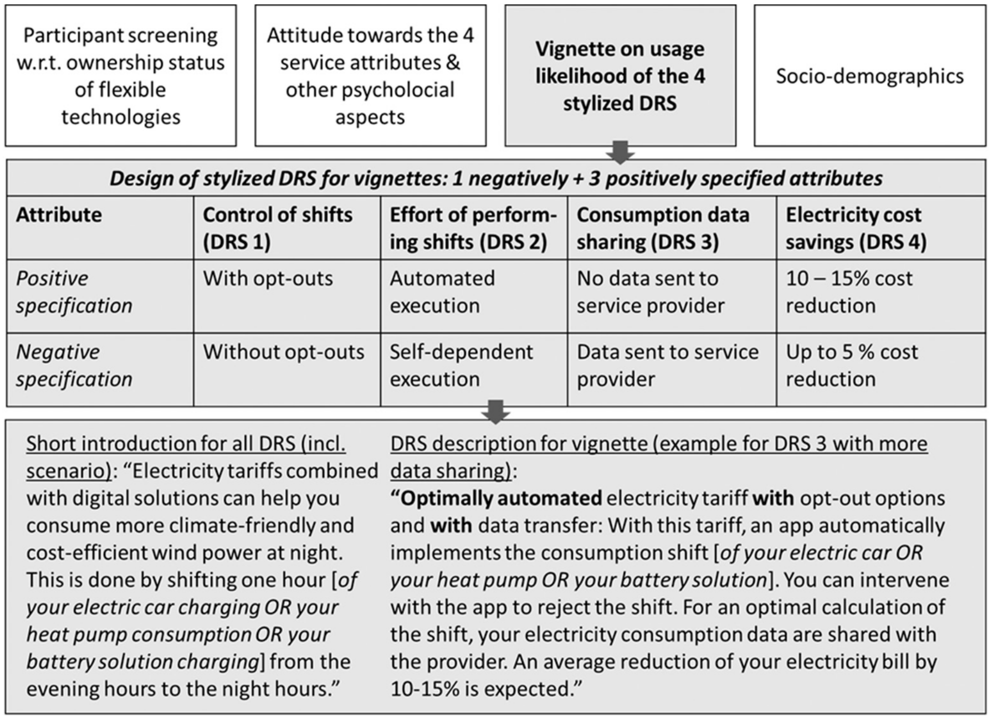

Fig. 1. Flow chart of the survey, vignette part shaded in grey with one text example of a vignette.

but a higher usage likelihood than DRS 4 (d). Consequently, households are less willing to compromise on consumption control and limited effort than on limited data sharing. But they are least willing to compromise on realizing energy cost savings.

The responses on the most popular DRS 3 (more consumption data sharing) and the least popular DRS 4 (less cost savings) show that participants prefer data-driven, automated DRS, which achieve energy cost savings effectively and efficiently. Staying in control over their consumption and limiting operational efforts are only important basic requirements if the cost-saving potential is realized. They are willing to share their consumption data if all three aspects can be covered with data-driven, automated services.

The extreme positions of the DRS that impact data privacy (DRS 3) and cost savings (DRS 4) are confirmed by sign test based on the ranked usage likelihood (see TableAnnex 9). In contrast, the results based on the ranked dependent variable show more extreme tendencies for the services that imply control loss (DRS 1) and effort (DRS 2) than the results based on the rated dependent variable. In particular, we find no significant difference between services that increase the effort (DRS 2) and that mitigate data privacy (DRS 3). The same applies to the services that increase the control loss (DRS 1) and that mitigate cost savings (DRS 4).

The relative importance of realizing cost savings over safeguarding data privacy is reinforced by the findings on the absolute importance of one attribute based on the ridge regression in TableAnnex 8. It analyses the effect of each attribute (coded in a binary way indicating whether the attribute was positively or negatively specified) on the usage likelihood of all DRS. While compromises on the cost savings strongly ($\beta = -0.27$) and on the need for control slightly ($\beta = -0.02$) decrease the usage likelihood, the automation in return for data sharing strongly ($\beta = 0.22$) and the self-dependent execution slightly ($\beta = 0.08$) increase the usage likelihood.

A small ($r < 0.1$) to medium ($0.1 < r < 0.3$) effect size is recognized for the six *t*-tests [63].

Testing Hypothesis 2 *"need for consumption control of EV-owners"*, the Kruskal-Wallis-test shows no significant difference in the usage likelihood between the five household groups for DRS 1 with less control (see Table 6). The Kruskal-Wallis test is non-significant, leading to no required subsequent analyses. Thus, Hypothesis 2 is not supported. We have chosen a nonparametric Kruskal-Wallis test to test Hypothesis 2 due to the significant Shapiro-Wilk tests indicating a violation of the ANOVA assumption that the dependent variable (i.e. adoption likelihood of DRS 1) is normally distributed within each household group. Nonetheless, the ANOVA results with planned contrast are displayed in the Annex, showing the same non-significant result (see TableAnnex 4). Interestingly, Hypothesis 2 is descriptively supported as the group of EV-owners reported the lowest likelihood to adopt DRS 1 compared to the other groups (non-significant result, see also TableAnnex 4).

