

The role of controllable household appliances for effective uptake of digital services by consumers and communities in the energy transition

Original

The role of controllable household appliances for effective uptake of digital services by consumers and communities in the energy transition / Chicco, G., Mustafayeva, G., Russo, A., Di Somma, M., Giannoccaro, G., Mottola, F., Villacci, D., Buonanno, A., Fabozzi, S., Palladino, V., Caliano, M., Valenti, M., Selim Türkolu, A., Ghanavati, F., Jesus, T.C., Catalão, J.P.S.. - In: ENERGY STRATEGY REVIEWS. - ISSN 2211-467X. - ELETTRONICO. - 67:(2026).
[10.1016/j.esr.2026.102355]

Availability:

This version is available at: 11583/3014989 since: 2026-08-30T16:45:00Z

Publisher:

ELSEVIER SCIENCE LTD

Published

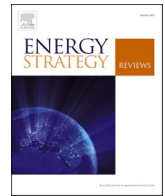
DOI:10.1016/j.esr.2026.102355

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)



The role of controllable household appliances for effective uptake of digital services by consumers and communities in the energy transition

Gianfranco Chicco^{a,*}, Gulshan Mustafayeva^a, Angela Russo^a, Marialaura Di Somma^b, Giovanni Giannoccaro^b, Fabio Mottola^c, Domenico Villacci^b, Amedeo Buonanno^d, Salvatore Fabozzi^d, Valeria Palladino^d, Martina Caliano^d, Maria Valenti^d, Aligül Selim Türkoğlu^e, Farideh Ghanavati^e, Thiago C. Jesus^{e,f}, João P.S. Catalão^e

^a ENSIEL/POLITO, Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Corso Duca Degli Abruzzi 24, Torino, 10129, Italy

^b ENSIEL/UNINA, Department of Industrial Engineering, University of Naples Federico II, Naples, Italy

^c ENSIEL/UNINA, Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy

^d ENEA, Department of Energy Technologies and Renewable Sources, Portici, Italy

^e Research Center for Systems and Technologies (SYSTEC), Advanced Production and Intelligent Systems Associate Laboratory (ARISE), Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, Porto, 4200-465, Portugal

^f UEFS, Department of Technology, State University of Feira de Santana, Feira de Santana, Bahia, Brazil

ARTICLE INFO

Handling Editor: Henrik Lund

Keywords:

Appliance
Customer
Electrification
Energy community
Flexibility
Residential user
User engagement

ABSTRACT

Digitalisation is transforming modern energy systems into complex socio-technical ecosystems where interconnected devices, user practices and governance structures must be considered together. To analyse this landscape and address relevant research questions concerning controllable household appliances, a multilevel conceptual framework has been developed by organising the investigation into five interconnected thematic domains: digital control of the appliances, flexibility analysis, user engagement, management by aggregators, and relations with energy communities. Through discussions of selected scientific articles and real-world projects, this article reviews the categorisation of household appliances, methods for controlling them, and indicators to assess load-shifting capabilities and flexibility. It then addresses user engagement based on users' behaviour, active role, and comfort. Operational strategies for aggregators are identified to manage controllable appliances, develop suitable business models, and participate in flexibility markets. Finally, the deployment of smart household appliances within energy communities is discussed as a further opportunity to involve more users and share their available resources. The synthesis distinguishes comparatively established approaches from promising but still weakly validated combinations of appliance types, control strategies, engagement mechanisms, and aggregator models.

1. Introduction

Digitalisation and grid modernisation are promoting an unprecedented transformation of the global energy landscape. Digital infrastructures make large amounts of data available to support new developments in grid and generation system operation, widespread transport and heating electrification, and the emergence of prosumers

[1]. Every kilowatt-hour is paired with kilobytes of information. Smart meters, Internet of Things (IoT) sensors, and cloud analytics drive this transition. Digital technologies promise lower operating costs, smoother integration of renewables, and new income sources. Yet, technological developments alone do not guarantee societal uptake. Users must value the service, trust the data pathway and feel that comfort is achieved without unnecessary sacrifice.

Technological evolutions and the possibilities of offering grid

* Corresponding author.

E-mail addresses: gianfranco.chicco@polito.it (G. Chicco), gulshan.mustafayeva@polito.it (G. Mustafayeva), angela.russo@polito.it (A. Russo), marialaura.disomma@unina.it (M. Di Somma), giovanni.giannoccaro@unina.it (G. Giannoccaro), fmottola@unina.it (F. Mottola), domenico.villacci@unina.it (D. Villacci), amedeo.buonanno@enea.it (A. Buonanno), salvatore.fabozzi@enea.it (S. Fabozzi), valeria.palladino@enea.it (V. Palladino), martina.caliano@enea.it (M. Caliano), maria.valenti@enea.it (M. Valenti), asturkoglu@fe.up.pt (A.S. Türkoğlu), ghanavati@fe.up.pt (F. Ghanavati), jesus@fe.up.pt (T.C. Jesus), catalao@fe.up.pt (J.P.S. Catalão).

<https://doi.org/10.1016/j.esr.2026.102355>

Received 7 May 2026; Received in revised form 27 July 2026; Accepted 28 August 2026

Available online 30 August 2026

2211-467X/© 2026 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

List of acronyms			
AI	Artificial Intelligence	GAMS	General Algebraic Modeling System
API	Application Programming Interface	GUI	Graphical User Interface
DER	Distributed Energy Resources	HEMS	Home Energy Management System
DFS	Demand Flexibility Service	HVAC	Heating, Ventilation and Air Conditioning
DR	Demand Response	ICT	Information and Communication Technologies
DSO	Distribution System Operator	IoT	Internet of Things
EMS	Energy Management System	M&V	Measurement and Verification
ENTSO-E	European Network of Transmission System Operators for Electricity	MQTT	Message Queuing Telemetry Transport
ESO	Energy System Operator	PMV	Predicted Mean Vote
EU	European Union	PPD	Predicted Percentage Dissatisfied
EV	Electric Vehicle	QoE	Quality of Experience
FERC	Federal Energy Regulatory Commission	REDD	Reference Energy Disaggregation Dataset
		RQ	Research Question
		TSO	Transmission System Operator
		UKPN	United Kingdom Power Networks

services require updating the view of today's role of household appliances. Controllability of the assets becomes the key issue. However, controllability is not only a technical issue. It largely depends on users' behaviour and their willingness to accept and apply innovations emerging from progressively increasing digitalisation. Conversely, technological developments could lead to unequal participation in digital energy services among different kinds of users. Households with higher incomes, longer access to electricity, better education, reliable power supply, good internet connectivity and greater technical confidence are more likely to adopt controllable appliances [2]. By contrast, participation remains lower among rural populations, older adults and low-income groups. Energy communities face further challenges when digital skills are limited, or data responsibilities are not clearly defined.

Moreover, flexibility addresses the capability of a consumer, producer, or storage asset to change its normal generation or consumption pattern (upward/downward, and in time) in response to an external signal [3]. Flexibility may be requested to relieve grid congestion, follow wholesale price variations, or balance power fluctuations. Flexibility requests and rewards are generally managed by aggregators [4]. Independent aggregators operate portfolios of supply contracts, while supplier-aggregators can integrate retailing and flexibility into a single offer [5]. Community-based aggregators act on behalf of cooperatives or municipalities. By setting incentive structures, defining data-sharing rules and curating user interfaces, aggregators influence whether consumers perceive digital control as an opportunity or a burden [6].

In this context, this article aims to identify and explain the factors that foster or impede consumers and communities adopting digital energy services in households. By synthesising information from the literature and applied research projects, the article identifies gaps between technological potential and practical implementation. The findings provide indications for policymakers, aggregators, energy

communities, technology developers, and researchers.

A systematic search has been carried out starting from the main keywords of specific interest, namely, “appliance”, “controllab*”, and a third keyword that considers the alternative terms “household”, “home” and “residential”, to encompass different ways to refer to the location of interest.

The search has been carried out on the Scopus database, widely available and fully appropriate for the topics under investigation. Only sources written in English have been considered. No limit has been set to publication dates, and no other filter has been introduced. Two search modes have been considered, namely, ALL to include all fields, and TITLE-ABS-KEY to limit the search to title, abstract and keywords. These indications allow full replicability of the search.

The results are presented in Table 1, considering all sources, as well as limiting the count to review articles. The specific search strings are explicitly indicated for the various combinations of keywords. Since no filter has been imposed on the subject areas, the results refer to all the subject areas considered by Scopus. Table 1 indicates the number of review articles categorised by the most used or relevant subject areas (multiple subject areas may appear for the same article).

The number of review articles to consider has then been limited to the Energy subject area in the post-processing phase. The results indicate that restricting the search to title, abstract, and keywords yields too few review articles. The 146 review articles that result in the Energy subject area by adding “household” OR “home” OR “residential” to the initial search string in the “ALL” search mode have been extracted. Since selecting review articles based on the indication of the Energy subject area does not guarantee that Energy is the primary subject area of the review article, further investigation was carried out on the individual articles. Fig. 1 summarises the steps of the search process, up to the final selection of the relevant review articles.

Table 1
Search carried out from the Scopus database (19 July 2026).

Search string	Number of sources	Number of review articles	Review articles per subject area (multiple areas may appear for the same article)					
			Engineering	Energy	Computer science and Mathematics	Materials science	Chemistry and Chemical engineering	Social science
ALL("appliance" AND "controllab*")	4202	547	248	163	98	220	200	15
TITLE-ABS-KEY("appliance" AND "controllab*")	629	13	7	5	3	3	3	0
ALL("appliance" AND "controllab*" AND ("household" OR "home" OR "residential"))	3171	461	216	146	91	174	158	14
TITLE-ABS-KEY("appliance" AND "controllab*" AND ("household" OR "home" OR "residential"))	387	4	4	3	3	0	1	0

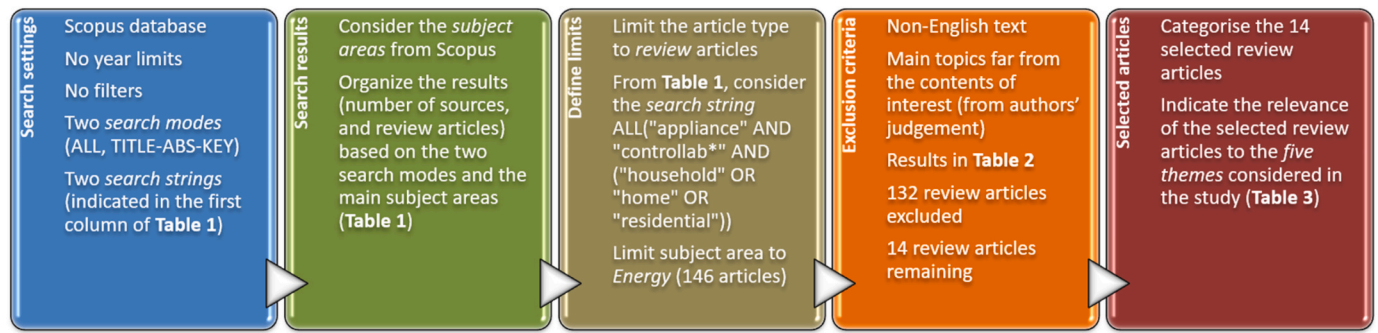


Fig. 1. Steps of the systematic search carried out in Scopus for review articles.

The 146 review articles were further categorised through individual assessment, aiming to exclude review articles with main topics far from the contents of interest for this article. The results of the categorisation led to the exclusion of the groups of review articles that address the main topics indicated in Table 2.

After the exclusion of the 132 review articles indicated in Table 2, the remaining 14 review articles address main topics like energy management, demand response, flexibility, monitoring, and the keywords contain the word “smart” combined in different ways with other terms. The three review articles indicated in the last row of Table 1 for the Energy subject area ([7], [8] and [9]) have not been excluded during the last step of selection carried out by the authors, confirming that the indications provided in the title, abstract and keywords in these articles are appropriate for the scope of the review carried out.

