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A multi-criteria assessment framework for direct load control in residential buildings from an occupants' perspective

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ABSTRACT

Based on economic and occupants-relevant criteria, this paper proposes an assessment framework for direct load control schemes, using the Analytic Hierarchy Process approach for a multi-criteria decision analysis. For direct load control, as a form of demand response, a third-party provider (e.g., grid operator, aggregator) is allowed to control or limit the residential electric load upon a control signal. The assessment framework enables the transparent evaluation of different direct load control approaches from a residential perspective, with criteria derived from literature. Five criteria were found to be particularly relevant for evaluating direct load control approaches (in descending order): financial compensation, guaranteed comfort, control, transparency, frequency and duration. The assessment framework includes value scores, which represent the degree to which a specific approach meets a given evaluation criterion, and combines them with the criteria weights derived in the Analytic Hierarchy Process. While direct load control is mostly accepted in the context of heating technology, there is less acceptance for impacted charging of electric vehicles. The results seem useful for third-party providers and policy-makers that need to find better ways to design and implement demand response measures in the private household sector and such that are also acceptable to occupants.

1. Introduction

In recent years, the transition to a low-carbon society has led to a shift towards electrification of energy consumption. In the residential sector, households are rapidly adopting distributed energy resources such as electric vehicles, heat pumps, air conditioners, electric boilers, and batteries. This surge in the adoption of such vehicles and devices has led to a significant increase in residential electricity demand, which in turn can strain existing distribution grid infrastructure and lead to temporary grid congestion. However, the widespread adoption of distributed energy resources also provides an opportunity to utilize demand response mechanisms. Demand response refers to the modification of electricity consumption patterns in response to specific signals. It can be divided into two types: indirect demand response and direct demand response. Indirect demand response involves the use of time- or location-based price signals to incentivize consumers to adjust their consumption patterns. Notable examples include time-of-use pricing and critical peak pricing. On the other hand, direct demand response involves giving a third party, such as a grid operator or aggregator, the ability to control or limit load by sending a control signal. This approach, known as direct load control (DLC), requires operational control of selected residential energy end-use devices during predetermined time periods [1].

DLC programs have been around for quite some time and have seen numerous pilot initiatives [2]. These programs can provide benefits to both consumers (e.g., cost savings) and grid operators (e.g., increased efficiency and stability of the grid). However, despite these positive findings, the adoption and use of DLC programs remain relatively low [3]. Several factors may contribute to this limited uptake. For instance, Fell [4] highlighted that a perceived lack of control significantly affects the acceptability of demand-side response programs and underlined the need for technological solutions that minimize complexity while maximizing consumer benefits. In line with that, Yilmaz et al. [1] argued that intuitive and user-friendly designs could significantly enhance

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participation in DLC programs. Stenner et al. [3] demonstrated that consumer mistrust of grid operators is a key barrier, suggesting that transparent communication and trust-building measures are essential for increasing program participation. Additionally, Yilmaz et al. [5] stated that limited awareness and knowledge about DLC programs remain significant challenges. The introduction of the amended §14a of the German Electricity and Gas Supply Act *(Energiewirtschaftsgesetz - EnWG)* in 2023 marks a pivotal development in the evolving landscape of energy regulation and policy. It pertains to the grid-oriented control of controllable consumption devices and controllable grid connections. This legislative framework enables new avenues for managing energy demand and supply, particularly through DLC programs. Given the importance of these programs in balancing grid loads, enhancing the integration of renewable energy sources, and ensuring overall grid stability, it is paramount to investigate the preferences and acceptance of residential consumers towards DLC programs. An investigation is necessary to understand the societal and individual impacts of this legislative shift and to design and implement DLC initiatives that are effective and match with consumer expectations. This alignment is essential to ensure the successful adoption and sustainability of DLC programs under the new legislative environment, ultimately contributing to a more efficient and resilient energy system.

In the present paper, the acceptance of DLC programs is addressed by establishing a new assessment framework for DLC approaches in residential buildings from an occupants' perspective. While frameworks for evaluating DLC solutions already exist, the application of the AHP method in this context is novel, thereby enriching the literature with an appealing new approach and offering actionable insights for stakeholders (e.g., grid operators and policymakers). Furthermore, the framework is based on the responses of a sample of households that have agreed to participate in DLC, so it can be assumed that this group is familiar with the concept of DLC. However, this introduces a potential selection bias, as the sample may not fully represent the broader population, including those who are unaware of or resistant to DLC programs.

In line with Fabianek and Madlener [6], the creation of this framework involved three steps: (1) obtaining occupants-relevant assessment criteria from literature; (2) defining "value scores", representing the degree to which a specific DLC approach meets a given assessment criterion; (3) and deriving criteria weights via a survey using the Analytic Hierarchy Process (AHP) of Saaty [7] – a multi-criteria decision analysis approach.[1] This survey was distributed amongst 62 voluntary participants in a German DLC pilot project called FLAIR[2] [8] in March 2023. In the households of these participants, control boxes capable of matching local electricity generation and consumption were installed in December 2021. These control boxes could achieve this match by controlling large, flexible electricity end-use devices such as heat pumps and electric cars. Nilsson and Bartusch [9] emphasize the critical role of personalized and equitable demand response programs, highlighting how tailored incentives and improved accessibility can significantly enhance household engagement with energy-saving initiatives, particularly among diverse socio-economic groups. In the study by Vesely and Klöckner [10] a divergent perspective on the subject is presented. Utilizing survey data from 5970 participants, they conducted a comprehensive investigation into the acceptance of Direct Load Control (DLC) across 31 European countries. Their findings indicate that specific attitudes towards DLC, including personal norms and anticipated feelings of pride, emerge as primary predictors of acceptance. In contrast, socio-economic characteristics are found to play a secondary role in this process. In previous studies, which were for instance reviewed in Parrish et al. [2], the preferences of individuals towards DLC approaches have been investigated. Fell et al. [11] conducted a survey to address the acceptance of DLC for heating. They found that DLC may be acceptable in principle, but the availability of an override option may play a significant role. The importance of an override option has also been emphasized in other studies [12,13], highlighting the importance of households' perceived control during a DLC program. In addition, research has shown that acceptance of DLC may vary depending on the type of electrical appliance or device being controlled. Yilmaz et al. [5] found that this acceptance was higher for appliances such as heat pumps, electric boilers, and solar photovoltaic systems, as compared to appliances such as tumble dryers, washing machines, dishwashers, and electric vehicles. The duration and frequency of DLC, as well as the limits of control (e.g., the extent of power reduction) were also identified as important factors [12]. Kubli et al. [14] investigate the readiness of individuals to participate in co-creating flexibility in energy consumption, with a focus on prosumers. They examine three main domains of residential energy 'presumption' using choice experiments: solar photovoltaic plus storage, electric mobility, and heat pumps. The study highlights the varying willingness of consumers to adapt their energy usage, emphasizing the importance of consumer preferences in the design and implementation of smart grid solutions and flexibility business models. Aloise-Young et al. [15] use two methods, SMARTER and AHP, for quantifying consumer preferences in smart home energy management systems, considering aspects such as air conditioning/room heating, water heating, dishwashing, washing and drying clothes. Significant implications are suggested for the design of future smart homes that are responsive to individual preferences and capable of delivering improved comfort, lower operating costs, and enhanced demand response. Yilmaz et al. [16] explore the acceptance and preferences of DLC programs for heat pumps and electric vehicles. Utilizing a discrete choice experiment conducted amongst 556 respondents in Switzerland, the study investigated the heterogeneity in preferences among different socio-economic groups, offering new insights for designing DLC programs that cater to diverse household preferences. In summary, the type of appliance controlled, and specific operating parameters are critical factors influencing the acceptance of DLC approaches. Also from an economic perspective, the level of financial compensation offered can significantly affect the acceptance of DLC approaches and thus influence the adoption [13].