Testing Hypothesis 3 *"need for effort limitation for interested households"*, a significant difference between the household groups is recognized for DRS 2 with more effort by conducting the Kruskal-Wallis test (see Table 6). Participants with a purchase intention of flexible technologies (interested only) are less likely to use DRS 2 than participants owning more than one flexible technology. No significant differences between participants owning one technology and the ones with purchase intention were identified. The related descriptive statistics are displayed in TableAnnex 4. Therefore, Hypothesis 3, assuming a lower usage likelihood of interested participants than others for the DRS 2 with more effort, is only partially supported. A medium effect size ($0.1 < r < 0.3$) is recognized [63]. We conducted a Kruskal-Wallis test due to the same reasons as for testing Hypothesis 2. In contrast, we performed further subsequent analyses (non-parametric Kruskal-Wallis pairwise comparison with Bonferroni correction) to identify between which groups the differences in preference for DRS 2 exist. A summary of the results from hypothesis testing (as pre-registered) and the results from the exploratory analyses is presented in Table 6.

These findings are confirmed by the results based on the ranked usage likelihood (see TableAnnex 10): Participants owning multiple flexible technologies are more likely to use DRS than heatpump owners and interested ones. In the case of the ranked dependent variable, the analysis for DRS 1 provided significant results. The analysis for DRS 2 is not significant.

Table 2
Psychological measurements of the vignette study.

Measure	Item	Reference	Position in the survey w.r.t. the vignettes
Attitude towards control loss	I do not want my daily routine to be affected by limited use of [my heat pump OR my battery storage OR my electric car]. [a]	[21]	Prior
	It is important to me to maintain control over the use of [my heat pump OR my battery storage OR my electric car]. [a]	[21]	Prior
	I accept limited use of [my heat pump OR my battery storage OR my electric car], provided I am notified in a timely manner.	[21]	Prior
	I accept limited use of [my heat pump OR my battery storage OR my electric car] provided it saves me money.	[21]	Prior
Attitude towards effort	I am confident in using digital solutions to save electricity, or I am already using them confidently.	[46]	Prior
	The functionality of digital solutions for saving electricity is easy to understand.	[46]	Prior
	It would be easy for me to find information on how to use digital solutions to save electricity.	[47]	Prior
Attitude towards data privacy	Sharing my electricity usage data puts me under surveillance.	[39]	Prior
	I have concerns about security breaches that could compromise the privacy of my electricity usage data.	[39]	Prior
	I am concerned that my electricity usage data will be misused.	[39]	Prior
	I am concerned that my electricity usage data will be shared with third parties.	[39]	Prior
Attitude towards cost savings	I am motivated to keep my electricity costs below a certain level.	[48]	Prior
	The price of electricity plays an important role for me when choosing my electricity tariff.	[48]	Prior
	I am concerned that the initial cost of a digital solution will exceed the potential savings.	[48]	Prior
Environmental awareness	I think I am someone who behaves in an environmentally friendly way.	[49]	Posterior
	I think the environment is more important to me than to other people.	[49]	Posterior
	I think environmentally friendly behavior is an important part of me.	[49]	Posterior
Technology openness	I'm very curious about new technical developments.	[23]	Posterior
	I quickly take a liking to new technologies.	[23]	Posterior
Social norm	The people I care about like digital solutions for saving electricity.	[46]	Prior
	Digital solutions for saving electricity have a positive image in society. [b]	[50]	Prior

Instruction: Please indicate to what extent the following statements apply to you. 5-point Likert scale ranging from 1 - fully disagree to 5 - fully agree.
[a] Reversely coded.
[b] Excluded due to a reliability analysis assessing Cronbach's α.

Table 3
Sample characteristics in relation to the German population (n = 962).