Based on the contents of the review articles and on the conceptualisation of the aspects proposed in this article, recurring topics have been identified to fit with the household appliance controllability scope, resulting in five themes:

1. Digital control of the appliances — management of controllable devices.
2. Flexibility analysis — from the system and end-user perspectives.
3. User engagement — behaviour, motivation, trust and perceived comfort.
4. Management by aggregators — how aggregator models translate small-scale flexibility into market products.
5. Relations with energy communities — exploring peer influence, collective incentives, and enablers of community engagement.

These themes have been organised along a three-level conceptual framework to provide a common structure for assessing technical feasibility, user acceptance, and implementation conditions. In particular, the framework (detailed in Section 2) considers appliance control at the *micro* level (Themes 1–2), user engagement at the *meso* level (Themes 2–3), and aggregator and community-level intermediation at

the *macro* level (Themes 4–5).

Table 3 shows the main contents of the 14 selected review articles identified in the previous search and the possible fit with the five themes considered in this article.

Table 3 shows that no review article has been found that addresses all five themes within a broad spectrum to identify emergent strategies of evolution for controllable household appliances. This confirms the originality of the set of themes outlined by the proposed conceptual framework.

To proceed further, a research question has been formulated for each theme (Table 4) to capture the main aspects of residential digital energy services.

The main contribution of this article lies in integrating, within a single framework, the appliance control examined at the *micro* level, the user and community dynamics examined at the *meso* level, and the aggregator and market interactions examined at the *macro* level.

Within this framework, the integrated socio-technical perspective represents a novelty of this article. Rather than examining appliance controllability solely as a technical optimisation problem, this article connects the technical characteristics of controllable household appliances with the behavioural and social dimensions that determine their practical adoption. This holistic perspective highlights how technical flexibility can only be effectively translated into real-world energy services when supported by active user participation, appropriate aggregator mechanisms, and community-based governance. Indeed, while advances in smart appliances, interoperability, and control algorithms have significantly enhanced the technical capability to provide flexible demand, these capabilities alone are insufficient to achieve large-scale implementation.

The effectiveness of implementing controllable household appliances depends on active user engagement, which determines the willingness to participate in demand response programmes, the business models and coordination strategies implemented by aggregators, and the governance structures provided by energy communities. Energy communities, in particular, represent an important organisational layer, in which controllable household appliances can collectively support demand response, local balancing, collective self-consumption, and peer-to-peer energy exchanges, thereby translating individual flexibility into community-wide energy services.

By connecting these technical, behavioural, market, and governance dimensions within a single framework, this article highlights how an effective strategy for successful deployment of residential flexibility requires an integrated socio-technical perspective rather than isolated technological advances. This holistic approach distinguishes the present study from previous studies, providing researchers, policymakers, and practitioners with a comprehensive understanding of the interdependencies that underpin digital energy services and community-based energy transition. Another distinctive contribution is the discussion of the findings taken from a selection of relevant recent projects funded by the European Union (EU).

The remainder of this article is organised as follows. Section 2 reports

Table 2

Main topics and number of review articles excluded from the 146 review articles found in the Energy subject area.

Main topic	Number of review articles excluded
Materials	28
Operation and planning of distribution networks and microgrids	36
Computational methods for power and energy system applications	22
Storage and electric vehicle technologies	16
Energy management in systems and buildings mostly related to thermal energy considerations	26
Review articles with the title in English and text in another language	4
Total review articles excluded	132

Table 3

Main contents of the selected review articles and fit with the five themes introduced in this article.

ID	Main contents	Fit with the theme				
		Digital control of the appliances	Flexibility analysis	User engagement	Management by aggregators	Relations with energy communities
Shen et al. (2015) [7]	Controllable load management	☑				
Freire-Barceló et al. (2022) [10]	Demand flexibility		☑		☑	
D'Ettorre et al. (2022) [11]	Demand side flexibility	☑	☑			
Ali et al. (2022) [12]	Smart home energy management	☑				
Manembu et al. (2023) [8]	Residential load-shifting	☑				
Barabino et al. (2023) [13]	Energy communities					☑
Ahmed et al. (2024) [14]	Renewable energy communities					☑
Golmohamadi et al. (2024) [9]	Residential demand side flexibility	☑	☑		☑	
Mousa et al. (2024) [4]	Demand-side management		☑		☑	
Tsybina et al. (2025) [15]	Demand response implementation	☑			☑	
Nema et al. (2025) [16]	Thermostatically controlled loads	☑				
Lazdins et al. (2026) [17]	Demand flexibility and energy communities		☑			☑
Chen et al. (2026) [18]	Demand side management		☑	☑		
Su et al. (2026) [19]	Flexibility from load aggregation	☑	☑		☑	

Table 4

Main themes and research questions (RQs).

ID	Theme	Research question	Level	Addressed in Section
RQ1	Digital control of the appliances	How do the management strategies, degrees and types of controllability built into smart appliances influence their adoption, day-to-day use and perceived comfort?	Micro	3.1
RQ2	Flexibility analysis	How is flexibility defined, measured and priced from both the system side and the end-user side, and how do these methods affect its practical delivery?	Micro/ Meso	3.2
RQ3	User engagement	Which behavioural drivers and lifestyle considerations determine the extent to which users engage actively with digital energy services?	Meso	3.3
RQ4	Management by aggregators	In what ways do different aggregator management models and data-sharing practices shape the flow of value and trust between small-scale resources and energy markets?	Macro	3.4
RQ5	Relations with energy communities	How do governance structures, peer effects and collective incentives within energy communities support or hinder the uptake of digital services and flexibility?	Macro	3.5

the details of the conceptual framework. Section 3 reports and examines the findings for each of the five themes. Section 4 illustrates and discusses the results arising from case studies described in relevant applications and projects. Section 5 summarises the answers to the research

questions. Section 6 contains the concluding remarks.

2. Conceptual framework

Residential flexibility is commonly represented through multilevel frameworks. For instance, techno-economic frameworks organised on coordination layers have been used to schedule controllable appliances and to allocate incentives for upward and downward flexibility [20–23]. These layers usually correspond to the home energy management system (HEMS), the aggregator, and the distribution system operator (DSO). Extending these layered formulations, a few recent contributions move beyond scheduling and cost optimisation alone and couple household behaviour, energy-system operation, and community interaction within a single model [24]. From a different research perspective, socio-technical studies examine how the digitalisation of the energy system reshapes social inclusion, trust, and the digital divide [25,26], and characterise the digital tools and interfaces that mediate engagement in local energy initiatives [27]. These two lines of work, however, have progressed largely in parallel, with the models that optimise appliance flexibility rarely accounting for the social determinants of participation. In contrast, studies of digital inclusion seldom reach the level of individual appliance control. Consequently, households tend to be represented either as a controllable technical resource or as a social actor, but rarely as both at once.

To address the lack of integration across the appliance-user-aggregator chain, this article offers a comprehensive view of digital inclusivity for household applications. Fig. 2 illustrates the proposed framework, with three interdependent levels that reflect how digital energy services operate and interact:

- **Micro level** (appliance control): The operation of deferrable devices such as washing machines and EV chargers can be shifted in time. The outputs of thermostats and heaters can be modulated, and other appliances can be curtailed. These characteristics determine the technical flexibility that can be offered to the grid.
- **Meso level** (individual users and community dynamics): User preferences, comfort thresholds and behavioural responses determine whether technological capabilities translate into meaningful action.

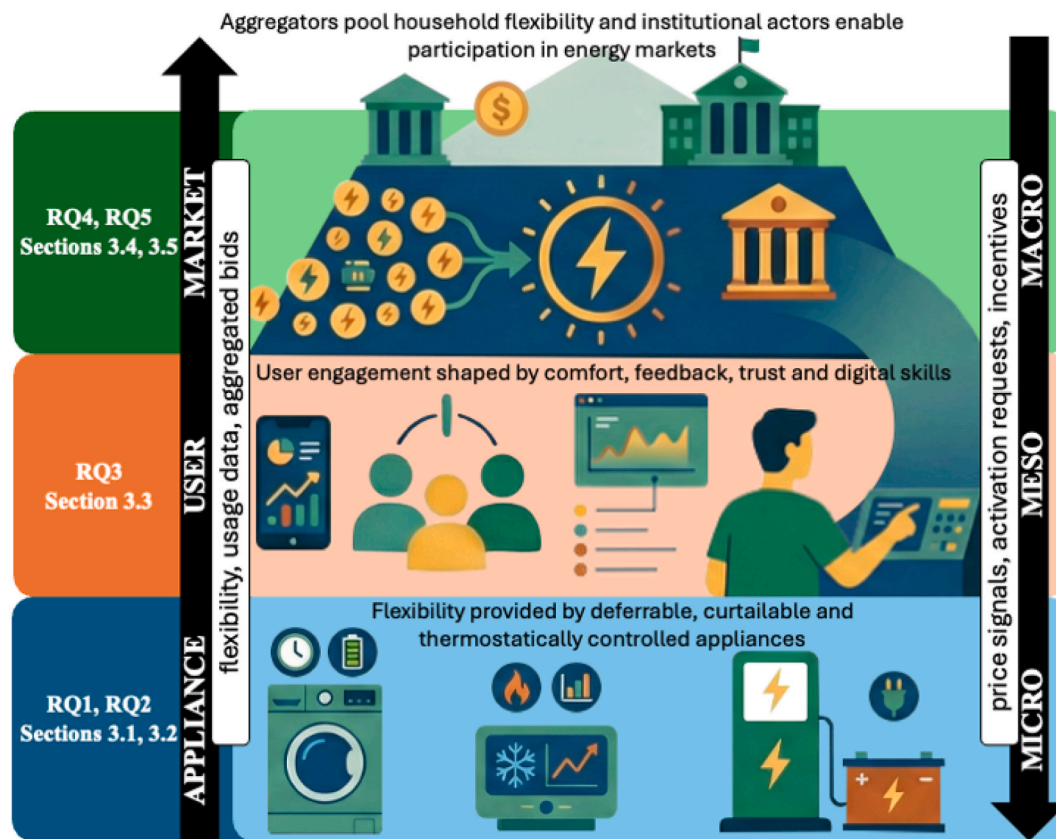


Fig. 2. Multilevel conceptual framework for household appliances and digital services in the energy transition.

Real-time feedback and peer support can increase digital literacy and boost confidence in using smart tools. Distrust of service providers remains a barrier: unclear billing and perceived misleading sustainability/environmental claims undermine user confidence, leading users to worry about availability of smart-control devices when expected or needed. Digitalisation can help rebuild trust by prioritising data transparency, personalised guidance, and easy-to-read statements. Nevertheless, adoption of information and communication technology (ICT) is irregular and often influenced by income, digital literacy and confidence in providers, highlighting the need for inclusive design and tailored engagement strategies.

- **Macro level** (interactions with an aggregator): Aggregators act as intermediaries that group multiple prosumers to support automated demand response (DR) or provide aggregated flexibility services by responding to grid signals. This grouping allows small and medium distributed energy resources (DER – local generation, storage, loads and electric mobility assets) to enter markets they could not access directly.

The two arrows in Fig. 2 represent the opposite flows that link the three levels. Flexibility, usage data and aggregated bids move upward from appliances to markets, while price signals, activation requests and incentives move downward from markets to appliances. Each level also corresponds to a specific part of this article. The *micro* level gathers the appliance categories, control strategies and flexibility indicators examined in Sections 3.1 and 3.2, which address the first and second research questions. The *meso* level covers the comfort, feedback, trust and digital skills discussed in Section 3.3, addressing the third research question. The *macro* level concerns the aggregator models, markets and regulation analysed in Sections 3.4 and 3.5, which address the fourth and fifth research questions.