In contrast to the literature described above, a flexible assessment framework is proposed in our study that allows different DLC approaches to be assessed without re-interviewing the AHP survey participants. This framework is created by combining the value scores defined and the criteria weights derived from the survey. Since the survey participants are voluntary participants in the DLC pilot project, they are considered to be early adopters in the sense of the diffusion of innovations theory of Rogers [17]. Accordingly, the framework can be used to evaluate DLC approaches from the perspective of these early adopters. If DLC approaches are accepted by early adopters, these individuals may in turn be beneficial to the market diffusion process of DLC technology [18,19]. Therefore, designing DLC approaches that are likely to be well accepted by early adopters will help grid operators, aggregators, and policy-makers who need to find improved ways to implement demand response in the residential sector.

The remainder of the paper is organized as follows. In Section 2, the methodology used to identify the assessment criteria and value scores within the multi-criteria assessment framework is presented. Section 3 reports on the value scores assigned to each criterion which enable a comprehensive characterization of different DLC approaches. The criteria weights obtained from the AHP and the results from the survey are presented and discussed in Section 4. Finally, Section 5 concludes and suggests some avenues for further research.

[1] A useful classification of AHP in the multi-criteria decision analysis methods can be found in Fabianek et al. ((2020)).

[2] Each survey participant received an expense allowance of €20 as a token of gratitude.

2. Methodical approach

The methodical approach illustrated in Fig. 1 essentially follows the one proposed in Fabianek and Madlener [20,21]. Accordingly, the creation of the assessment framework first requires a thorough research of the related literature on DLC. Based on this literature, assessment criteria for DLC approaches were selected and defined. The selection process in the present analysis was based on two main factors: the frequency with which criteria appeared in previous studies [3–5,11,12,22,23]- and their relevance to the specific research context. By analyzing existing literature, we identified commonly used criteria and assessed their applicability to ensure that they align with the objectives of our study. This approach allowed to establish a well-founded and contextually appropriate set of criteria for our analysis. Experts from industry and research, including an energy company, a municipal utility, a transmission system operator, several distribution system operators, as well as university and non-university researchers, confirmed the selection of criteria.

The 62 volunteering participants in the DLC pilot study were contacted by email in the beginning of March 2023. A PDF form containing the AHP survey was attached. In contrast to previous studies, this survey could be completed and returned in either analogue or digital format.[2] In this way, participation hurdles were reduced, as the survey participants were able to choose the data submission option with which they were more familiar or comfortable with. Out of the 62 questionnaires distributed, 34 were completed and returned, resulting in a participation rate of 55 %. Table A.1 in the Appendix shows the socio-demographic composition of the sample.

In terms of age distribution, the sample was predominantly within the 50–59 years age bracket, accounting for 32.4 % of the participants. This group was followed by the 40–49 years age group representing 29.4 %. The younger age bracket of 30–39 years comprised the smallest segment at 8.8 %; participants aged 70 and older constituted 14.7 % of the sample, highlighting a mature age profile overall. Gender-wise, there was a significant disparity with males comprising 79.4 % of the sample and females only 20.6 %.

Income distribution within the sample is skewed towards the higher end, with 38.2 % earning between €3501 to €5000 per month. There is also a notable small segment earning €2500 or less (5.9 %), while the remaining income brackets €2501 - €3500 and €5001 – €7000 are represented with 17.7 % each. A substantial 20.5 % of the sample chose not to disclose their disposable monthly net income.

The majority of respondents hold either a qualification from a German Fach-, Meister-, Techniker- or Berufsschule (20.5 %) or a university degree (23.5 %). In addition, 20.6 % of the respondents reported having a degree from a Fachhochschule, while 17.8 % completed their education with a German Realschulabschluss. A smaller portion, 8.8 %, have a secondary school diploma or equivalent. Advanced academic qualifications, such as a PhD, are held by 5.9 % of the sample. Interestingly, no respondents reported having completed their education with the German Abitur (A-level). In addition, 2.9 % of the participants chose not to disclose their educational background. In terms of professional contact, the sample has a strong leaning towards technology (38.2 %), energy (29.4 %), and grid operation (26.5 %). A minority of the participants (5.9 %) reported no contact with any of these sectors.

The sociodemographic data indicate a sample with a strong presence of educated, mature male individuals who are living primarily in small to mid-sized households and are engaged primarily in the technology and energy sectors. The distribution of income levels suggests economic diversity, although there is a tendency towards higher income brackets. The implications of this demographic distribution should be carefully taken into account when analyzing the study's outcomes and generalizing the findings.