Socio-demographic variables	Sample (n = 962)		German population
	Absolut	%	%
Gender			
Female	367	38.15 %	50.50 %
Male	595	61.85 %	49.50 %
Age			
Average	55.50	–	45.70 %
Household type			
Single	106	11.02 %	41.44 %
Couple	338	35.14 %	28.83 %
Couple with child(ren)	462	48.02 %	13.83 %
Other	56	5.82 %	15.90 %
Dwelling type			
Detached house	578	60.08 %	27.50 %
Non-detached house	224	23.28 %	13.70 %
Flat	136	14.14 %	56.10 %
Other	24	2.49 %	2.70 %
Monthly net income of household			
<1000 EUR	10	1.00 %	9.45 %
1000–2999 EUR	247	25.70 %	49.20 %
3000–4999 EUR	439	45.60 %	26.71 %
> 5000 EUR	266	27.70 %	14.63 %
Educational level			
No degree	1	0.10 %	4.20 %
Secondary school degree	74	7.69 %	3.80 %
General certificate of secondary education	497	51.66 %	31.10 %
Higher education	390	4.54 %	33.90 %
Home tenure			
Owner	902	93.76 %	62.40 %
Tenant	60	6.24 %	37.60 %
Employment status			
Full-time	570	59.25 %	40.40 %
Part-time	144	14.97 %	15.65 %
Retired	177	18.40 %	29.63 %
Other	71	7.38 %	14.32 %
Flexible technologies (1 = differentiation between sole and multiple owners for our sample, no such data available for the German population, only presentation of the share of households owning the technology)			
Owning (only)[1] HP	192	19.96 %	3.23 %
Owning (only)[1] EV	101	10.50 %	3.60 %
Owning (only)[1] stationary battery	52	5.41 %	1.08 %
Owning more than one flexible technology[1]	261	27.13 %	–
Purchase intention of at least one flexible technology (but not owning any)	356	37.01 %	–
PV panel ownership	345	35.86 %	3.25 %

Own calculations based on [52–57].

4.3. Exploratory analysis: Kruskal-Wallis test of psychological factors and regression for DRS 3 with more data sharing

To interpret the results of the hypothesis testing more comprehensively, we also conduct Kruskal-Wallis tests between the household groups on the corresponding psychological measurements from Table 1. The statistical figures on technology openness (general), the importance of data privacy and cost savings (ref. to H1), the acceptance of control loss (ref. to H2), the acceptance of effort (ref. to H3) can be found in Table Annex 2.

Across all three significant Kruskal-Wallis tests in Table 6, participants owning multiple technologies significantly differ from HP owners and those with purchase intention. Participants owning more than one flexible technology show a higher usage likelihood than participants with purchase intention. They are also more likely to use the DRS than participants with only an HP. This is not only proven for DRS 2 in the hypothesis testing but also for DRS 3 with more data sharing and DRS 4 with less energy cost savings in the exploratory analyses. Testing the most apparent difference between them, the Kruskal-Wallis test on technology openness proves that multiple owners have a higher technology openness than those participants who own only one technology or have a purchase intention.

Remarkably, the household groups with a lower usage likelihood than multiple owners also show a higher sensitivity towards cost savings. In particular, participants with a purchase intention assign higher importance to cost savings than multiple owners and EV-owners. This is also the case for HP owners compared to EV-owners. In contrast to the importance of cost savings, no group differences are identified for the characteristic attribute of the most popular DRS, the importance of data privacy.

While the group differences in usage likelihood for DRS 1 are insignificant, significant differences are recognized for its characteristic attribute, the acceptance of control loss. Participants owning an EV show significantly lower acceptance of control loss than those owning an HP or multiple flexible technologies. The discrepancy between the general measurement and the DRS indicates that other variables, such as technology openness and social norm, may influence DRS usage more than the acceptance of control loss.

To summarize the comparison between the household groups, all participants like and dislike the same kind of DRS, but the multiple owners show an overall stronger interest in all DRS than others. Descriptively, we find that DRS 3 is liked the most by all groups (except for owners of only a BSS who like DRS1 the most). DRS4 is least preferred by all groups (but for owners of multiple flexible technologies as preferred as DRS 1, see AnnexTable4). There are only slight descriptive differences between the groups regarding their preferences of DRS 1 and DRS 2. The common preferences among the household groups speak for a unified design across technologies and adoption levels.

After understanding the differences between the DRS and household groups, we explore the reasons behind the usage likelihood with a hierarchical linear regression (Table 8). The analysis is conducted for the most popular DRS, namely DRS 3 with more data sharing. Four models test how (i) the attitude towards the service specification (four predictors), (ii) the technology ownership (four predictors), (iii) established psychological aspects (four predictors), and (iv) the socio-demographics (five predictors) impact the usage likelihood of DRS 3. The four models are able to explain 18.9 % of the participants' choices (see adjusted R^2), which is relatively low. Model 1 on the attitude towards the service specifications explains 14.8 % of the participants' choices. This model also validates the participants' perception of the stylized DRS (construct validity). For the case of DRS 3 with more data sharing, this means that participants who are concerned about their data privacy are expected to indicate a lower usage likelihood, which is the case. The following three hierarchical regression models (Model 2–4) explain additional variance in the DRS preferences, but only with a decreasing tendency (i.e., the increase of the adjusted R^2 decreases across models).

The strongest predictor in Model 1 is the importance of data privacy, followed by the acceptance of control loss and the acceptance of effort. While we expected the design of the service specification of DRS 3 to "provoke" this response for importance of data privacy (i.e., data sensitive participants are less likely to choose DRS 3), the other two predictors require some interpretation. On the one hand, participants may associate the automated shift of DRS 3 with the need to share control over their energy consumption. On the other hand, they may assume that the operation of a DRS involves some effort, even if it is automated. Consequently, a higher willingness to face a certain level of control loss and effort may lead to a higher interest in participating in DRS 3.