The framework can also be used as a sequential assessment structure. The *micro* level assesses the available appliance flexibility and the

operating constraints to be preserved. The *meso* level assesses user acceptance, comfort, inclusiveness, and interaction with the digital service. The *macro* level assesses aggregation, governance, data exchange, settlement, and market implementation.

The value of the framework lies in treating the three levels jointly, since the choices made at each level condition what is achievable at the other levels. This structure can guide the formulation of research questions, pilot indicators, policy requirements, and implementation criteria.

Increasing adoption and diversification of household appliances are recognised as key contributors to residential energy consumption [28] and involve a growing volume of data exchange in the smart home or external clouds [29]. Typically, each appliance uses its manufacturer's control and communication protocol, with interoperability issues arising when devices from various manufacturers interact. In fact, as indicated in Ref. [30], the lack of standardisation in communication protocols and control architectures reduces interaction between appliances from different manufacturers, limiting the ability to easily expand these systems, which—for optimal operation—should be composed of devices from the same manufacturer (vendor lock-in). This issue can be addressed through standardisation of requirements and promotion of semantic interoperability for smart home appliances, such as that promoted voluntarily by some manufacturers coordinated by the JRC Smart Electricity System in the EU [31]. Data losses and cyberattacks introduce risks to smart home security and user privacy due to personal data sharing. In fact, with increasingly advanced information technologies that adopt artificial intelligence, attacks are becoming more dangerous.

In some cases, hackers may be able to take control of home devices or steal sensitive user data [32]. End-users are often not experts or aware of cybersecurity related to their smart home devices [33]. They are more likely to share sensor data on their energy consumption than personal data for privacy reasons, not only because of the risk that such information could fall into the hands of malicious actors, but also due to legislation where privacy and data governance are generally regulated

by standards not specifically tailored to the context of smart home device control [34]. Data sharing can be encouraged by highlighting the economic benefits for better energy management [35].

Smart contracts can effectively support data and energy transactions, which may enhance traceability, transparency, and automated data collection and verification. However, the effectiveness of data management merely depends on secure implementation, governance mechanisms, and the underlying blockchain infrastructure [36]. It should be emphasised that privacy, scalability, integrity, interoperability, and cybersecurity issues remain challenging in smart grids and microgrids considered as cyber-physical systems [37]. Practical deployment of blockchain requires addressing computational complexity, integrity, interoperability, governance, and privacy concerns. In this regard, it is essential to monitor and control the status of smart appliances and sensors [38], as well as the authentication and identification of IoT devices and the scalability issues [39].

Fig. 3 represents the interactions between controllable appliances, the user, and the aggregator. The aggregator manages multiple households, one of which is represented in the figure. The household is supplied by the grid, receives power inputs from local generation and vehicle-to-grid (if applicable), and serves the appliances and the electric vehicle chargers. The user interacts with controllable appliances with manual or assisted communication, for example through a natural language intermediary. The user receives data through displays and monitoring systems. The user interacts with the aggregator by sharing economic information for trading purposes or for enabling flexibility services through energy shifting, or participating in DR programmes. The user may wish to inform the aggregator of his/her behaviour and comfort, receiving information from the aggregator on performance indicators in comparison with other users to motivate the user to achieve better performance. The aggregator has access to household data that refer to local generation, storage and electric vehicle chargers, and develops tools for energy system management. If the user agrees to assign

control of certain appliances to an energy management system, the aggregator may interact directly with those appliances. By managing the users' resources, the aggregator can provide grid services (e.g., voltage control, frequency regulation, peak shaving and load balancing) and participation in DR programs. The system operator can inform the aggregator on how to prioritise the users depending on the service needed.

3. Analysis of specific aspects related to the research questions

This section discusses the five topics identified in the Introduction, namely, digital control of the appliances, flexibility analysis, user engagement, management by aggregators, and relations with energy communities, focusing on the household context.

3.1. Digital control of the appliances

3.1.1. Types of controllability

Controllable appliances are a central element in demand-side flexibility strategies [9]. Depending on the type of control operation, a distinction is made among deferrable (also called postponable in Ref. [40]), curtailable, and thermostat-controlled devices [41].

Deferrable appliances (e.g., washing machines, dishwashers, dryers, and EV chargers) can be scheduled to operate during off-peak hours or based on system load thresholds. Operation can be delayed or rescheduled without significantly affecting their pattern or user comfort (based on higher load-shifting capability than the other types). User-defined deadlines or comfort constraints can determine acceptable delay durations. Turn-on controllability is a typical metric [42]. Some articles distinguish fixed-cycle appliances (cannot be interrupted once activated), from more flexible loads that allow power modulation or dynamic start times [41].

For curtailable appliances, power consumption can be reduced,

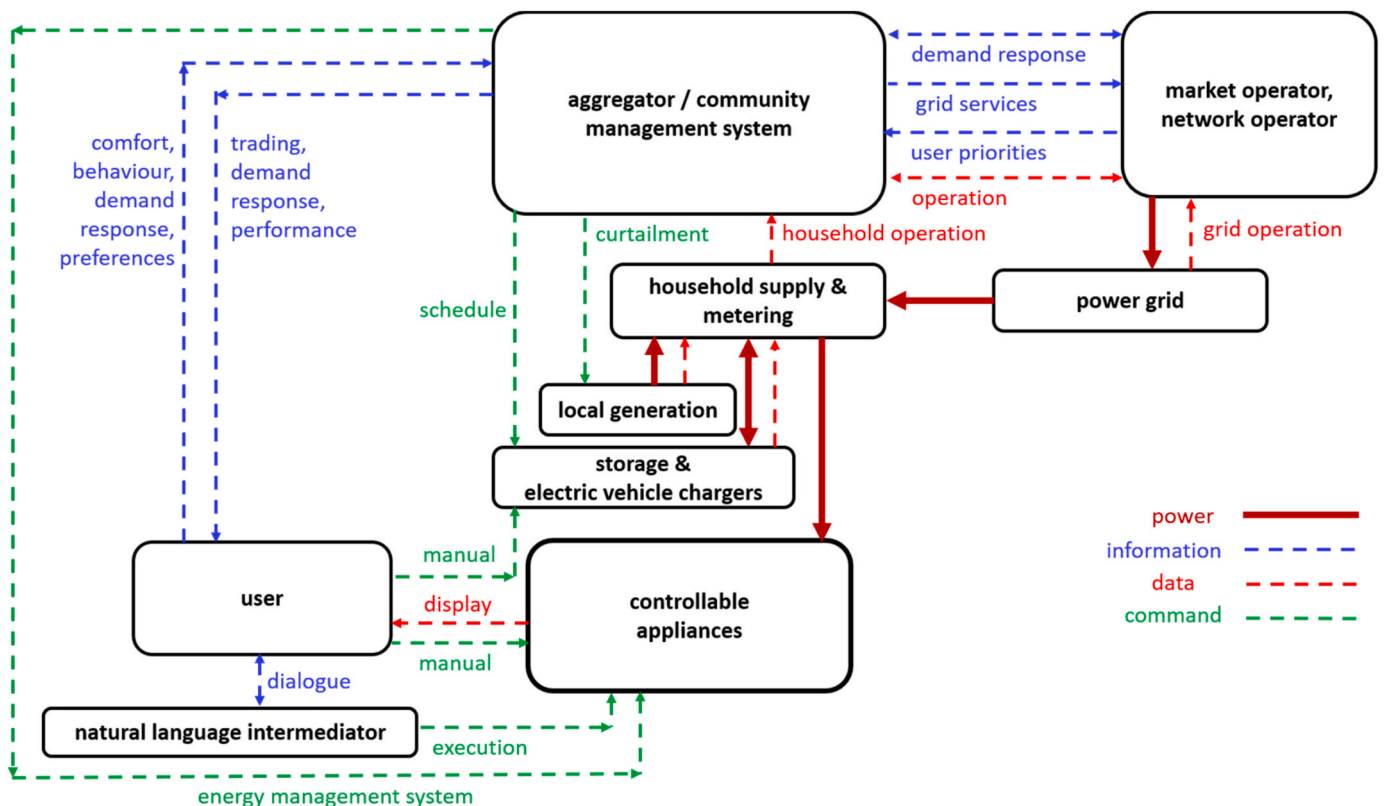


Fig. 3. Interactions in the links between controlled appliances, user, aggregator, and the external system. The arrows indicate the prevailing direction of information, data or command between the entities.

limited, or temporarily turned off during selected time intervals without causing damage. Common examples are heating, ventilation and air conditioning (HVAC) systems, water heaters, and energy storage systems. Turn-off controllability quantifies the curtailable power without significant user discomfort [42].

Deferrable and curtailable appliances are addressed in various references (summarised in Table 5, where the terms explicitly show the variety of the ways used in the categorisation), while other contributions [43–45] consider deferrable appliances only. Their operating potentials can be quantified by evaluating the minimum compensation required for participation in Demand Response programs, also defined as “Willingness-to-Accept” in Ref. [46].

The capability of a load—such as controllable appliances—to provide flexibility can be assessed by combining the flexibility characteristics of the generation system with a detailed load response model that quantifies the potential for coordinated regulation, as done in Ref. [54]. For thermostat-controlled devices, among the various methods found in the literature, flexibility can be quantified based on hourly aggregated data of the binary on/off profile of the devices considered under conditions of higher or lower thermal comfort. Based on the “on” occurrences of the devices for the different comfort levels and historical data on observed minimum and maximum temperatures, the mean and standard deviation of the devices’ energy consumption can be estimated. Consequently, the flexibility of the devices is calculated using an XG-Boost model [55].

Fig. 4 provides an appliance-classification scheme together with the conceptual flexibility framework. Table 5 summarises the different categorisations of appliances, indicating the specific terminology used in the corresponding articles. Fig. 4 uses consistent terminology for the flexibility features and associates appliances with one or more features. Some deferrable appliances are not interruptible because their task should be completed, even though at a different time than the initial schedule. Table 5 includes the further definition of “buffer devices” [40]: this definition highlights the type of flexibility that this class of devices can provide. However, it may fall into the categories of deferrable or thermostat-controlled devices depending on the type of control they can be subject to.

3.1.2. Appliance scheduling

Table 6 summarises the scheduling problems by type of optimisation (single- or multi-objective, linear or nonlinear), objective functions and

Table 5
Categorisation of the appliances in selected literature references.

Ref.	Number of categories	Categories
[40]	2	Postponable; Buffered.
[47]	2	Shiftable; Non-shiftable.
[48]	2	Non-thermostatically controllable; Thermostatically controllable.
[49]	2	Thermostatically controllable; Storage-based.
[50]	3	Type I: interruptible and deferrable; Type II: non-interruptible and deferrable; Type III: non-interruptible and non-deferrable.
[45]	3	Activity-dependent short-term; Activity-dependent long-term shiftable; Activity-independent long-term non-shiftable.
[43]	3	Deferrable; Thermostatically Controlled; Non-controllable.
[51]	3	Non-controlled; Switching controlled high loads; Thermostatically controlled high loads.
[42]	3	Non-controllable; Deferrable; Thermostatically-controlled.
[52]	3	Interruptible; Deferrable; Critical.
[53]	4	Controllable shiftable non-interruptible; Controllable shiftable interruptible; Controllable reducible; Uncontrollable.
[41]	5	Non-flexible deferrable; Flexible deferrable; Thermal; Curtailable; Critical.

constraints, with indications on solution methods.

Developing automated DR mechanisms requires adequate monitoring and control [11]. In the energy consumption scheduling algorithm [47], each user optimises its objective function based on the daily peak-to-average power ratio. DR management for residential appliances is formulated as a stochastic optimisation model in Ref. [50] to handle uncertainties in real-time electricity prices, applying a two-stage scenario-based method. In Ref. [52], the random variables involved in the scheduling (i.e., electricity price, renewable generation, outdoor temperature, occupancy status, deferrable load characteristics, and the actions) are handled using a Markov decision process. In Ref. [48], to preserve diversity in network consumption and avoid high power peaks during periods of lowest electricity price, hard and soft peak-power-limited DR strategies are exploited. Other indications on optimisation techniques can be found in Ref. [56].