In addition to a survey of socio-demographic aspects, the weights of the assessment criteria were determined using the pairwise comparisons provided by the AHP approach [7]. A common criticism of this AHP approach is that larger numbers of decision-makers complicate the process, and that effective decision-making requires domain-specific expertise [24] and the ability to clearly articulate personal preferences [25]. Conversely, the AHP method offers notable advantages, such as the ability to check for inconsistencies and to ensure clarity of objectives and criteria through its hierarchical structure. In addition, the openness of the decision-making process is a significant strength [26]. Kumar et al. [24] highlight other benefits, including the elimination of the requirement of complex mathematical calculations. Ultimately, identifying preferences based on these pairwise comparisons is described in the literature as intuitive and straightforward, leading to a frequent use of AHP in the mobility- and energy-related literature [21,27]. In this survey, 67.7 % of the respondents also stated that they understood the explanations in the AHP criteria-weighting process reasonably well. In these pairwise comparisons, in line with Franek and Kresta [28], individuals x had to compare all n criteria in isolation on a scale of 1–5. Here, 1 expresses indifference between the criteria and 5 expresses a significantly higher importance of one of the criteria. These pairwise comparisons between criteria i and j were stored in the evaluation matrix $A_x = (a_{ij})$ for each participant x:

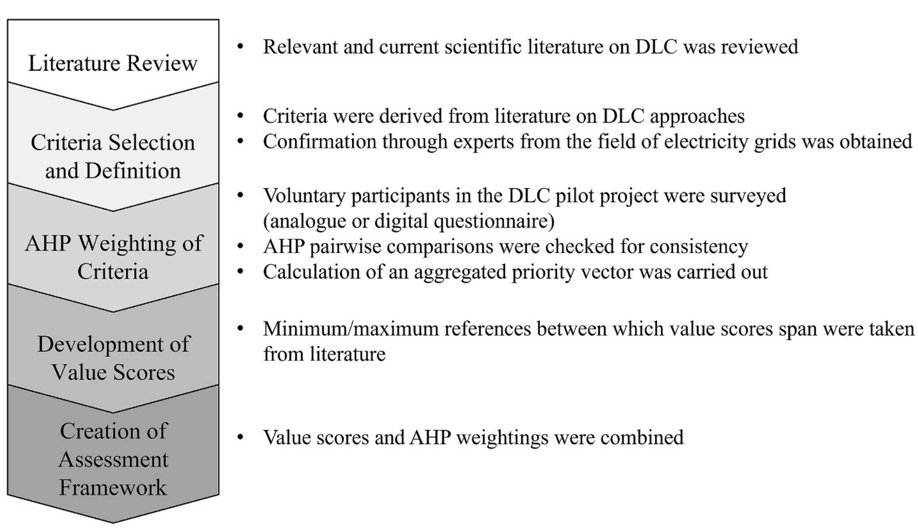

Fig. 1. Methodical approach to the creation of the assessment framework.

$$A_x = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}, \forall x \in \{1, 2, \ldots, 34\} \quad (1)$$

For a_{ij} it holds:

$$\forall i = 1, \ldots, n \quad \forall j = 1, \ldots, n : a_{i,j} > 0$$

$$\forall i = j : a_{i,j} = 1$$

$$\forall i = 1, \ldots, n \quad \forall j = 1, \ldots, n : a_{i,j} = a_{j,i}^{-1}$$

34 AHP questionnaires were fully completed. 23 respondents met the consistency ratio limit (CR < 0.2), determined by a mathematical test using the maximum eigenvalue to assess individual consistency [29]. In line with Aull-Hyde et al. [30], the sufficiently consistent evaluation matrices A_x were aggregated using the geometric mean procedure which enables to interpret the respondents as a synergistic individual. Finally, for this aggregated evaluation matrix, the priority vector containing the criteria weights, w_i, was calculated using the eigenvalue method [31]. This was done in a MATLAB environment. Goepel [32] is recommended for an accessible description of the step-by-step procedure, including formulas, to determine the aggregated weighting of the criteria.

Additionally, to these calculated criteria weights w_i, value scores v_{ic} ranging from 0 to 10 were developed as a measure of the degree to which the criteria i were met. Combining these criteria weights and value scores as illustrated in Fig. 2 enables to assess DLC approaches from the perspective of the group of early adopters surveyed. The so-called "DLC score" can be calculated as follows:

$$DLC \text{ score} = \sum_{i=1}^{n} w_i \bullet v_{ic}. \quad (2)$$

In the practical application of the assessment framework (see Fig. 2), the specific criteria characteristics of the DLC program to be evaluated are first quantified using the value scores. In a second step, the value scores determined in this way are weighted by multiplying them by the criteria weights from the survey. In the final step, the criteria-specific products are summed up to produce an overall score for the DLC program under consideration.

2.1. Selection of assessment criteria

Based on existing literature on DLC (see Table A.2 in the Appendix), five relevant criteria for the evaluation of DLC approaches were selected and defined (see Table 1). This selection of criteria is limited to the main tariff and technical characteristics of conceivable DLC programs. Individual factors and attitudes are not included as assessment criteria, because the intent is to create an objective assessment framework that only reflects the perspective of the respondents through their individual criteria weightings. However, these individual factors and attitudes of the respondents are also addressed in the survey using scales [33], multiple choice questions, and open questions.

Unlike traditional AHP applications, which often require re-surveying participants for each new scenario, the framework presented enables the evaluation of different DLC approaches without the need for repeated data collection. This is achieved by combining the criteria weights derived from the conducted AHP survey with the value scores defined in the next section (see Fig. 2).

3. Value scores of direct load control assessment criteria

In order to evaluate DLC programs, value scores are needed that represent the degree to which a given DLC program meets the assessment criteria. The scales of these value scores are shown with brief descriptions in Table 2. More details are provided below in the context of discussing the selected criteria.

3.1. Financial compensation

The households volunteering for the DLC pilot project were compensated financially for their participation. Their compensation over the whole project period was about €300 resulting in an effective compensation of around €150 per year. In the context of the German §14a EnWG (2023) an average compensation of €140 per year is considered [34]. Similar amounts of money were assumed in Xu et al. [13]. The value score for *financial compensation* increases with the amount of the compensation.