The variables on other psychological aspects (Model 3) and socio-demographics (Model 4) explain the usage likelihood better than the technology ownership (Model 2). Only the ownership of an EV is a significant predictor of the usage likelihood of DRS 3. At the same time, its explanatory power is shifted to other variables when we add the variables of Models 3 and 4. Technology openness, a strong social norm, identifying as male, and paying attention to cost savings better explain a high usage likelihood than owning an EV. A similar shift of explanatory power can also be recognized for the acceptance of effort, when the variables of Model 3 and 4 are added.

A logit regression based on the ranked usage likelihood (see TableAnnex 11) confirmed acceptance of control loss, importance of data privacy, technology openness, social norm and gender as significant predictors for the usage likelihood of DRS 3.

Design of stylised DR service for vignettes: 1 negatively + 3 positively specified attributes				
DR service / (sub-)sample	... with less control (1)	... with more effort (2)	...with more data sharing (3)	...with fewer cost savings (4)
All	**H1 comparison dimension (Wilcoxon signed-rank test)**			
Owning only HP	**H2 comparison dimension (Kruskal-Wallis-test)**	**H3 comparison dimension (Kruskal-Wallis-test)**		
Owning only EV				
Owning only stationary battery				
Owning more than one flexible technology				
Only with purchase intention				

Fig. 2. Hypothesis testing with regard to the sub-samples (vertical) and service specifications (horizontal).

Table 4
Mean, standard deviation, and Spearsman's correlation analyses for the psychological variables (incl. Cronbach's α for each scale).

	Mean	SD	1	2	3	4	5	6	7	8
1 - Acceptance of control loss	3.65	0.74	0.803	0.242**	−0.036	0.150**	0.217**	0.135**	0.304**	0.044
2 - Acceptance of effort	3.38	0.71		0.625	−0.0096**	0.106**	0.241**	0.504**	0.463**	−0.008
3 - Importance of data privacy	3.00	1.1			0.925	0.037	0.051	−0.033	−0.171**	0.054
4 - Importance of cost savings	4.12	0.70				0.658	0.183**	0.119**	0.234**	0.161**
5 - Environmental awareness	3.68	0.79					0.769	0.273**	0.235**	−0.017
6 - Technology openness	3.87	0.92						1	0.291**	−0.013
7 - Social norm	3.57	0.78							0.883	0.083*
8 - Electricity tariff change in 2022	3.90	0.82								

Note: Diagonal shows Cronbach's α.
n = 962.
Significance levels
*$p < .05$. **$p < .01$. ***$p < .001$.

5. Discussion

Our simple vignette design allowed us to involve households with different flexible technologies and adoption levels in one study and challenge them to choose between contrasting DRS designs. We show that the preferences of German households are more homogeneous than expected. Independent of whether they are prospective or actual owners of flexible technologies and which technology they (prospectively) own, they prefer data-driven, automated DRS, which achieve energy cost savings effectively and efficiently. They are least willing to compromise on realizing the full cost-saving potential, followed by staying in control over their consumption and limiting their operational effort. Households owning more than one flexible technology are more likely to use DRS than households with no or only one flexible technology.

In the following paragraphs, we contrast our findings with the ones from the literature and reflect on our methodological choices and limitations, particularly the design of the vignette study and the selection of the sample.

Complementarily to studies with one household group (e.g., [9,10]), we show that safeguarding control needs is no distinctive driver for the participation in DRS of EV-owners, but are equally important for all household groups. This is also the case for reducing the operational effort and participants with purchase intention. Participants are more willing to compromise on both attributes than demonstrated in other studies (e.g., [17,22]). On the one hand, participants might respond more indifferent since such operational attributes are harder to assess or due to the order effects of the vignette. On the other hand, the participants might assign more importance to the attribute cost savings than expected due to the data collection during the energy crisis or the prerequisite of investing in flexible technologies. Especially, the ones with purchase intention might associate the monetary-driven investment decision with the more effort- and comfort-driven participation decision [12]. We further discuss the reasons behind the discrepancy with the existing literature in the following.

The lower usage likelihood of DRS with limited energy cost savings is likely to be affected by the timing of the survey. The evolving energy crisis and increasing energy prices during the data collection from March to June 2022 raised concerns about high energy bills among households. A new dimension of awareness for energy cost savings was triggered. Households owning energy-intense technologies (e.g., HPs) and having no alternatives to limit the impact of the prices (e.g., the interested households with no generation and flexible technologies so far) were especially affected. This may also explain the high preference for energy cost savings assigned by participants who own an HP or do not yet own any flexible technology.