The appliance scheduling presented in Ref. [41] includes both market price signals and penalties for power limit violations. The consumer’s satisfaction level is defined as “the percentage volume of the daily energy curtailment relative to the potential energy consumption of the curtailable appliances”. Approaches based on Quality of Experience (QoE) are also adopted. QoE-driven usage profiles are used to schedule each appliance according to expected user behaviour, aiming to minimise electricity costs [51]: an algorithm shifts the operating cycles of controlled appliances during off-peak times, while another algorithm handles the presence of renewable energy production. Other cases address grid service provision considering DR strategies (e.g., peak load shaving) [57].

Although diverse optimisation models have been proposed in the literature, there is no consensus that one methodology consistently outperforms the others across all residential applications. MILP remains the dominant approach because of its deterministic formulation and computational efficiency. In contrast, the Markov decision process, which requires reinforcement learning, offers greater adaptability under uncertain operating conditions, but such techniques require extensive training data. Stochastic optimisation provides improved robustness against uncertainty, but it imposes higher computational complexity. Therefore, the choice of the optimisation technique depends more on problem characteristics than on algorithmic superiority.

Among the reviewed studies, deferrable appliances with fixed operating cycles are the most frequently represented category for scheduling. Thermostatically controllable appliances and storage-based devices provide wider modulation options, subject to comfort and operating constraints [40,49]. Deterministic mixed-integer formulations with explicit appliance and comfort constraints are the most established control approach in the reviewed set [41,48]. Stochastic and learning-based control can better represent uncertainty, but require broader field validation [50,58].

3.2. Flexibility-related aspects

The existing literature highlights different definitions and valuations of flexibility that the residential sector can provide. Engineering-oriented studies quantify flexibility through technical metrics such as load-shifting capability. In contrast, market-oriented studies highlight the economic value and the remuneration mechanisms and incentives necessary to procure flexibility from households. This fragmentation highlights the need for standardised flexibility metrics that simultaneously address technical feasibility, economic value, and consumer acceptance.

3.2.1. Flexibility and controllability of the appliances

Postponable or deferrable appliances exhibit turn-on flexibility with shiftable cycles [40,45,48,51–53,59,60]. Buffered appliances (e.g., hot water buffers) can rely on turn-off flexibility [40,51]. Thermostat-controlled appliances, such as HVAC systems and water heaters, can be controlled by temperature settings [48,51] or by

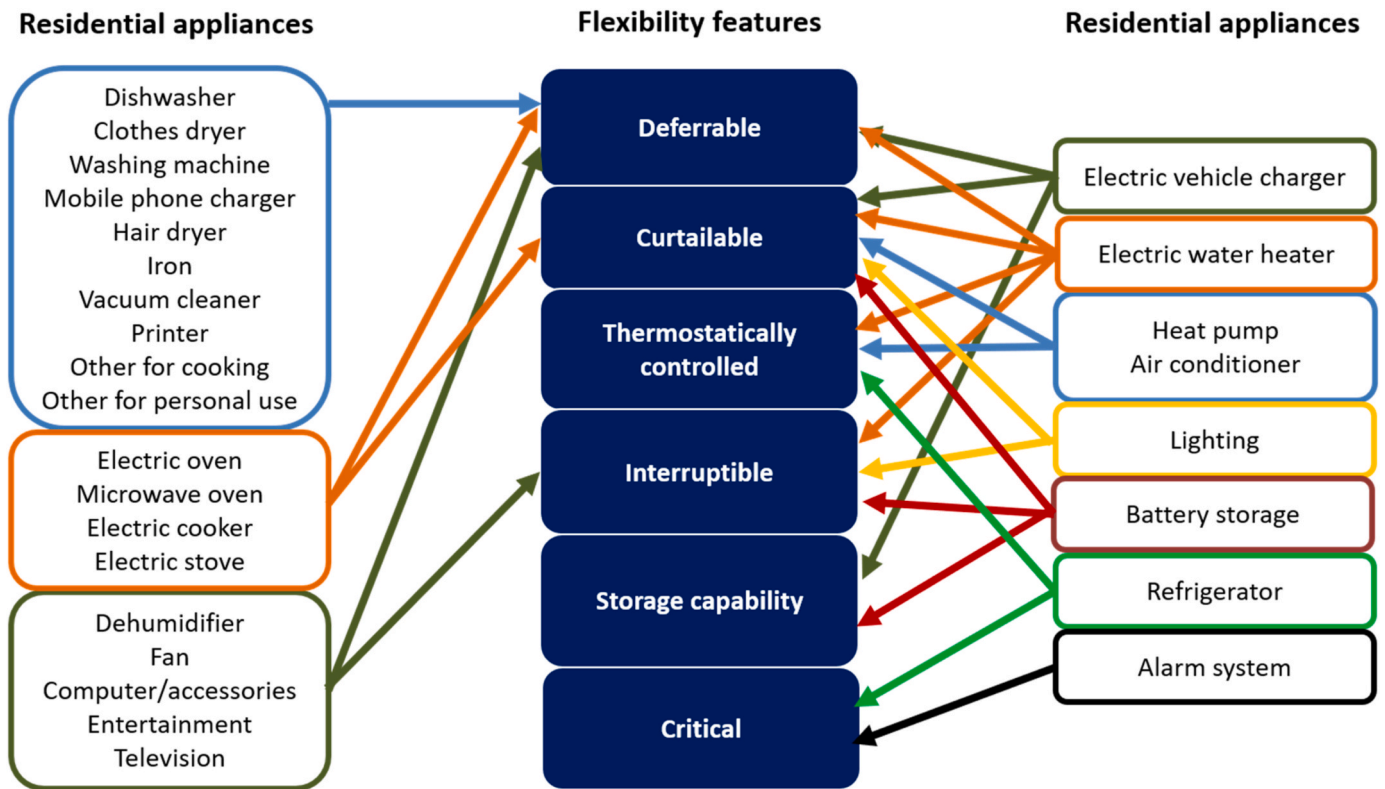


Fig. 4. Relations between household appliances and their flexibility features.

reducing their absorbed power, considering them curtailable in amplitude [52,53] without significantly affecting the users' discomfort.

Mathematical models and robust optimisation, accounting for time constraints and control logics based on physical variables, are available for each kind of controllable appliance [43,50]. Statistical approaches can apply maximum likelihood estimation techniques to forecast usage patterns using historical data [61]. Considering individual devices, appliances are classified based on delay tolerance, and probabilistic sensitivity functions are used to describe each device's likelihood of deferring its usage [44]. Behaviour-aware predictive energy management system (EMS) models based on user activity recognition [45] aim at optimising appliance operation while maintaining user comfort and meeting grid constraints. The probability that a given appliance is "on" or "off" for a duration longer than a given amount of time [62] is used to build a conditional probability model for "off"-"on" transitions (and vice versa) by considering the duration for which the appliances were in the different state at the previous time step. The flexibility potential is evaluated in Ref. [49] by comparing normal and flexible appliance operation.

Table 7 shows a set of indicators that quantify load shifting and flexibility. The table presents the input data, the indicator definition with the corresponding equation, and some notes. Each indicator captures a specific aspect of flexibility, energy use, or user experience. Common notation has been applied to represent users (households) $u = 1, \dots, U$, appliances $a = 1, \dots, A$, and hours $h = 1, \dots, H$. The other terms and variables are specifically indicated in the table.

3.2.2. Flexibility analysis from the distribution system operator (DSO) side

From the Distribution System Operator (DSO) viewpoint, flexibility analysis assesses the temporal and locational availability of flexible resources to enhance operation and economics of distribution networks. The objective is to integrate flexibility into distribution grid planning, real-time operations, and market-based coordination mechanisms. The flexibility offered by residential appliances can be leveraged by DSOs for

voltage control [40], preventing transformer overloading and/or extending transformer lifetime [40,41], optimising grid stability [49], and alleviating grid congestion [59]. DR can help DSOs shift peak demand, reduce the load during high-demand periods, or create new peaks during low-price intervals [41]. Local flexibility markets are introduced to provide a framework where demand-side flexibility supports grid stability [57].

3.2.3. Flexibility analysis from the end-user side

The end-user's perspective emphasises the impact of user behaviour, comfort, and preferences in demand-side management. Users can adjust appliance deployment and energy consumption patterns in response to flexibility signals, enabling cost optimisation and energy savings [49], or in response to time-based pricing (e.g., Time-of-Use tariffs or Real-Time Pricing) [50]. Users' behaviour can be integrated into flexibility analysis by modelling appliance usage patterns and habits, and by measuring how user preferences (e.g., preferred operating times, shiftable times, and temperature settings) affect appliance controllability [42,50,51,59,61]. An intrusive load monitoring system that accounts for uncertainty and user behaviour is presented in Ref. [42]. Users are actively involved in shifting appliance usage according to grid flexibility demands [59]. Considering the collective trend of demand variation, the time-dependent flexibility index of aggregate demand identifies the periods of the day (e.g., the morning load ramp) in which the aggregate response of the users is less likely to change because of common habits, making it challenging to induce variations in the users' behaviour in those periods [63].

3.3. User engagement

User engagement is a fundamental prerequisite for the successful implementation of smart energy systems, as the effectiveness of demand-side management strategies relies on the active participation of end-users. Programs such as demand response, dynamic electricity

Table 6
Methods for appliance controllability.

Ref.	Category of optimisation problem	Objective function	Constraints	Solution method
[47]	Linear optimisation	Peak-to-Average Ratio	Energy consumption of each appliance	Simplex method or interior point method combined with a game-theory approach
[47]	Convex optimisation	Energy cost	Energy consumption of each appliance	Interior point method combined with a game-theory approach
[50]	Stochastic optimisation	Electricity bill	Operation of each appliance (common constraints and specific constraints according to the appliance's tasks)	Robust optimisation
[41]	Mixed integer non-linear optimisation	Daily electricity bill	Consumer's satisfaction level; specific constraints according to the appliance's type	Advanced integrated multidimensional modelling software
[48]	Mixed integer non-linear optimisation	Daily operation cost	Specific constraints according to the appliance's type, the operation of energy storage systems and distributed generation	CPLEX 12 (GAMS)
[53]	Mixed integer non-linear optimisation	Electricity bill plus consumer's discomfort cost	Specific constraints according to the appliance's type of operation with an energy storage system and photovoltaic	Mixed integer linear programming
[43]	Lyapunov optimisation	Average of the second moment of the total power consumption	Constraints on queues	Dedicated algorithm
[52]	Markov decision process	Expected total cost in terms of thermal discomfort cost, non-completion penalty and electricity cost	Specific models for each appliance's type	Soft actor-critic deep reinforcement learning algorithm

pricing, and flexible appliance scheduling can significantly improve grid reliability, facilitate the integration of renewable energy sources, and reduce peak demand. However, these benefits can only be achieved if users are willing to modify their energy consumption patterns. Such willingness is influenced by several factors, including expected economic incentives, preservation of comfort, ease of participation, degree of automation, trust in the energy management system, and concerns related to privacy and data security [64]. Therefore, user-centric approaches that minimise inconvenience while providing transparent and tangible benefits are essential to ensure long-term participation and maximise the effectiveness of smart grid services.