3.2. Guaranteed comfort

In the context of the *guaranteed comfort*, two scales are taken into consideration. On the one hand, the comfort enabled through electric heating appliances is quantified. In line with Schild and Willems [35], Grandjean [36], Fanger [37], Frank [38], and Roedler [39], the highest score of 10 is reached when a room temperature of 20–22 °C is guaranteed. Room temperatures above or below that temperature range result in lower value scores.[3] On the other hand, the restricted mobility in terms of the guaranteed state of charge (SOC) is used [14,40]. Here, a guaranteed SOC of >90 % results in the highest value score possible.

When calculating the resulting value score in the case of both existing BEV and electric heating technologies, the mean of both included value scores is taken.

3.3. Transparency

For the quantification of the quality of a DLC program's *transparency*, the time between the DLC measure and the pre-DLC notification of households about this measure is used. The scales used in Yilmaz et al. [5] and Schöne et al. [22] are expanded in order to fit in the 0 to 10 rating scheme.

3.4. Control

To quantify the perceived quality of the *control* criterion, the number of permitted uses of the override option by residents is considered. The rating scale proposed by Yilmaz et al. [5] is extended.

3.5. Frequency and duration

For this criterion, the value score obtained on the *frequency* rating scale is added to the score obtained on the *duration* rating scale used to calculate the total score. In line with Kubli et al. [14] and Carmichael et al. [41], the frequency rating scale considers the maximum number of DLC interventions permitted. The duration rating scale is based on the scales developed by Yilmaz et al. [5] and Xu et al. [13], with minor modifications.

By combining these value scores and the weights of each criterion, an assessment framework for DLC programs can be created.

4. Results and discussion

First, the weights of the AHP criteria are listed and analyzed. Then the individual factors and the attitudes of the respondents are discussed. Finally, a short case study is conducted, and the limitations of the study are pointed out.

[3] According to DIN 4108-2, room temperatures below 12.7 °C and normal humidity levels lead to mold formation. In line with DIN 4108:2013–02, the living comfort is jeopardized for room temperatures above 27 °C.

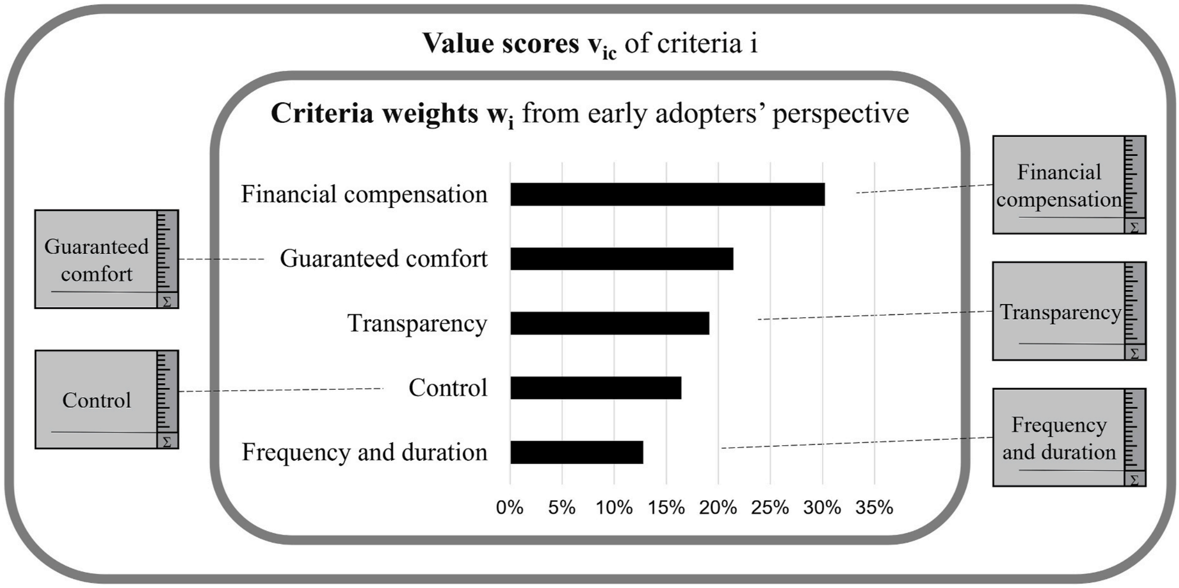

Fig. 2. Graphical representation of the assessment framework, corresponding to eq. (2).

Table 1
Assessment criteria for DLC approaches derived from literature.

Criterion	Definition
Financial compensation	Discount on the electricity bill that participating households receive from the electricity grid operator as compensation for the DLC.
Guaranteed comfort	Guaranteed minimum comfort for occupants that is always maintained despite DLC.
Control	Override option with which the DLC of the power grid operator can be manually overridden to use the household appliances as usual. The extent of this override option is variable.
Transparency	Level of detail of DLC information provided to households by the electricity grid operator.
Frequency and duration	Frequency and duration with which the electricity grid operator can actually directly control the household electricity load.

Note: In order not to increase the number of pairwise comparisons too much, the duration and frequency criteria were combined, and in order not to allow too much inaccuracy in the final calculation of the DLC score, the duration and frequency criteria were again considered separately for the value scores.

4.1. Analytic Hierarchy Process criteria weights

To determine the overall preferences of the participants, the evaluation matrices of the households were computed and combined. The aggregated criteria weights are shown in Table 3.

In the context of DLC measures used by electricity grid operators to manage the load of electrical appliances in private households, different criteria have been assigned different weights, based on their relative importance as perceived by individuals from the households polled. By far the most important criterion is financial compensation, with a weight of 30.2 %. In line with Yilmaz et al. [5], this indicates a strong preference among individuals to receive monetary benefits in exchange for allowing the DLC of their electrical appliances. The second-most important criterion is guaranteed comfort, with a weight of 21.4 %, highlighting the importance that individuals attach to maintaining a certain level of comfort during these DLC measures. The first-mover households that volunteered to take part in the pilot project obviously had few concerns or reservations about the DLC measures. Otherwise, they would probably not have signed up (i.e., some sample selection bias is expected). It makes sense that they would be pleased to receive as much financial compensation as possible, especially if their comfort standards were not cut.