The literature states that the passive operation of HPs leads to a higher acceptance of DRS than interactive technologies, such as EVs since the consumption shifts are less noticeable [22,26]. Our results show the opposite. HP owners are less likely to use DRS than others. One alternative interpretation of the role of interaction may be that the interaction with flexible technologies better qualifies the participants to assess the impact. Due to the lack of experience, consumption shifts of

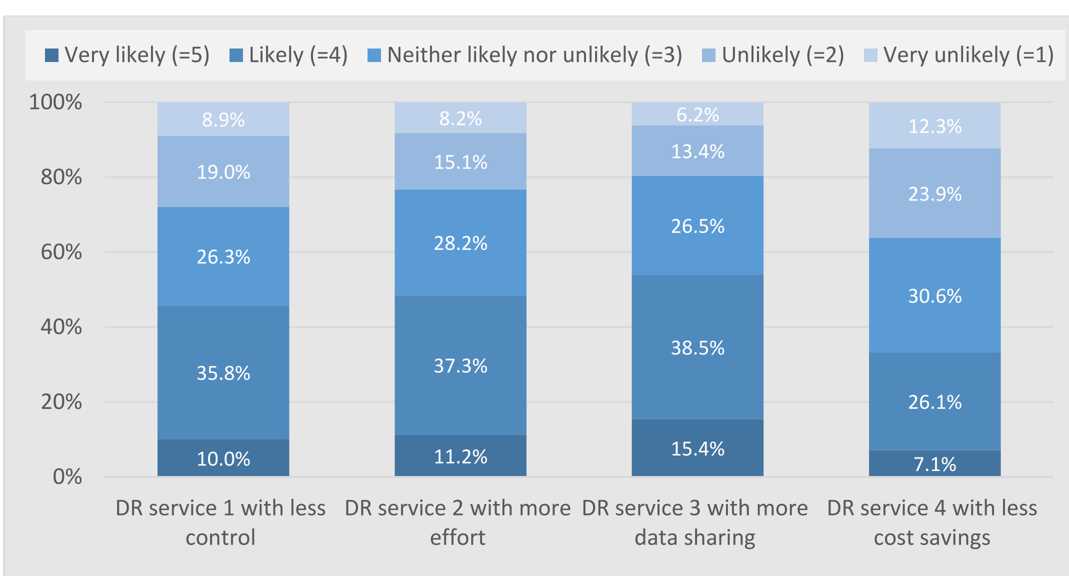

Fig. 3. Usage likelihood of DRS (rated on a 5-point Likert scale ranging from 1 – very unlikely to 5 – very likely).

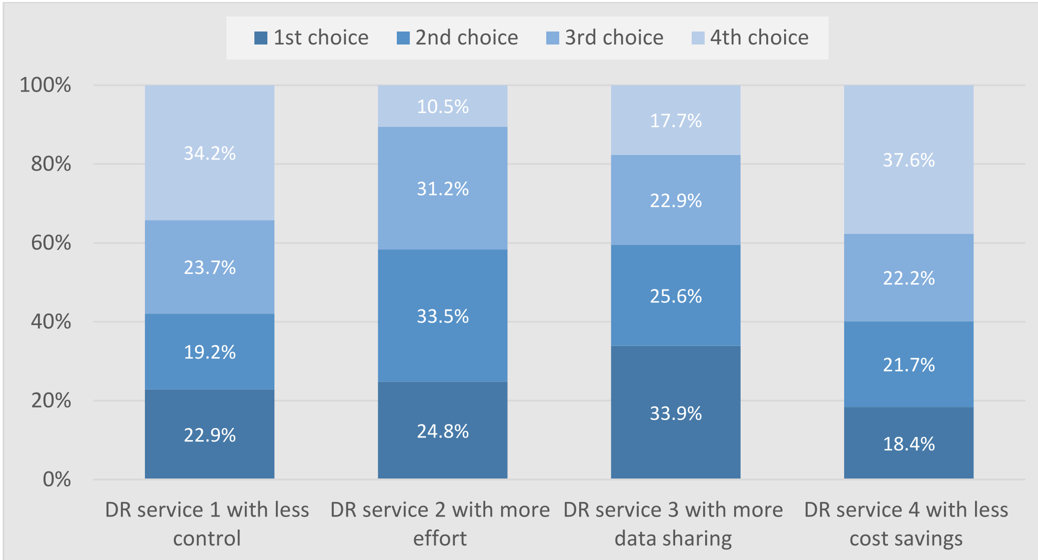

Fig. 4. Usage likelihood of DRS (ranked from the first choice as the most likely one to the fourth choice as the least likely one).

Table 5
Results of Wilcoxon signed-rank test testing Hypothesis 1.