3.3.1. Behaviour and active role of end-users

User engagement is essential for optimising the use of household appliances while maintaining comfort and improving grid operation. Users' feedback, also through surveys [65], reflects their preferences and behaviours in appliance usage [42]. Feedback can be classified along six aspects [66], including transmission (with online digital and offline printed formats), frequency (how often data are recorded and reported, from millisecond-level to daily, weekly, or monthly reports), access (how users reach feedback), information content (what ultimately reaches the user), presentation (how the information is displayed), and engagement (to which extent users perceive the feedback as valuable). Feedback can be further refined by adding disaggregated information, providing additional benefits despite increased complexity and cost [67]. Disaggregation for a limited number of appliances has been widely examined [68,69]. Some researchers highlight the usefulness of disaggregated feedback at the room level [70,71].

Feedback is classified in Ref. [72] into direct and indirect. Direct feedback provides real-time information on energy usage, typically through fixed or mobile in-home displays. Indirect feedback provides energy consumption information (e.g., monthly bills). How consumers perceive energy feedback is often analysed to achieve financial rather than environmental benefits [73]. Effective feedback provides clear information, enabling individuals to monitor, manage, and optimise their energy use [74]. Practical implementation of feedback relies on hardware embedded in devices [75]. Advanced metering infrastructures (smart meters, home area networks, software interfaces, and data management applications) support two-way communication, enabling the provision of both direct and indirect feedback.

Feedback can be explicit (e.g., via app settings) or implicit (e.g., via usage data, appliance classification, and inventory information). Usage apps require appliances equipped with hardware for measurements (sensors), communication (transmitters), and visualisation (displays). Table 8 summarises the different feedback approaches together with the type of behavioural flexibility required from users to enable the corresponding energy service. Most of the literature focuses on implicit approaches. Explicit approaches widely adopt advanced metering infrastructures, typically with limited contribution compared with other solutions (e.g., augmented reality technologies or web-based interface devices).

It has to be noted that household participation in flexibility services is inherently heterogeneous and cannot be assumed to be uniform across the residential sector. The existing literature highlights that participation is shaped by a combination of socioeconomic, demographic, and technological factors [91]. These factors include household income, family age composition, digital literacy, housing type and size, ownership of flexible appliances and distributed energy resources. Other relevant aspects include internet connectivity, trust in energy service providers, and data-sharing arrangements. These factors influence both households' willingness and ability to engage in flexibility programs. They should therefore be considered when assessing the potential uptake and effectiveness of residential demand-side flexibility initiatives. Consequently, the design of flexibility schemes should account for this heterogeneity to avoid unequal access and to maximise participation across different household groups.

It is also important to distinguish between the technical flexibility potential of residential appliances and the flexibility that can be effectively realised in practice. Although many household devices are technically capable of shifting or modulating their electricity consumption, their actual contribution to demand-side flexibility depends on users' willingness to participate. Behavioural factors, perceived comfort, financial incentives, trust in service providers, and the degree of automation all influence whether technically available flexibility is ultimately made accessible to the power system [92]. Therefore, estimates of residential flexibility should account not only for technical constraints but also for consumer acceptance and engagement.

Table 7
Load shifting-related indicators.

Ref.	Input data	Indicator	Equation	Notes
[42], [47], [61]	Energy W_{uah} used by all users and appliances in $h = 1, \dots, H$ hours	Peak to Average Ratio	$PAR = \frac{W_{peak}}{W_{avg}} = \frac{H \max_{h \in H} \sum_{u \in U} \sum_{a \in A_u} W_{uah}}{\sum_{h=1}^H \sum_{u \in U} \sum_{a \in A_u} W_{uah}}$	Set A_u of the appliances available in the household u . Total energy W_{uah} used by household u at hour h . Sum W_h of all users' consumption at hour h
[42], [61]	Probability distribution $f(t_{uah}^{(on)})$ of the turn-on time of the appliance $t_{uah}^{(on)}$ with mutually exclusive appliance operational states $k = 1, \dots, K_{uah}$	Turn-on controllability	$C_{uah}^{(on)} = - \sum_{k=1}^{K_{uah}} f(t_{uah}^{(on)}) \log_2(f(t_{uah}^{(on)}))$	Entropy calculated by considering the probability distribution $f(t_{uah}^{(on)})$
[42]	Probability distribution $f(t_{uah}^{(off)})$ of the turn-off time of the appliance $t_{uah}^{(off)}$ with mutually exclusive appliance operational states $k = 1, \dots, K_{uah}$	Turn-off controllability	$C_{uah}^{(off)} = - \sum_{k=1}^{K_{uah}} f(t_{uah}^{(off)}) \log_2(f(t_{uah}^{(off)}))$	Entropy calculated by considering the probability distribution $f(t_{uah}^{(off)})$
[42], [49]	Nominal power $\bar{P}_{ua}^{(nom)}$ of the appliances Power pattern in normal conditions Deviations from the normal conditions in the controlled mode	Ratio of appliance flexibility	$Flex_{uah}^{(\%) } = 100 \frac{Flex_{uah}}{\bar{P}_{ua}^{(nom)}}$	The percentage referring to $\bar{P}_{ua}^{(n)}$ of the deviation $Flex_{uah}$ from its normal operation when providing upward or downward flexibility.
[40]	Reference power pattern $P_h^{(ref)}$ Actual pattern P_h of the group of appliances for $h = 1, \dots, H$ Power $P_h(\Delta t)$ with variation in the duration Δt of the flexibility window	Flexibility potential [kW] (for power increase or decrease)	$P_h^{(inc)}(\Delta t) = P_h(\Delta t) - P_h^{(ref)}$ $P_h^{(dec)}(\Delta t) = P_h^{(ref)} - P_h(\Delta t)$	The power increase $P_h^{(inc)}$ or decrease $P_h^{(dec)}$ that can be realised at hour h , considering for what flexibility window Δt the power variation can be sustained
[51]	Vector $\mathbf{s}^{(t)} = \{\Delta t_1, \dots, \Delta t_N\}$ of shift times and vector $\mathbf{s}^{(a,\theta)} = \{\Delta \theta_1, \dots, \Delta \theta_N\}$ of shift temperatures for appliance a , with N values. Surveyed subjects $b = 1, \dots, B$ to give information on annoyance	Relative satisfaction level	$\sigma(\Delta \theta) = \frac{q^{\max} - \hat{q}_a(\Delta \theta)}{q^{\max} - q^{\min}}$	Annoyance factor vector $\mathbf{q}_{ab}(\Delta \theta)$ with N values, mapped into integers from $q^{\min} = 1$ to $q^{\max} = 5$, with value chosen by the subject b . Then, $\hat{q}_a(\Delta \theta)$ is the most chosen annoyance factor by the subjects for $\Delta \theta$
[41]	Set C_u of curtailable appliances for user u with rated power $\bar{P}_{uc}^{(nom)}$ for $c \in C_u$. Power p_{uch} of curtailable appliances at hour h . Priority Γ_{uc} to disconnect the curtailable appliances. Preferred periods of operation of curtailable appliances (binary parameter σ_{uch})	Satisfaction level	$S = 1 - \frac{\sum_{h=1}^H \sum_{u \in U} \sum_{c \in C_u} \rho^{\Gamma_{uc}} (\bar{P}_{uc}^{(nom)} \sigma_{uch} - p_{uch})}{\sum_{h=1}^H \sum_{u \in U} \sum_{c \in C_u} \rho^{\Gamma_{uc}} (\bar{P}_{uc}^{(nom)} \sigma_{uch})}$	Large constant ρ (ratio of the largest and the smallest rated power of curtailable appliances) to curtail first the smallest priority appliances

3.3.2. Demand-side strategies

Usage data can be collected using non-intrusive load monitoring systems, without installing sensors [93,94]. A controller for building energy management can integrate user feedback into its objective function through an adaptive thermal-comfort model [86]. Users who actively annotate and manage their energy data are encouraged to adopt environmentally and economically beneficial practices [95]. End-users can accept or reject energy-saving suggestions or time-shifting proposals based on personal preferences [60,61]. User-specific profiles can also be dynamically refined based on feedback from annoyance ratings after significant events [51].

End-user flexibility preferences are incorporated into optimisation frameworks mostly with cost minimisation and comfort maximisation objectives. The optimal solution is searched for through load shifting [78], management of interruptible and deferrable loads [50] or explicitly incorporating criticalities associated with particular loads [41]. User satisfaction is integrated by quantifying the user's temporal convenience during appliance operation [77] or by leveraging historical energy-consumption patterns to shift appliance operating times strategically [89]. Household appliance models can be integrated in optimisation procedures within home energy management systems (HEMS) together with battery energy storage and EVs [58], as well as thermostat-controllable appliances to exploit user flexibility for frequency regulation services [49] and photovoltaic systems [83] in a data-driven model to minimise electricity cost, including loading constraints of the distribution transformer.

With residential HVAC, user comfort is an objective in a data-driven control strategy for DR [81] or as a constraint in daily electricity consumption optimisation [76]. Real-time adjustments of flexible loads, while ensuring user satisfaction, appear in optimal appliance scheduling to minimise daily energy costs [87] or in an optimisation based on a Markov decision process that continuously adapts the energy demand considering supply patterns and consumer behaviour [88]. An aggregator model can be adopted to shift home appliance operation to provide

flexible services to the distribution network, alleviating congestion and balancing loads [59].

3.3.3. Integration of User's behaviour and preferences

Integrating consumer behaviour into control mechanisms is challenging due to the non-linear and uncertain nature of human behaviour. Specialised behaviour-modelling approaches need to incorporate end-users into the system's feedback loop and support user-centric control strategies. This, in turn, depends on accurately modelling users and detecting behaviour from real-time consumption data. Clustering algorithms can group users based on different consumption behaviours [96] and can then be integrated with forecasting techniques to predict future consumption patterns. Hidden Markov models can model the dynamic processes involved in managing household appliances, comparing grid signals and user convenience constraints [45]. The stochastic dynamics of the load can be captured using a conditional hidden semi-Markov model that accounts for temperature and seasonal effects [79]. In data-driven approaches, human behaviour can be represented in a training dataset based on the results of a voluntary questionnaire [51] or as a random variable to capture its inherent variability for model training [83].

Psychology-based models can be developed to describe the dynamics of users' motivation and energy-related behaviour [84]. Learning processes can be established to understand residents' appliance usage behaviour better, using deep neural networks and supervised learning to predict energy consumption [82] or applying deep reinforcement learning to account for uncertainty in user behaviour [88]. The system thermodynamic state and charging level of EVs can be estimated using a deep constrained Q-learning algorithm with a multilayer perceptron [87]. The users' willingness to participate in DR can be represented within a Stackelberg game-based energy management framework [90].

Price sensitivity can be incorporated in demand-side management applications. HEMS can use a static user characterisation based on price sensitivity and on-site generation presence [78]. A consumer-centric

Table 8

Features related to feedback and required behavioural flexibility.

Reference	Feedback	Required user behavioural flexibility
Chen et al. (2012) [50]	smart meter	deferral and interruption
Ali et al. (2014) [76]	smart thermostat	adjustment
Collotta et al. (2015) [60]	management unit and smart meter	shifting
Althaher et al. (2015) [41]	appliance classification	deferral and curtailment
Jovanovic et al. (2016) [77]	appliance classification	deferral
Javaid et al. (2017) [78]	advanced metering infrastructure	shifting
Pilloni et al. (2018) [51]	usage data	deferral and temperature setting
Ahmed et al. (2018) [45]	smart meter, appliance inventory	shifting
Hong et al. (2020) [61]	augmented reality technology	threshold setting
Ji et al. (2020) [79]	usage data	adjusting
Heylen et al. (2020) [80]	usage data	shifting and curtailment
Kou et al. (2021) [81]	distributed system architecture	shifting
Khajeh et al. (2022) [49]	appliance classification	adjusting
Dinh et al. (2022) [82]	usage data	adjusting
Amer et al. (2023) [83]	appliance classification	shifting and adjusting
Feng et al. (2023) [84]	smart home controllers and apps	adjusting
Aguar et al. (2023) [85]	usage data	energy price setting
Kaisermayer et al. (2024) [86]	web-based interfaced devices	shifting
Premkumar et al. (2024) [59]	registration of flexible devices	shifting and adjustment
Saberi et al. (2024) [87]	measurements and user settings	adjustment, interruption and deferral
Aldahmashi et al. (2024) [88]	smart meter	adjustment, deferral, interruption
Zhang et al. (2024) [58]	appliance classification, usage data	adjustment, deferral, interruption
Saroha et al. (2025) [89]	usage data	shifting, adjustment
Teng et al. (2025) [90]	usage data	adjustment

strategy can account for users' sensitivity to electricity bill volatility within a multi-layer human-cyber-physical system framework [85]. The economics considered could incorporate marginal interruption costs of residential users as preference indicators when optimising an aggregator's flexible-load portfolio [80].