As previously established in studies conducted by Fabianek and Madlener [6] and Fabianek et al. [27] on the subject of charging tariffs for electric vehicles, tariff transparency plays a moderately significant role. This is also demonstrated in our results: Transparency, with a weight of 19.1 %, indicates that clear and honest communication about the DLC measures is valued by households. In free text form, some respondents explicitly expressed the wish for an app to communicate with the electricity grid operator and to view the current and upcoming DLC measures. Control is not far behind with a weight of 16.4 %. This reflects the desire of individuals to retain some degree of influence or authority over how their appliances are managed under these programs. Some individuals have expressed a desire to include their photovoltaic systems in the control algorithm and to always use their self-generated electricity autonomously. Finally, the frequency and duration of DLC measures is considered with a weight of 12.8 %, indicating that it is of lesser importance compared to other factors such as financial incentives and comfort assurance. Taken together, these weights provide insight into the priorities and preferences of households when participating in DLC programs facilitated by electricity grid operators.

4.2. Individual factors and attitudes

As mentioned further above, the individual factors and attitudes are not included as assessment criteria but are addressed in the survey by means of Likert scales. The responses were captured ranging from 'Strongly disagree' to 'Strongly agree'.

When investigating people's preferences for allowing DLC of different technologies, participants were provided with a list of technologies and asked to indicate their level of agreement with allowing those technologies to be controlled. The technologies included air conditioners (HVAC[4]), electric storage heaters, heat pumps, and battery

[4] Heating, Ventilation and Air Conditioning.

Table 2
Scales of value scores for each criterion.

Value score/Criterion	0	1	2	3	4	5	6	7	8	9	10
Financial compensation[a]	none	≤ 15	≤ 30	≤ 45	≤ 60	≤ 75	≤ 90	≤ 105	≤ 120	≤ 135	> 135
Guaranteed comfort SOC[b]	none	≤ 10	≤ 20	≤ 30	≤ 40	≤ 50	≤ 60	≤ 70	≤ 80	≤ 90	> 90
Guaranteed comfort T[c]	< 11; > 31	11-12; 30–31	12-13; 29–30	13-14; 28–29	14-15; 27–28	15-16; 26–27	16-17; 25–26	17-18; 24–25	18-19; 23–24	19-20; 22–23	> 20; < 22
Transparency[d]	no notification	while DLC	≤ 3	≤ 6	≤ 9	≤ 12	≤ 15	≤ 18	≤ 21	≤ 24	> 24
Control[e]	none		> once per half-year		> once per quarter		> once per month		> once per week		always possible
Frequency[f] and duration[g]	> once per day ≥ 240	> once per week ≥ 180	> once per month ≥ 120	> once per quarter ≥ 60	> once per half-year ≥ 30	> once per year < 30					

Notes.
[a] yearly compensation in €.
[b] state of charge of BEV in %.
[c] room temperatures that are neither exceeded nor undercut in °C.
[d] time interval between pre-DLC notification and DLC measure in h.
[e] number of permitted uses of the override option by residents.
[f] permitted number of DLC measures taken by the grid operator.
[g] duration of DLC measures in min.

Table 3
Relative importance of the criteria used.

Criterion	Weight [%]
Financial compensation	30.22[+++]
Guaranteed comfort	21.43[++]
Transparency	19.12[+]
Control	16.45[+]
Frequency and duration	12.79

Note: Relative importance >25 % (+++), 20–25 % (++), 15–20 % (+).

electric vehicles (BEVs). The responses reveal a spectrum of attitudes towards the control of each technology, as shown in Fig. 3.

The majority of participants showed a favorable inclination towards controlling air conditioners and heat pumps, as seen by the larger proportion of 'Agree' and 'Strongly agree' responses. Electric storage heaters also saw a positive response, albeit to a lesser extent, while the readiness to control BEVs was comparatively lower, as indicated by the balance of agreement versus neutral and disagreement categories. The neutrality among participants was most evident with BEVs, indicating an increased importance of mobility in relation to the indoor climate. This finding is consistent with the results of Fabianek and Madlener [42, 43], who investigated the user-side acceptance for the grid operator-side flexibility use of private BEVs. As expected, the extension of charging processes reduces the utility of individuals, although this negative influence on the utility in residential areas is significantly lower than in destination or highway charging scenarios. When interpreting these results, it is important to consider the distribution of energy-consuming technologies among the respondents (see Table A.1 in the Appendix). While households are very familiar with the use of heat pumps in particular, none of the households surveyed have air conditioning. It cannot be excluded, though, that the answers would have been different if the households had more experience in using these air conditioners. However, the importance of mobility and indoor climate is likely to be independent from technology familiarity.

Respondents were also asked about the benefits of DLC. Results are shown in Fig. 4. The statement 'Enhances the use of local and renewable electricity' received an overall positive level of agreement, suggesting that most participants perceive DLC as facilitating the integration of regional and renewable energy sources. The statement 'Society can benefit' also appears to have a high level of agreement, indicating that respondents are inclined to see DLC as having a positive societal impact. This may reflect an acknowledgment of the wider benefits of DLC beyond individual gains. When asked about the personal financial impact, a majority of respondents also agreed with the statement 'Saves

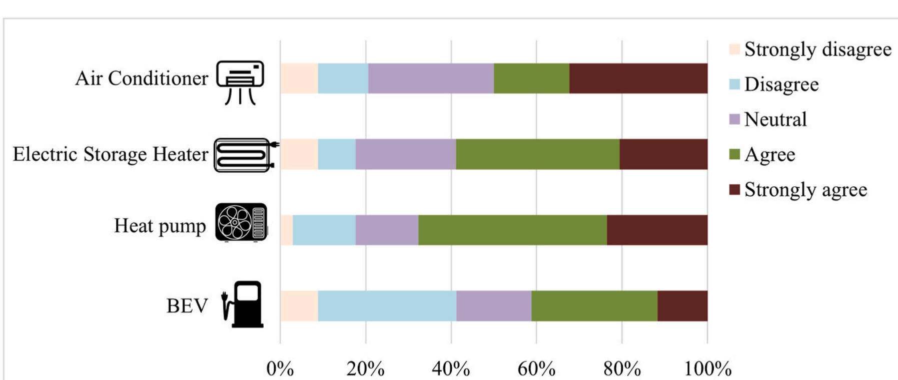

Fig. 3. Declared agreement to allow direct load control (DLC) of different technologies.