#	DR service	Z	Effect size r	Asymp. Sig. (2-tailed)	Relevant aspects to test Hyp. 1: Lower usage likelihood for DR service with...	Result
1	1 vs. 2	−2.14[b]	0.069	0.033	–	–
2	1 vs. 3	−5.49[b]	0.177	0.000***	Less control than more data sharing	Supported
3	1 vs. 4	−5.18[c]	0.167	0.000***	Less control loss than less energy cost savings	Not supported
4	2 vs. 3	−3.29[b]	0.106	0.001**	More effort than more data sharing	Supported
5	2 vs. 4	−8.07[c]	0.260	0.000***	More effort than less energy cost savings	Not supported
6	3 vs. 4	−10.81[c]	0.349	0.000***	–	–

Adj. *p*-value based on Bonferroni Correction: *p*-value/6.
Significance levels
[a]Wilcoxon Signed Rank Test. [b]Based on negative ranks. [c]Based on positive ranks.
**p* < .0083. ***p* < .0017. *p* < .0002.

passive technologies, such as HPs, may be more intimidating and lead to a lower usage likelihood of DRS. The contradicting results on passive and interactive technologies require further research.

The chosen vignette design with four attributes and binary attribute specifications allowed us to position contrasting attributes as salient information and describe them comprehensively for non-experienced participants. We refrain from the common practice of having more than two specifications for each attribute [62]. It would not be beneficial for analyzing the contrasting attributes but overwhelms the participants. The largely consistent responses for the general service statements, rated, and the ranked usage likelihood support their validity [42,64].

Within the household group that owns multiple technologies, the participants responded consistently to the vignettes, although their technology references on the vignette were different, depending on which of their owned technologies is most prevalent and long-established in the German population. This confirms our initial

Table 6
Results of Kruskal-Wallis test testing Hypothesis 2 based on DRS 1 and Hypothesis 3 based on DRS 2, the results for the grey shaded DRS 3 and 4 are complementary, explorative analyses.

	DRS 1 with less control	DRS 2 with more effort	DRS 3 with more data sharing	DRS 4 with fewer cost savings
Asymp. sig. for Kruskal-Wallis–Test (n = 962)				
Household groups	0.754	0.000***	0.000***	0.001**
Significance adjusted for Bonferroni corrections - pairwise comparison based on Kruskal -Wallis –tests (effect size r for significant outcomes)				
Only HP vs. only interested	–	0.601	1.000	1.000
Only HP vs. only EV	–	0.935	0.266	1.000
Only HP vs. multiple	–	0.000***1 (0.206)	0.002**1 (0.175)	0.009**1 (0.156)
Only interested vs. only EV.	–	1.000	0.210	1.000
Only interested vs. multiple	–	0.023*1 (0.123)	0.000***1 (0.168)	0.002***1 (0.149)
Only EV vs. multiple	–	0.724	1.000	0.195

n = 910 if not stated differently - For pairwise comparison, owners of BSS only were excluded from these analyses due to a small subgroup size and power issues.
*** p < .001.
** p < .01.
*1 p < .0083.
**1 *p* < .0017
***1 *p* < .0002.

assumption that their response is not limited to the referred technology. The other owned flexible technologies are salient in their minds as well. Alternatively to our predefined hierarchy for reference selection, participants could have also selected a reference technology by themselves (e.g., the most frequently used one).

To have sufficient power for the comparison of the household groups, we decided to present all vignettes to each participant and limit the number of vignettes to four, the smallest sub-set of vignettes for defining

Table 7
Overview of the results for hypotheses testing and the exploratory analyses.

Hypothesis	Selection & aggregation		Test	Results of hypothesis testing
	Sample	DRS		
H1 "consumption control and limited effort as basic DR requirements" Decomposed into four sub-hypotheses: "lower usage likelihood of DRS...	All	1, 2, 3, 4	Wilcoxon signed-rank tests with Bonferroni corrections	Partially confirmed, in particular:
a) with less control than with more data sharing" (1 vs. 3)				a) Supported
b) with less control than with fewer cost savings" (1 vs. 4)				b) Not supported
c) more effort than more data sharing" (2 vs. 3)				c) Supported
d) more effort than fewer cost savings" (2 vs. 4)				d) Not supported
Exploratory: 1 vs. 2 & 3 vs. 4				No significant difference between DRS 1 with less control and 2 with more effort, but a preference for DRS 3 with more data sharing over 4 with less cost savings
H2 "need for consumption control of EV-owners"	EV-, HP-, multiple owners, interested participants	1	Kruskal-Wallis –test with Bonferroni corrections	Not supported (not significant)
H3 "need for effort limitation for interested households"		2		Partially supported (only when comparing "only interested" and "multiple")
Exploratory: Higher usage likelihood of a group for DRS 3?		3		For DRS 3 and 4: Higher usage likelihood of multiple owners than participants with purchase intention or owning HP.
Exploratory: Higher usage likelihood of a group for DRS 4?		4		
Exploratory: Which factors determine the usage likelihood of the most popular DRS?	All	With the highest usage likelihood	Hierarchical linear regression	Significant predictors: all attitudes towards the DRS specifications, EV-ownership, technology openness, social norm, gender

each attribute once reversely to the other three (i.e., one attribute per vignette was positively specified while the other attributes were negatively specified). A reason for this decision was also the overall research aim to examine the dilemma in relative terms between the attributes.