Table 9 summarises some significant methods that explicitly model human behaviour within optimisation objective functions. These approaches include passive characterisation of user profiles, assumptions based on random variables, and forecasting methods. In contrast, more engaging applications rely on active user participation and employ techniques such as hidden Markov models, dynamic and future-agnostic methods, and psychology-based approaches.

3.3.4. Users' comfort

User-defined thresholds or constraints can be integrated into optimisation models to balance energy efficiency and DR actions with comfort, making end-user engagement more attractive. Different variables are considered to establish satisfactory ranges and corresponding thresholds. The main variable is indoor temperature, with lower/upper bounds. Indoor temperature adjustments using air conditioners directly affect occupants' comfort, while exploiting the infrastructure's thermal inertia to mitigate temperature variations [97]. The predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) [98] are traditionally used [99]. The startup delay time between the preferred time-of-use period and the actual running time for time-shiftable loads includes

Table 9

Objectives and human behaviour modelling in the literature.

Ref.	Other objective	Human behaviour model
Jovanovic et al. (2016) [77]	user satisfaction	-
Javaid et al. (2017) [78]	-	profile characterisation
Pilloni et al. (2018) [51]	-	profile characterisation
Ahmed et al. (2018) [45]	-	hidden Markov
Ji et al. (2020) [79]	-	hidden semi-Markov
Heylen et al. (2020) [80]	inconvenience cost	dynamic and future-agnostic model
Kou et al. (2021) [81]	user comfort	-
Khajeh et al. (2022) [49]	frequency regulation service	-
Dinh et al. (2022) [82]	-	deep neural networks & supervised learning
Amer et al. (2023) [83]	user comfort, transformer loading	random variable assumption
Feng et al. (2023) [84]	social welfare	psychology-based dynamics
Aguar et al. (2023) [85]	-	mean-variance trade-offs
Kaisermayer et al. (2024) [86]	user comfort, undesirable behaviour	-
Premkumar et al. (2024) [59]	network balancing support	-
Saberi et al. (2024) [87]	-	deep constrained Q-learning
Aldahmashi et al. (2024) [88]	augments the power factor	deep reinforcement learning
Zhang et al. (2024) [58]	user dissatisfaction and comfort	-
Teng et al. (2025) [90]	-	adaptive load-type conversion

permissible ranges for various types of loads [100]. The power level should remain within satisfactory values to avoid insufficient cooling or heating [101].

The reference temperature for appliances with thermostatic control [49] is constrained by the maximum and minimum temperatures set up by the control system, also considering the occupancy status [52]. The average temperature is also considered inside electric water heater tanks [102] or heat-pump water heaters [103]. The state of charge of a hot water buffer is defined as the ratio of the energy content of the water in the buffer corresponding to the minimum acceptable temperature for comfort to the reference energy content of the hot water buffer at full charge [40]. Other variables include the lighting effect, with minimum lighting power to guarantee acceptable brightness for visual comfort [104]. The charging time of EVs depends on the state of charge. It is evaluated by considering the remaining charging time (time anxiety) and the expected driving range that requires a minimum state of charge (or state of energy) before starting (range anxiety) [83,101]. Comfort is also indicated by the difference between the desired and actual power consumption of the entertainment system [105].

Comfort thresholds are set for single appliances or categorised groups of appliances [106]. Control actions can be limited when thresholds are exceeded, or extra costs can be assigned if the relevant variable falls outside the acceptable comfort range, introducing specific cost coefficients [100]. Appliances with variable usage time can also be categorised according to the level of conflict with occupants' comfort levels [61]. HEMS aim to balance energy saving and comfort while accounting for the associated costs [107]. Multi-objective optimisation can be set up to minimise multiple objectives, such as electricity costs, waiting time, peak-to-average power ratio, battery degradation, and various types of user discomfort [104]. If HEMS integrates photovoltaic systems, batteries, and DR, aspects such as self-consumption and self-sufficiency are considered [108], along with solar power

uncertainty [109] and penalties for users' discomfort.

Users' discomfort also depends on the occurrence of interruptions [104] or emergency operating conditions, where the service restoration process includes priorities based on users' comfort levels [105]. Further approaches define a satisfaction factor as the percentage of energy curtailment from curtailable appliances, accounting for appliance priority-based curtailment [41], or considering comfort constraints such as the maximum waiting time for a request in a virtual queue [43].

Clear and timely feedback is the engagement mechanism most consistently supported by the reviewed studies [66,73]. User-defined comfort limits are also recurrent in appliance-control formulations [41,49]. Conversational interfaces are promising because they can reduce the effort required to access energy information, but evidence on sustained participation remains limited [74]. The available evidence is also less conclusive for users with low digital or energy literacy and across different social and cultural settings.

3.4. Management by aggregators

Aggregators have emerged as strategic entities in the digitalised energy ecosystem, acting as management hubs that coordinate, optimise, and monetise distributed flexibility across thousands of small consumers and prosumers. By interacting with DSOs, Transmission System Operators (TSOs), and energy retailers, they transform local flexibility into system services such as peak shaving, load balancing, and frequency regulation, ensuring distributed resources participate in both local and wholesale markets while preserving end-user comfort and data privacy [110]. Using digital platforms and optimisation algorithms, they manage physical coordination of controllable appliances and oversee the data, economic, and contractual layers of flexibility markets, providing financial incentives and feedback to sustain user engagement. The Demand Response Aggregator coordinates household appliances and delivers demand-side services to DSOs [59,111]. At a broader scale, aggregators are indispensable for enabling smart homes and small prosumers to contribute to system-level flexibility, transforming fragmented household flexibility into a structured, tradable product for both technical coordination and market integration.

The following subsections examine the aggregator roles and the business models adopted by aggregators, their operational strategies, the ever-evolving rules of the flexibility markets in which they operate, and regulatory frameworks governing their roles and functions.

3.4.1. Aggregator roles & business models

Aggregators recruit households and businesses into DR programs and commercialise aggregated flexibility as tradable services. Typically, third-party aggregators negotiate with utilities or system operators to sell aggregated demand reductions, retaining part of the incentives while redistributing the remaining value to participants, ensuring tangible benefits [112]. By operating across diverse consumers, aggregators exploit the portfolio effect, balancing flexibility shortfalls at some site with additional flexibility at others. This improves predictability, reliability, and market value of distributed demand-side resources, making aggregators key intermediaries between household-level technical control and system-level economic optimisation [113]. At the operational level, the aggregator may send market price signals to users. In a decentralised control model, the users independently define their own resource scheduling strategies and submit them to the aggregator. Conversely, through distributed control based on the operational function of load aggregators, users' flexibility capacity is aggregated and presented to the flexibility markets. At the end of the market session, the results are communicated to the aggregators, who issue control commands based on the data received. The aggregator forwards the control commands directly to the home control terminal via the cloud service. The home control terminal manages the appliances based on this request [114,115].

Aggregators play a crucial role when individual flexible loads are too

small to satisfy market participation thresholds [49]. By pooling numerous low-capacity resources, they can satisfy minimum capacity requirements and provide MW-scale flexibility suitable for TSO balancing markets [116]. At the TSO level, minimum bid sizes, and pre-qualification push residential portfolios toward formal aggregation. Studies have confirmed that smart homes can technically offer both local (distribution-level) and system-level services, but in practice harnessing this potential requires coordination through an aggregator that can aggregate many small contributions into a significant total. Indeed, at the transmission system level, aggregators are indispensable for assembling enough capacity from residential prosumers to participate effectively [49]. Moreover, aggregators can operate under business models designed for flexibility markets across various time scales: they can participate in day-ahead or intraday markets or operate in real time in power reserve markets for balancing or in congestion management service [116,117].

Different business models have emerged for aggregators, shaping their interactions with consumers and the energy system. Independent aggregators operate as third-party flexibility providers, aggregating loads across customers independently of electricity suppliers, whereas supplier-aggregators integrate DR services within retail energy offerings. Some community-based aggregators act on behalf of local energy cooperatives or municipalities [116,118,119], prioritising local benefits and trust-building. These models differ in terms of data management, revenue allocation, and customer relationships, directly affecting participation rates. Across all models, transparent incentive structures and clear data-sharing practices are critical for consumer engagement, as trust and perceived fairness strongly influence enrolment and responsiveness [120,121].

Aggregators' business operations must ensure that value is appropriately distributed to maintain participant engagement, with aggregators typically retaining only a limited share of revenues while transferring the majority to consumers. Additional engagement mechanisms, such as bill credits, loyalty points, and prize draws, are often implemented to improve retention and participation. As portfolios grow, aggregators must coordinate with DSOs to avoid any local issues when many devices respond together. In practice, leading aggregators are now engaging in local flexibility markets and working with DSOs so that their control actions help the grid at all levels [122,123]. This may involve stacking services – providing flexibility to both transmission and distribution – and requires decisions to allocate portfolio capacity to the most beneficial uses while respecting network constraints [124]. Fair allocation of rewards and transparent measurement and verification (M&V)/baseline methods underpin durable participation.

3.4.2. Operational strategies for flexibility management

To manage distributed flexibility in real time, aggregators employ advanced ICT platforms and control algorithms integrating smart meter data, device telemetry, and market or grid signals [122]. Artificial Intelligence (AI) and advanced optimisation techniques are increasingly adopted to support flexibility management while respecting operational and user-defined constraints. Their effectiveness depends on the quality of available data, model transparency, computational requirements, and user acceptance. Recent studies demonstrate that advanced optimisation methods – from bi-level models to reinforcement learning – can maximise an aggregator's demand reduction while minimising costs and discomfort [59,111,122,125]. This highlights that aggregators are active managers of flexible demand, continually balancing grid signals with customer comfort.

Trust is reinforced by ensuring user autonomy through comfort customisation and opt-out options, while also providing tangible and transparent benefits that enhance long-term engagement. Strong cybersecurity, privacy protection, interoperability, and open standards are essential to maintain trust, prevent vendor lock-in, and ensure consumer control through explicit, revocable participation. Real-world trials have shown that when these factors align – clear incentives,

minimal impact on comfort, and trust in the provider – consumers respond enthusiastically. National Grid ESO's DFS mobilised 1.6 million customers across 22 events during winter operations, reducing demand by more than 3300 MWh; this was underpinned by clear rules on eligibility, data handling and settlement [126].

Real-world aggregators also invest in forecasting methods to estimate available flexibility and in verification systems to measure the actual response from devices during an event [127].