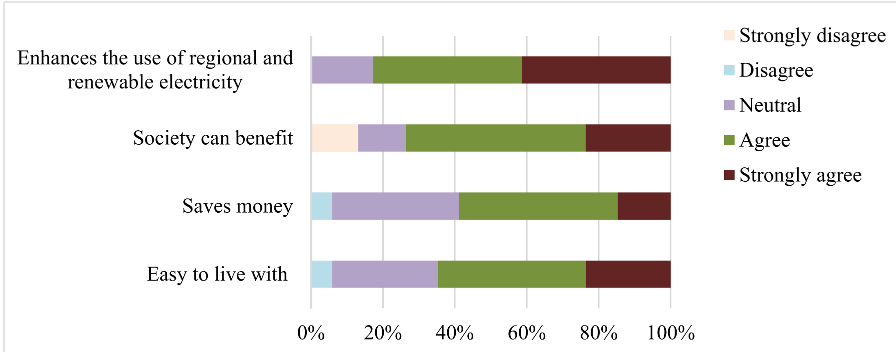

Fig. 4. Declared agreement to advantages of direct load control (DLC).

money', although there is a notable presence of neutrality, suggesting some uncertainty or lack of information about the economic benefits of DLC. Finally, the ease of integrating DLC into daily life was assessed with the statement 'Easy to live with'. Here the responses were split between the 'Agree' and 'Neutral' categories, suggesting that while there is a degree of confidence in the manageability of DLC, there is also a degree of ambivalence which may reflect concerns about the practical implications of adopting such systems.

In contrast, consumer trust and concerns about DLC were also assessed. The findings are summarized in Fig. 5. A majority of the respondents exhibit a positive attitude towards the grid operator's transparency, with a significant fraction agreeing, or strongly agreeing, with the statement. The issue of incomplete information is of considerable concern to respondents. Data protection concerns are similarly low on the list of priorities for respondents, with many expressing disagreement that this is a worrying aspect of DLC. However, and in contrast to the incomplete information aspect, there are respondents who are extremely concerned. This is also reflected in the overall confidence of the respondents in DLC. A large majority are not concerned about DLC, although a small proportion expressed strong concerns. These strong concerns do not appear to be due to mistrust in the operator or the intransparency of the information available, as there seems to be no strong distrust or concern about transparency among the majority of respondents. However, they may be partly due to privacy issues. It is important to check whether these privacy concerns, which must be independent of trust in the grid operator, indicate a concern about hacking (cybersecurity), for example. Another possible explanation for the proportion of respondents with concerns about DLC could be concerns about the loss of convenience or comfort.

Finally, the prospect of paying more to avoid DLC does not find favor among the majority of respondents. This suggests that a pricing strategy that penalizes those who do not allow DLC is not per se a necessary condition to increase uptake. However, a financial incentive for those who do allow DLC could be beneficial.

The framework provides grid operators with a clear set of priorities for program design. Based on the criteria and their weights derived in this study, an ideal DLC program would ensure that participants receive fair and attractive financial incentives. Compensation would be structured to reflect the frequency and duration of DLC events, ensuring that it is aligned with the perceived value of consumers. High value incentives can increase consumer acceptance and participation. Comfort would be non-negotiable, with minimum indoor temperature thresholds maintained between 20 and 22 °C and electric vehicle charge levels maintained at above 90 %. This would reassure participants that their basic needs are not compromised during DLC events. Real-time communication and accessible information would be essential, providing consumers with clear details of DLC events, including timing, duration, expected energy savings and cumulative financial rewards. Transparency builds trust in the program. Participants would have override options to maintain device autonomy, ensuring flexibility and encouraging enrolment by keeping users in control of their energy use. DLC events would be limited in frequency and kept as short as possible to minimize inconvenience while maximizing grid stability and energy optimization. Policy makers can use the framework to establish regulations that balance consumer protection with grid management objectives. They can impose minimum comfort standards and transparency requirements to protect consumer interests. Germany's §14a EnWG is a notable regulatory example in this context. In particular, it sets minimum comfort standards to ensure that essential needs such as adequate indoor temperatures and equipment functionality are maintained during DLC events. This is an important step towards aligning the regulatory framework with consumer expectations. It facilitates network-oriented control of appliances and provides a legal framework for DLC programs. One of its strengths is that it provides a clear basis for integrating

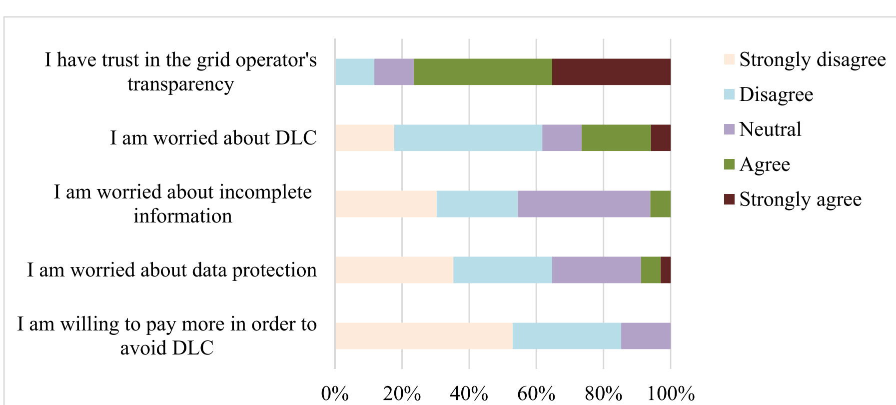

Fig. 5. Declared agreement to trust and concerns about direct load control (DLC).

controllable devices into grid management strategies, thereby enabling a more stable and efficient energy system. However, the legislation has its limitations, particularly in addressing consumer concerns about autonomy and privacy. While it allows for operational control of devices, it does not require sufficient measures to ensure consumer trust, such as real-time transparency or override options. It is important that the financial compensation schemes outlined in this regulation (minimum of €110/a, increasing in case of high demand) are scientifically reviewed to ensure that they adequately incentivize participation and reflect the true value of consumer contributions.