The attribute specifications can be combined more diversely for future studies without a power-demanding sub-group comparison. The ridge regression in TableAnnex 8 indicates that the relative importance of one attribute is consistent with its absolute importance. Still, the data collected from our limited vignette sets creates collinearity between attributes, making the regression coefficients vulnerable to inaccuracy. The penalty term of the ridge regression mitigates this risk (see FigureAnnex 3). A vignette with only positively or negatively specified attributes would have created a comparison baseline and prevent the collinearity. This would allow for a more systematic and robust analysis of each attribute. This greater variety in the vignettes would also enable the determination of isolated utilities per attribute.

We follow the recommendation of Treischl and Wolbring [50] for a unified order of vignettes and attributes to ensure a logical flow and create a more comprehensible running text. Thereby, we refrain from the common practice of randomizing the order within and between the vignettes [43]. Having the same order of attributes within each vignette creates the risk that participants relate the adjoining attributes more closely to each other than the other attributes. We limit this risk by positioning all attributes briefly next to each other in the title of each vignette (see vignette description in Appendix F).

By asking the participants to rate one vignette after the other and rank them relative to each other, inconsistencies between both measurements indicate order and learning effects. While the participants responded consistently for three of the four vignettes based on the descriptive analysis, only the one on control loss is less popular in the ranking than in the rating. The signed test based on ranked usage likelihood (see TableAnnex 9) shows that both DRS with less extreme ratings are closer to both DRS with more extreme ratings, when looking at the ranked usage likelihood: There is no significant difference between the DRS with control loss and fewer cost savings, nor between the DRS with data sharing and more effort. For control loss, this finding is also confirmed by the psychological factors in the regression: a higher acceptance of control loss leads to a higher usage likelihood. Its position as the first presented vignette might have led to an over-rating due to learning effects, meaning that the first response is less reliable and consistent than the others in the course of the vignette, since participants become more knowledgeable and reflected [50,65]. A stronger unwillingness to compromise on control loss is also in line with the findings in the literature [11,15,16].

Auspurg and Jäckle [65] argue that the immunity towards order effects increases with the assigned importance of attributes by the participants, which might be the case for the three consistently answered vignettes. The consistency also indicates that participants rate the value of each vignette independently instead of the incremental change from one vignette to another. If a prior vignette is used as a reference point for the rating of the current vignette, the switch from the negatively specified attribute to the positively specified attribute would lead to a more favorable rating of the current vignette. Since we do not recognize a more favorable perception in the rating than in the ranking, we conclude no or only a marginal effect of the incremental change between the vignettes.

Some aspects of decision-making are hard to capture by stated preferences [66]. The specific contextualization of the vignette makes the questions more assessable for the participants. We selected the described shift of the electricity consumption from the evening to the night hours in the expectation that most households are at home during these hours and are impacted similarly. Still, some attributes might be easier to assess than others. The quantitative description of the energy cost savings may be more tangible and persuasive for participants than the qualitative ones of the other attributes. Also, the cost attribute relates to the objectives for participating in DRS, while the others to how they are operated (e.g., automated shifts). The ones related to the objective might be more salient in the households' decision-making process than the operational ones. Still, the operational aspects are key for keeping households involved over time, especially in the context

Table 8
Results of hierarchical linear regression on usage likelihood of DRS 3 with more data sharing.

	Model 1: Service specifications		Model 2: Technology ownership		Model 3: Other psychological aspects		Model 4: Socio-demographics	
	Coefficient[a]	p-Value	Coefficient[a]	p-Value	Coefficient[a]	p-Value	Coefficient[a]	p-Value
Acceptance of control loss	0.163***	0.000	0.169***	0.000	0.160***	0.000	0.156***	0.000
Acceptance of effort	0.186***	0.000	0.172***	0.000	0.084*	0.029	0.069	0.075
Importance of data privacy	−0.242***	0.000	−0.251***	0.000	−0.240***	0.000	−0.242***	0.000
Importance of cost savings	0.036	0.233	0.076*	0.015	0.056	0.082	0.069*	0.034
Owning only HP (1 = yes, 0 = no)			−0.051	0.225	−0.052	0.209	−0.058	0.180
Owning only EV (1 = yes, 0 = no)			0.126**	0.001	0.102*	0.010	0.074	0.072
Owning only stationary battery (1 = yes, 0 = no)			−0.004	0.911	−0.004	0.910	−0.010	0.775
Purchase intention (but not owning) (1 = yes, 0 = no)			−0.066	0.204	−0.071	0.166	−0.071	0.175
Environmental awareness					−0.040	0.209	−0.031	0.340
Technology openness					0.139***	0.000	0.120**	0.001
Social norm					0.072*	0.035	0.082*	0.016
Electricity tariff change in 2022					0.013	0.658	0.008	0.782
Age							−0.047	0.156
Gender (1 = male, 0 = female)							0.100**	0.002
Tenure							−0.009	0.781
Education							0.024	0.459
Income							0.000	0.988
Adjusted R^2	0.148***		0.169***		0.184***		0.189***	

$n = 962$.
[a] Standardised beta coefficient.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

of fatigue effects. Studies with revealed preferences are more suitable to capture them [66].