3.4.3. Market framework

The development of practical solutions to make digitalisation effective highly depends on an appropriate market framework. Baseline errors or opaque clawbacks may erode trust, while predictable settlement rules stabilise response [128]. Key examples are:

- *Minimum bid sizes, pre-qualification and baseline:* Since residential devices rarely meet TSO minimum sizes individually, aggregation is essential [49,129]. Pre-qualification often requires ramping, telemetry and baseline accuracy tests. Poor baselines increase imbalance risk and reduce market trust. Where DSOs procure services season-ahead and closer to real time, aggregators segment portfolios according to deferrable/curtailable characteristics and comfort windows, matching them to products with specific notice periods and response requirements. UKPN results demonstrate investment deferral and multi-GWh dispatch volumes from distributed assets—evidence that granular local markets can absorb residential flexibility at scale when product and settlement rules are predictable [130].
- *Interoperability and industrial practice:* Successful aggregation requires robust, secure and interoperable data paths between devices, HEMS and aggregator platforms. Industrial practices outline operational technology/information technology integration and secure communications stacks underpinning reliable telemetry and control while avoiding proprietary lock-in Ref. [131].
- *Multi-timescale operation:* Distribution-level frameworks (e.g., UK Power Networks' Secure/Dynamic services and dispatch rules) show how multi-timescale procurement and clear event windows align aggregator optimisation with local constraints [122,132–134].
- *TSO–DSO interface and local flexibility:* DSOs such as UK Power Networks define procurement windows, lead times, dispatch frameworks, and verification procedures through transparent service definitions and open data portals [135,136]. These requirements directly shape aggregator optimisation strategies, influencing bidding windows, device pre-activation, telemetry, and M&V settings; transparency regarding control strategies, event duration and frequency, comfort impacts, and financial compensation is essential. Programs such as the UK's Demand Flexibility Service (DFS) have established strict participation criteria ensuring consumer protection and data privacy.

Most of the existing studies consistently recognise the importance of aggregators as essential intermediaries between the residential sector and energy markets. However, preferred market design and governance structures may differ from aggregators' perspective. Independent aggregators seek market competition, whereas supplier-integrated aggregators prefer to simplify customer participation. Moreover, successful aggregation depends not only on optimisation algorithms but also on transparent regulation, standardised communication protocols, and consumer trust.

Independent aggregation has the clearest regulatory basis in the reviewed jurisdictions [137–140]. Supplier-integrated aggregation provides a direct contractual interface with customers and can combine electricity supply and flexibility services within a single offer [116]. Community-based aggregation is promising for retaining value locally and building on existing social relations, but remains less extensively validated in the reviewed evidence. Peer-to-peer exchange should be

interpreted as a market and settlement arrangement rather than as an aggregator model.

3.4.4. Regulatory context

Regulators in various jurisdictions have recognised the role of aggregation in integrating distributed flexibility.

In the United States, FERC Order No. 2222 enables DER aggregators to participate in wholesale energy, capacity, and ancillary service markets, removing barriers for aggregations of DERs to participate in organised wholesale markets, requiring Regional Transmission Organizations or Independent System Operators to implement participation models covering telemetry, metering, and coordination with distribution utilities [137].

In Europe, Directive (EU) 2019/944 mandates fair conditions for independent aggregators, enabling DR participation across energy, capacity, and ancillary markets while requiring transparent frameworks to ensure their market participation and customer benefits [138]. The 2024 Electricity Market Design reforms introduced national flexibility-needs assessments, helping harmonise product calendars and settlement rules [141]. In this framework, EU governance is converging on common assessment and settlement principles through the DR Network Code and national methodologies that address flexibility needs, thereby shaping aggregator portfolio design [141]. The Network Code on DR, submitted by ENTSO-E and the EU DSO Entity, clarifies aggregation rules, pre-qualification and data exchange across voltage levels, ensuring consistent access while avoiding national-local dispatch conflicts [128].

In Great Britain, Ofgem's approval of the BSC P415 reforms enabled independent aggregators to trade in the wholesale market on the same footing as suppliers from 7 November 2024 [139,140]. These measures expand monetisation channels and shift aggregator portfolios from single-program DR to service-stacking across wholesale, ancillary, and local services.

The examples shown, drawn from the EU, UK, and US, are illustrative rather than exhaustive, and similar regulatory approaches may work differently in other jurisdictions.

3.5. Relations with energy communities

Household appliances play a pivotal role in enabling effective uptake of digital services by energy communities [142]. Through digital connectivity and smart control capabilities, household appliances provide the physical flexibility that energy communities need to participate in digital energy services. When equipped with sensors, communication interfaces, and controllable settings, these appliances can respond to price signals, grid constraints, or community-level optimisation strategies. This enables DR, maximising self-consumption, and local balancing of renewable generation, which are essential services offered by energy communities to both their members and the wider grid [143].

Digital services enabled by household appliances allow energy communities to engage in peer-to-peer energy sharing, collective self-consumption, and flexibility markets. By linking individual household behaviour with community-level optimisation and system-wide objectives, they support a shift toward more participatory, flexible, and citizen-centred energy systems [144]. Their effective integration is essential to realising the full potential of energy communities as active actors in a digitalised, decarbonised energy future [145]. Moreover, energy communities can adapt electricity consumption and production in response to grid conditions, price signals, and renewable generation variability, thereby supporting system balance and local grid stability [146]. AI significantly enhances energy communities' ability to deliver flexibility effectively and reliably. AI-based forecasting methods improve predictions of electricity demand, renewable generation, and user behaviour, reducing uncertainty and enabling more accurate planning of flexibility actions [147]. AI-driven optimisation and control tools coordinate the operation of numerous small-scale assets in real time, ensuring that flexibility is activated where and when it is most

valuable, while respecting technical constraints and user comfort preferences.

Beyond technical optimisation, AI contributes to scalability and user engagement within energy communities. Automated control reduces the need for continuous manual intervention, making participation easier for community members. AI-based feedback and personalised recommendations can increase transparency and trust, encouraging sustained participation in flexibility schemes [148]. However, automation-driven approaches frequently overlook the diverse cultural and social practices of local communities, limiting the depth of user engagement. Integrating smart connected devices - particularly household appliances and heat pumps - into energy community infrastructures offers a powerful means to deepen this engagement. Smart home management systems modulate device use based on real-time energy availability, respecting user comfort while participating in DR programs [149]. Similarly, leveraging smart devices within renewable energy communities can support cost optimisation and equitable benefit-sharing, especially when households collectively schedule device use to maximise shared photovoltaic generation and take advantage of governmental incentives [145].

Smart household appliances can significantly enhance the operation of energy communities by providing distributed demand-side flexibility that complements local renewable energy generation. Through coordinated scheduling and control, flexible appliances such as washing machines, dishwashers, water heaters, HVAC systems, and electric vehicle chargers can increase collective self-consumption, reduce peak demand, and support local balancing of electricity production and consumption. When integrated with Home Energy Management Systems (HEMS) and coordinated by aggregators or community energy management platforms, these appliances enable residential users to collectively participate in demand response and flexibility markets while preserving occupants' comfort. Consequently, smart household appliances not only improve the technical and economic performance of energy communities but also facilitate higher renewable energy penetration, greater grid resilience, and more active consumer participation in the energy transition [14].

Recent European initiatives treat smart devices as both technical enablers and engagement touchpoints, combining several complementary approaches:

- *Co-design Living Labs and Pilot Deployments*: energy communities and households are central to living labs and pilot projects, where appliances and digital services are tested under real-world conditions. These deployments gather insights on user preferences (e.g., comfort trade-offs and scheduling choices) and build local champions to foster adoption [150–156].
- *Integrated Local Controllers and Digital Energy Assistants*: household-level controllers and digital assistants serve as both home energy hubs and user interfaces, coordinating appliances locally while linking to community platforms. They enable personalised scheduling of appliances - such as laundry, heating, or EV charging - based on photovoltaic generation, tariffs, and user comfort, providing technical flexibility while delivering seamless experiences and tangible benefits like cost savings and reduced environmental impact [150,157,158].
- *Behavioural Design*: engagement is enhanced through gamification, trust-building, simplified dashboards, and default opt-in settings [153–156,159]. Placing user engagement at the core of energy communities requires interoperability, robust data governance, and inclusive support. Transparent data policies and privacy-preserving tools enable households to connect devices safely while protecting autonomy and building trust.

The existing literature confirms that energy communities are leveraging the value of residential flexibility by enabling collective optimisation and self-consumption within the community. A few studies investigate governance, fairness, sustained consumer engagement, and

social acceptance. This imbalance prompts future research studies to adopt more integrated socio-technical perspectives.

4. Indications provided by case study applications

Various case studies have been proposed in the literature and in applied research projects. The following subsections present examples from real cases and the outcomes of recent EU projects.

4.1. Real-case scenarios

The reviewed literature shows a range of methodological approaches applied across various objectives and contexts, aiming to demonstrate the effectiveness, scalability, and user-centric nature of flexible demand-side management systems in experimental and practical settings.

Several works adopt a simulation-based framework [41,43–45,47,49–53,59–61] in which appliance scheduling, energy management strategies, or user behaviour models are tested under defined scenarios relying on historical, synthetic, or real-world data. For example [50], incorporates actual electricity price and temperature data, while REDD data are used to evaluate flexibility metrics in Ref. [42]. Further real-world datasets support validation in Refs. [43,44,52]. Other studies emphasise practical applications in pilot implementations or laboratory experiments [40]. These evidence types should not be treated as equivalent. Simulation studies assess technical feasibility, laboratory studies examine implementation under controlled conditions, and pilots provide evidence on user and stakeholder interaction. Repeated real-world deployment is needed to assess sustained participation and market scalability. Table 10 summarises the main aspects for scenarios based on real applications.

4.2. Notes on recent EU projects

Recent European research was identified through a structured search of the CORDIS platform. The search used combinations of the terms “demand response”, “energy flexibility”, “smart appliances”, “building energy management”, “interoperability”, “consumer engagement”, “citizen empowerment”, and “energy communities”. Additional terms, including “artificial intelligence”, “digital twins”, “energy data spaces”, “IoT”, “gamification”, and “chatbots”, were used to capture projects addressing specific technological or user-interaction dimensions. Projects were included when they addressed at least one of the two main review dimensions, controllability of energy devices or user participation in energy flexibility. They provided sufficient public information on the adopted technologies, interaction mechanisms, services, or demonstration activities. Projects were excluded when they did not directly address either of these dimensions, fell outside the defined funding and temporal scope, or lacked sufficient publicly available documentation for a consistent assessment. The scope of the review was limited to Research and Innovation Actions and Innovation Actions funded under Horizon 2020 and Horizon Europe, targeting projects launched after 2017. In total, 19 projects were selected; publicly accessible resources (e.g., technical deliverables, final reports, and official websites) were analysed, focusing on several aspects. Finally, the review considered how each project promoted flexibility, such as enabling participation in DR schemes, supporting peer-to-peer energy exchanges, or incentivising adaptable consumption through dynamic pricing.

4.2.1. Device control approaches

Control strategies range from basic remote operation of legacy devices to highly automated, adaptive systems. BRIGHT [157] relies on mobile applications and centralised platforms. Comparable solutions appear in DEDALUS [151], where control extends to boilers and smart plugs, and in DIGITISE [159] where smart home devices are controlled via Application Programming Interfaces (APIs). InterConnect [165] proposes Graphical User Interfaces (GUIs) with gamified applications for

Table 10
Scenarios from studies based on real applications.