In this study, a novel multi-criteria assessment framework for evaluating DLC programs from an occupant perspective is presented. To highlight the strengths and uniqueness of the approach, it is compared with other widely used multi-criteria decision making (MCDM) methods, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination et Choix Traduisant la Réalité (ELECTRE), and Fuzzy MCDM, which are commonly used in energy and sustainability assessments [26,27]:

TOPSIS determines the best alternative by minimizing the distance to the positive ideal solution and maximizing the distance to the negative ideal solution. While TOPSIS is effective in ranking alternatives based on quantitative performance measures, it does not explicitly account for subjective stakeholder preferences in the same structured way as AHP.

4.3. Case study

To demonstrate the practical application of the framework designed in this paper, one of the world's largest DLC programs, the Florida Power & Light (FPL) On-Call Program, is evaluated in this section. This program, introduced in the 1980s, manages up to 1000 MW of power under normal conditions and 2000 MW during emergencies, leveraging load control transponders to manage appliances such as air conditioners and water heaters during peak demand. Participants benefit from financial incentives while contributing to grid stability [44]. The case study evaluation was conducted using publicly available reports, regulatory filings, and utility documentation to assess key performance criteria within the developed AHP framework. Potential influencing factors include the reliance on secondary data sources, assumptions about customer experience, and the absence of direct user feedback, which may affect the accuracy of the results.

An assessment of the program reveals its strong performance across multiple criteria. Financial compensation exceeds €135 annually, ensuring a top score (10). Guaranteed comfort is maintained through minimally disruptive measures that ensure temperature stability (10). Transparency is exemplary, with timely and clear communication about event frequency and duration (10). The frequency and duration of load control events are well-optimized, occurring sparingly and lasting less than 30 min (10). However, the program scores low on participant control (1), as users have no ability to override load control measures. Weighted scoring, prioritizing financial compensation, comfort, and transparency, yields an overall score of 8.52 out of 10, showcasing the program's ability to balance customer benefits with operational efficiency.

By evaluating various programs using the framework presented, DLC initiatives become more easily comparable for consumers. For grid operators, this approach offers valuable insights to align programs with customer preferences, enhance competitiveness, and drive broader adoption.

4.4. Limitations

Additional application of the assessment framework will be carried out in future papers. The need for further research and the limitations of this exploratory study conducted are explained below.

In the context of the AHP, the independence of criteria is a crucial assumption for the validity of the decision-making process. However, in practice, achieving independence is not always possible. The AHP approach applied assumes that the different criteria used to evaluate the options are independent from each other, allowing for a clear hierarchical comparison. However, in many real-world scenarios, these criteria can be interrelated or interdependent, leading to complexities in the decision-making process [6,21]. Even with our proposed criteria, there does not appear to be a clear-cut independence: as long as an elementary level of comfort is guaranteed and there is even an override option (control), it may be less important how long and frequently DLC interventions take place. Nevertheless, these criteria are independent elements of possible DLC programs and have already received independent attention in the literature.

In the analysis of comfort presented in the context of heating, attention was primarily given to temperature, a significant aspect - yet only one part of a comprehensive understanding of comfort. A more holistic view of air comfort, which encompasses temperature, air velocity, and humidity, was not covered in the study. Moreover, various aspects of space heating, including surface temperatures, thermal radiation, and short-wave radiation, were not considered. These elements are critical in shaping the thermal environment and, consequently, the levels of comfort experienced [35]. Additionally, the analysis excluded factors such as clothing and activity levels, both of which have a significant impact on individual thermal comfort. Therefore, it should be understood that the findings represent a limited perspective on the multifaceted concept of comfort.

In the current approach, the mean of the value scores for both BEV and electric heating technologies is calculated to represent the overall comfort level. This methodology was adopted primarily for reasons of practicality and simplicity, as it provides a straightforward means of combining the comfort contributions from both systems. However, it is acknowledged that individual comfort preferences for each device may differ significantly, and this simplification may not fully capture the nuances of user experience. Therefore, future studies should aim for a more differentiated approach, where the comfort preferences for BEV and heating technologies are evaluated separately, to better account for the distinct factors influencing comfort in each context.

The technologies considered in this DLC study are already established on the market and were taken into account in §14a EnWG. However, some technological solutions were not considered. Niche technologies, such as heating with green hydrogen, which could be produced by electrolysis and consumed flexibly on-site [45], were not considered due to their lack of economic competitiveness [46], among other reasons. Likewise, electrolyzers, saunas and swimming pools, which are large and flexible consumers of electricity, are not taken into account in §14a EnWG.

Due to the limited scope of the DLC pilot project, it is not possible to divide the respondents into socio-demographic groups for the AHP evaluation. These groups would have been too small to obtain reliable results. Additionally, the households surveyed were first movers in the sense of the theory of diffusion of innovations [17], and their preferences may not necessarily align too well with those of the general public nationwide [47]. Therefore, the next step should be to conduct a large-scale study in Germany with a representative sample of respondents. Methodologically, discrete choice experiments or choice-based conjoint experiments are suitable methods for investigating priorities related to DLC tariffs in more depth.

The study focuses on the preferences of early adopters, treating them as a homogeneous group to determine the criteria and their respective weights, which led to the assumption that varying parameters was unnecessary for validating the results. Additionally, the primary aim of the study was to develop a framework for evaluating DLC programs, rather than analyzing uncertainties or variability in detail, delivering a robustness analysis beyond the study's immediate scope and in line with a representative survey potential for future research or validation efforts.

5. Conclusions and outlook

This paper presents a thorough analysis of DLC in residential buildings, with a focus on the occupant's viewpoint. The developed multi-criteria assessment framework, which integrates the AHP approach, provides a new method to evaluate DLC approaches, taking into account relevant criteria such as financial compensation, guaranteed comfort, control, transparency, frequency, and duration. The quantification of the importance of the criteria and the results of the survey of individual factors and attitudes have added value. The study's findings seem intuitive and reveal critical insights into the preferences and attitudes of early adopters towards DLC programs.

The primary factors influencing the acceptance of DLC programs is financial compensation, followed by the need for guaranteed comfort. Control and transparency are also crucial in these programs as they directly impact consumer trust and willingness to participate. It can be concluded that load interventions in slow energy systems such as heat pumps in combination with large radiators would be particularly useful. The slow drop in temperature as a result of a DLC measure would limit comfort only slightly and households would probably be satisfied with lower financial compensation.