The low explainability of the regression on the DRS with more data sharing (18.9 %) and the inconsistent responses of EV-owners on the general control statement and DRS 1 with control loss imply the need for additional variables explaining the usage likelihood of DRS. In the latter case, EV-owners might be willing to deviate from their general control need if they trust in the DRS. Research on other data-driven services highlights trust in the service provider and digital literacy as drivers for the acceptance of a service [15,21,38,39].

We are aware of the criticism of single-item measures for dependent variables. Nonetheless, using single-items after a vignette is a common approach in vignette experiments. Since the to-be-measured construct (i.e., adoption of the DRS) can be considered as not multidimensional (in comparison to other psychological constructs, see [67]), we follow the literature on efficient questionnaire design and vignette experiments and used a single-item measure for the dependent variable (see also Ausprung). Nonetheless, further studies building on our results could use a multi-item measure (also for comparison of results).

By focusing on (prospective) owners of flexible technologies, our study represents only a specific part of the German population. One non-represented group is tenants relying on their landlords for investments in their homes and low-income households. Both have hardly access to (rather) technology-derived demand response but to (rather) socially-derived demand response. Our study does not cover the drivers and barriers of the latter [4,28,66]. Another non-represented group is the potential owners of flexible technologies without purchase intention. The observed differences between the actual and prospective owners might magnify for this group. The prospective owners have a lower income level and weight the importance of cost savings higher than the actual owners. Still, the socio-demographics and psychological factors are relatively homogeneous among actual and prospective owners (see TableAnnex 1). We recommend repeating the study later (with a more heterogeneous, representative sample) when an increasing diffusion of DRS creates further insights.

Our non-representative sample collected during exceptional circumstances creates insights into the diffusion of DRS over time. The realization of energy cost savings is likely to remain a key driver. The results on the usage likelihood for DRS, the technology ownership status, and the technology openness confirm that the attitude of early adopters of flexible technologies makes them more likely to participate in DRS. Their assumingly high intrinsic motivation makes them more tolerant towards the effort and comfort losses of DRS. Vice versa, the diffusion of DRS among households not yet owning flexible technologies cannot be driven by their intrinsic motivation but (currently) depends on external incentives in energy cost savings. This was demonstrated for households with a purchase intention and is also likely to be the case for the ones without a purchase intention yet, which are not represented in the survey.

The need for realizing energy cost savings effectively and efficiently will gain importance for these prospective owners of flexible technologies to participate in DRS. Thus, we recommend that providers of DRS consider cost savings in their design. However, due to the rapid developments in flexible technologies, their adoption rate, and the availability of DRS, changes are not unlikely - especially for households who do not own a flexible technology yet. Thus, DR research should continuously monitor and examine the driving factors for participation in DRS to develop empirically-driven recommendations for DRS providers.

6. Conclusion

Our vignette study examined the preferences of households towards contrasting DRS designs, considering both the type of flexible technologies they have and their adoption levels. Our results show that preferences do not fundamentally differ between the household groups. Generally, households prefer data-driven, automated DRS - independent of whether they are current or prospective technology owners, or the specific technology they currently own or intend to own. The primary motivator for adopting DRS is the potential for efficient and effective energy cost savings, which dominates concerns about data privacy. The hypothesized special control needs of EV-owners and comfort needs of households not yet owning flexible technologies were not confirmed. Households whose technology openness already led to the ownership of more than one flexible technology are more likely to use DRS compared to those who own (or plan to own) only one (e.g., EV or HP).

The design process for DRS by service providers demands empirical evidence, especially when prioritizing contrasting service attributes.

External incentives in the form of energy cost savings are shown to drive a broad diffusion among current and prospective owners of flexible technologies. Thereby, existing and new flexibility potential can be unlocked, which supports the decarbonization of the energy system in a two-fold manner. The unlocked flexibility can increase the consumption of fluctuating renewable energy generation, and it can help to avoid load peaks that would lead to complications or additional investments in the existing infrastructure, such as electrical distribution grids. Both the energy system and the households themselves profit from the coordinated use of flexible technologies facilitated by DRS. It is crucial that the industry develops DRS grounded in empirical findings and that policymakers provide incentives for such systems. Only then notable cost savings and alleviated pressure on the energy infrastructure can be ensured.

Pre-registration of the research

This research was pre-registered at https://aspredicted.org/blind.php?x=9Q3_3QG with reference number #100425.

CRediT authorship contribution statement

Sabine Preuß: Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Judith Stute:** Conceptualization, Investigation, Visualization, Writing – review & editing. **Emile Chappin:** Supervision, Writing – review & editing. **Laurens de Vries:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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