It is also highlighted that attitudes towards different technologies are different under DLC control, with a preference for control of electric room air-conditioners such as heat pumps, electric storage heaters, and air conditioners over BEVs. The study discusses the varying degrees of importance that occupants place on different aspects of their home environment and mobility. It also highlights that the participants perceive the societal benefits and potential for DLC to enhance the use of local and renewable electricity.

The surveyed households generally agreed to make their electric indoor climate appliances available for DLC by the grid operator. Especially the acceptance of such temperature-regulating electricity consumers in terms of DLC seems to be particularly high. In addition to the electrical appliances already covered by §14a EnWG, other large and flexible appliances, such as privately owned saunas and swimming pools that are electrically heated, should be included as controllable loads.

Liepold et al. [48,49] propose the introduction of greenhouse gas mitigation quotas for heating technologies, which is likely to drive a shift towards more electrified heating technologies in households. This proposal would make fossil-fuel-based heating systems less attractive due to regulatory constraints and potentially higher costs associated with emission allowances or penalties, as they are significant contributors to GHG emissions. Consequently, this shift would encourage the adoption of cleaner, electricity-based heating solutions such as heat pumps, which have a lower carbon footprint. As more households adopt electrified heating technologies, the potential for DLC in the residential sector grows. This could increase the flexibility potential to stabilize the electricity grid.

In conclusion, the proposed assessment framework is a significant step forward in better understanding and designing DLC approaches that align well with residential occupants' preferences and needs. This research provides valuable insights for grid operators, aggregators, and policymakers who must navigate the complexities of implementing demand response initiatives in the residential sector.

There is substantial research potential remaining for studying in more detail the impact that effective communication can have on people's perceptions and attitudes regarding DLC. This area of study is crucial, as public perception and acceptance are key determinants in the successful implementation of DLC initiatives. Future research could investigate how various communication strategies, such as message framing, information clarity, and channel selection, affect public comprehension and acceptance of DLC. Additionally, the impact of transparency in communication, trust in utility providers, and the perceived personal and communal benefits of participating in DLC programs could be investigated. Research could further examine the impact of demographic factors, such as age, education level, and environmental awareness, on the effectiveness of communication strategies. Understanding these aspects could aid significantly in designing more effective communication campaigns that increase public support of and participation in DLC programs.

Due to the small sample size of households in this study, it is recommended that large-scale studies be conducted by using methodical approaches such as choice-based conjoint analysis. This approach involves surveying a large and representative sample, which is crucial for accurately capturing the diverse and complex preferences across different household demographics. By systematically varying the attributes of DLC programs in these studies, it is possible to discern how households trade off between various aspects of DLC, such as cost, convenience, control, and environmental impact. These detailed insights are invaluable for designing DLC programs that are more effectively tailored to consumer needs and preferences, thereby enhancing program uptake and effectiveness. Additionally, understanding these preferences at scale can further inform policymakers and energy providers about potential barriers to adoption and areas requiring targeted communication strategies.

CRediT authorship contribution statement

Paul Fabianek: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Constanze Liepold:** Writing– original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Reinhard Madlener:** Writing – review & editing, Supervision, Resources,Project administration, Funding acquisition, Conceptualization.

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.

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Appendix

Table A.1
Socio-demographic distribution of our sample

Variable	Value	Sample share [%]
Socio-demographic distribution		
Gender	Female	20.6
	Male	79.4
Age	30–39 years	8.8
	40–49 years	29.4
	50–59 years	32.4
	60–69 years	14.7
	70 years and older	14.7
Main profession	Full-time employed	61.8
	Part-time employed	8.8
	Marginally employed	2.9
	Self-employed	2.9
	Pensioner	23.5
Persons per household	1	8.8
	2	41.2
	3	11.8
	4	23.5
	5	5.9
	6	8.8
Net household income per month	€1501–2500	5.9
	€2501–3500	17.7
	€3501–5000	38.2
	€5001–7000	17.7
	No answer	20.5
Education	German Volkshochschule or Hauptschulabschluss	8.8
	German Realschulabschluss	17.7
	Degree from a German Fach-, Meister-, Techniker-, or Berufsschule	20.5
	German A-Levels (Abitur)	0.0
	University of applied science degree	20.6
	University degree	23.5
	PhD	5.9
	No answer	2.9
Professional contact with (multiple answers possible)	Grid operation	26.5
	Energy	29.4
	Technology	38.2
	None of the above	50
Existing energy appliances (multiple answers possible)	Heat Pump	94.1
	Electric Car	17.7
	Electric Storage Heater	11.8
	Air Conditioner	0

Table A.2
Technical, tariff, and individual factors from the literature that have an influence on preferences concerning DLC programs

Criterion	Sridhar et al. [23]	Schöne et al. [22]	Yilmaz et al. [5]	Yilmaz et al. [1]	Stenner et al. [3]	Fell [4]	Fell et al. [11]	Newsham and Bowker [12]
Financial compensation*	✔	✔	✔	✔	○	✔	✔	✔
Guaranteed comfort*	○	○	✔	○	○	✔	✔	○
Control*	○	○	✔	○	○	✔	✔	○
Transparency*	○	○	✔	○	○	✔	○	○
Frequency and duration*	○	✔	✔	○	○	✔	✔	○
Personal and social norms	✔	✔	✔	○	○	○	○	○
Understandig of DLC	○	○	✔	✔	○	○	○	○
Trust in company	○	○	○	○	✔	✔	○	○
Type of device	○	✔	○	✔	○	✔	✔	○
Timing of notification ahead	○	✔	○	○	○	○	○	✔
Smart home automation	✔	○	○	○	○	✔	○	○
Interest in technology	✔	○	○	○	○	○	○	○
Environmental impact	✔	✔	○	○	○	○	○	○
Utilization of local generation	✔	○	○	○	○	○	○	○
Perceived usefulness	○	○	✔	○	○	✔	✔	○
Perceived ease-of-use	○	○	✔	○	○	✔	✔	○

✔ - factor available; ○ - factor not available; *included as criteria.

Data availability

Data will be made available by the authors upon request.

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