Studies or projects	Main Features	Real applications
Digitised DR in practice: the role of digital housekeeping for smart energy technologies (Vindegg & Julsrud, 2025 [160])	The goal was to test residential DR under real market conditions, with minimal manual intervention. For most participants, the system was too complex, leading to limited use and, thus, smaller-than-expected energy shifting. The study concludes that simpler, more user-friendly interfaces and better user training are needed.	In a Norwegian pilot, about 200 households were each given a “Smart Energy Technology” hub controlling home electric heating systems via a mobile app. The system was integrated with hourly dynamic electricity pricing and demand-based tariffs.
Empirical case study of a digitally enabled energy community with prosumers and P2P trading (Staudt & Richter, 2025 [161])	A digital platform enabled participants to trade local solar photovoltaic energy and provided a home app for monitoring and automated or assisted control of flexible loads. Willingness to pay a premium for local green electricity was lower than expected, and manual DR was very limited.	13-month field study of the Landau Microgrid Project (LAMP) in a German city, involving 11 households in a local energy community with its own microgrid and a peer-to-peer energy market.
ACCEPT (Active Communities & Energy Prosumers for the Energy Transition), H2020, 2021–24 [150]	Developed a digital toolbox for energy communities to offer innovative services and tap new revenue streams that sustain their operations.	4 pilot communities (GR, NL, ES, CH) involving 750 households in renewable-energy cooperatives and local energy networks. Pilots validated community flexibility services in diverse national contexts.
REDREAM (Real Consumer Engagement Through a User-Centric Ecosystem), H2020, 2020–24 [162]	Introduced an open, user-centric platform allowing direct interaction between consumers/prosumers and energy market actors. Employed advanced ICT tools to automate DR and improve consumption forecasting.	4 large-scale pilots (ES, IT, UK, HR) involving diverse user groups: households with photovoltaic systems, community buildings, small industries, etc. These pilots demonstrated the platform's effectiveness in different grid setups.
SENDER (Sustainable Consumer Engagement and Demand Response), H2020, 2020–24 [163]	Co-created next-generation DR services with end-users from design to rollout. Deployed a “Smart Home Box” that automates home energy control (appliances, HVAC) and uses AI-based digital twins to forecast and optimise household consumption.	3 pilot sites in different regions: an energy cooperative in Alginet, Spain, a rural town (Weiz, Austria), and urban districts in Tampere/Espoo, Finland. The pilots validated proactive load shifting strategies and tested the user co-creation approach under real grid conditions.
iFLEX (Intelligent Assistants for Flexibility Management), H2020, 2020–24 [164]	Developed the iFLEX Assistant, an AI-based tool for flexibility management in households. Co-created with consumers to ensure usability and trust.	Pilots in 3 climatic regions (North, Central, and South Europe) with real households to validate the assistant under varied conditions. These pilots evaluated the user experience (ease of use, comfort levels) and grid impact (peak shaving, energy savings), with feedback from a consumer organisation.

active participation. ACCEPT [150] follows a similar path with its Citizen-App. FLEXGRID [166] and I-ENERGY [167] move toward greater automation. FLEXGRID combines sensor-based management of grid assets, market-driven coordination, web-based flexibility control, and home integration. At the same time, I-ENERGY applies adaptive methods, which leverage AI, external signals, and real-time feedback for tasks such as EV charging. PLATOON [168] employs IoT-based sensor control and machine-to-machine communication. LIGHTNESS [154], among others, adopts hybrid solutions combining remote and adaptive control. Single-mode control is giving way to multilayered, automated schemes, though user interaction remains vital. From a technical perspective, lightweight communication protocols are central. Message Queuing Telemetry Transport (MQTT) is frequently deployed for IoT and machine-to-machine communication, as seen in DEDALUS [151] and EDDIE [169]. At the same time, RESTful APIs with JSON underpin interoperability in Eco-Bot [170], FLEXGRID [166], and OPENTUNITY [171]. For real-time, high-volume data, Apache Kafka is preferred, notably in BRIGHT [157] and EDDIE [169]. Many initiatives emphasise open standards and open APIs to secure cross-domain compatibility, a principle explicitly reinforced in DIGITISE [159] and PLATOON [168].

4.2.2. Interaction with end users and external stakeholders

User participation is fostered through mobile apps, dashboards, and conversational agents. ACCEPT, InterConnect [165], and ENPOWER [153] deploy apps with personalised insights and community planning tools, often with region-specific features. BRIGHT and DATACELLAR [158] opt for centralised dashboards that integrate data streams or smart devices. FLEXGRID and I-ENERGY use real-time visualisation dashboards to guide market participation, while Eco-Bot employs a chatbot to simplify energy advice. EDDIE prioritises user control over data sharing, stressing privacy. More experimental approaches emerge in OMEGAX [155] and ENERSHARE, where gamification or blockchain marketplaces have been proposed to support participation through rewards or peer-to-peer transactions. Interaction with external actors (DSOs, aggregators, and service providers) also plays a key role. ACCEPT explores this through simulations, in which virtual DSOs and operators send real-time signals to communities. BRIGHT explores blockchain technologies to support decentralised transactions, enabling consumers to engage without intermediaries. Eco-Bot integrates DSO data, and EDDIE facilitates secure exchanges between consumers and providers via its Marketplace App. At the same time, ENPOWER offers a sandbox for testing innovative models such as peer-to-peer trading.

4.2.3. Lessons learned and recommendations

Across the reviewed projects, AI emerges as a promising enabler for energy efficiency, DR, and community empowerment. ACCEPT's Living Lab highlights iterative, context-aware, and participatory design, underlining that trust and stakeholder engagement are essential for sustainable energy communities. Technical advances include BRIGHT's hybrid models for consumption forecasting, near-human conversational AI for user engagement (as highlighted by Eco-bot), and digital twins or blockchain frameworks for decentralised control. Consumers welcome smart control when it improves comfort and safety, yet remain hesitant to change behaviour with older devices, as shown in BRIGHT. Costs, regulations, limited awareness, and cybersecurity risks slow down the adoption of smart DR. Eco-Bot underscores the importance of personalisation and clear communication. EDDIE emphasises data sharing as a cornerstone of flexibility. I-ENERGY highlights the difficulty of integrating AI into real-time systems and the central roles of usability, trust, and privacy. LIGHTNESS emphasises social engagement and tailored digital platforms. BRIGHT suggests physics-informed simulators and pre-trained models for adaptive control; Eco-Bot calls for EU-wide smart meter deployment and trial-based awareness campaigns; FLEXGRID and I-ENERGY argue for transferable AI models and low-latency automation; LIGHTNESS and PRELUDE stress continuous monitoring and engagement; PLATOON demonstrates advanced infrastructures, from self-

healing grids to privacy-preserving AI and blockchain-based data sharing. These projects collectively recommend integrating technological, regulatory, and social strategies to create scalable, secure, and user-centred European energy systems aligned with Green Deal ambitions. Table 10 summarises real-world scenarios and pilots from scientific articles and Horizon 2020/Horizon Europe projects, highlighting smart appliance solutions, consumer engagement, and DR services across diverse European settings. Across the project portfolio, mobile applications, dashboards, remote control, and open interfaces recur in several demonstrations. AI-based control, digital twins, blockchain-supported exchange, and peer-to-peer marketplaces are more frequently reported as prototypes, demonstrations, or planned Living Lab functions than as large-scale market deployments. This distinction is considered when interpreting maturity in the concluding synthesis.

These findings also lead to actor-specific implementation requirements. Policymakers need to align flexibility procurement with consumer protection, interoperability, baseline, and settlement rules. Aggregators need to match appliance capabilities and user constraints to products with compatible activation times, durations, and verification

requirements. Energy communities need transparent governance and benefit-allocation procedures that accommodate members with different levels of digital literacy. Technology developers need to translate control and optimisation capabilities into understandable interfaces, comfort-preserving operation, and simple override options.

For pilot design, the three framework levels define complementary evaluation criteria. Micro-level tests should quantify available flexibility, response duration, and compliance with appliance and comfort constraints. Meso-level tests should assess understandability, perceived usefulness, trust, override behaviour, and participation persistence. Macro-level tests should assess portfolio reliability, interoperability, baseline and settlement accuracy, benefit allocation, and coordination with market and community actors.

5. Discussion

The proposed framework has formulated the five research questions indicated in Table 4. The following paragraphs answer each research question in turn, drawing on the evidence that emerged from the study

Table 11
Synthesis of the review findings according to the research questions.

Id	Main Evidence	Key Findings	Current Limitations	Research Gaps
RQ1	- Classification of appliances - Scheduling methods - Optimisation models - Level of controllability	The operational flexibility can be provided by smart appliances using automated control strategies and self-scheduling frameworks. Most studies classify appliances according to their controllability and optimise operation to reduce costs, peak demand, or user discomfort. Optimisation-based energy management strategies remain the dominant approach in the existing literature.	- Ideal communication backbones are considered in most existing research. - Most of the existing literature assumes rational user participation in demand response actions. - Simplified models and constraints often reflect user comfort or discomfort levels.	- Standardised controllability models for different appliances are missing. - Interoperability between manufacturers, middleware, and control systems should be considered. - Cybersecurity and data-privacy issues should be reflected. - Optimisation models need to be integrated with realistic human-oriented behaviour.
RQ2	- Flexibility concept and definitions - Controllability metrics - Demand response - Flexibility valuation and pricing schemes - User participation in flexibility market	The flexibility term is represented as a multidimensional concept which depends on appliance characteristics, user preferences, market incentives, and system requirements. Residential flexibility can effectively support demand response, renewable integration, and ancillary services when properly coordinated.	- There is no generalised, globally accepted methodology for quantifying or pricing residential flexibility. - The current studies offer different and inconsistent flexibility indicators, making comparison difficult. - There is no techno-economic perspective available in the existing works.	- It is necessary to develop standardised flexibility metrics and valuation methods that can integrate techno-economic and behavioural flexibility assessments. - Harmonised market mechanisms must be established to incentivise flexibility services provided by the residential sector fairly.
RQ3	- User engagement activities - Energy literacy concepts - Trust and motivation - Feedback mechanisms - Digital energy acceptance	- Consumer engagement is a decisive feature for a successful digital energy service. - For long-term acceptance, financial incentives are not sufficient. Transparency, trust, perceived fairness, digital literacy, and preservation of comfort are the key pillars.	- Behavioural evidence is limited to the pilot projects and surveys with limited samples. - Consumer engagement in the long term requires extensive investigations to reflect different energy literacy levels. - User preferences should be considered in the optimisation studies.	- Human-centric digital services can be upgraded using personalised AI and explainable decision support system tools. - Sustained behavioural changes across a diverse range of households with different energy literacy should be analysed.
RQ4	- Aggregator management - Business models - Flexibility aggregation - Market participation - Data-sharing mechanisms - Interoperability models - TSO-DSO coordination	- Aggregators play a central role by combining distributed flexibility into marketable services. - The success and effectiveness of the aggregators depend on secure data exchange, interoperable platforms, and transparent regulations.	- Existing studies confirm that the regulatory frameworks differ across countries and interoperability standards are still evolving. - Remaining challenges include precise estimation, trust, cybersecurity issues, and data governance in real-world applications.	- Secure, transparent, and standardised communication protocols are necessary for aggregator management. - Privacy-preserving, data-sharing frameworks, AI-assisted aggregation platforms, and harmonised regulations should be further investigated to support a cross-sector market for flexibility services.
RQ5	- Energy communities - Collective self-consumption - Governance structure - Digital services	- Distributed flexibility can be collected at the appliance-level and extended to the energy community. - Energy sharing between households and increasing self-consumption activities are ever-growing within energy communities. - AI tools leverage forecasting, coordination, and community-level flexibility management.	- Recent studies primarily focus on technical optimisation problems, with limited attention to governance, social aspects, fairness, trust, and long-term community participation. - Real-world demonstrations and approved community-level benchmarks have remained limited.	- Integrated socio-techno-economical frameworks combining AI, governance frameworks, and fairness metrics are still missing. - Consumer engagement and real-world application of digital services within renewable energy communities need more investigation and development.

and indicating where the answer remains limited or inconclusive. A synthesis of the findings, limitations and further research gaps is provided in Table 11.

Concerning the first research question (RQ1), the adoption of smart appliances depends less on their technical capabilities than on the effort their management demands from users and on how far control actions intrude on comfort. This burden differs across appliance types, as deferrable cycles can be shifted with little effort and limited impact on comfort. At the same time, curtailment and thermostatic control act directly on comfort and are accepted only within limits set by the user. Across all categories, management systems demanding frequent manual intervention tend to discourage uptake. In contrast, automated control earns acceptance when the resulting gains in comfort and safety are readily perceived [157], and users retain simple choices such as deadlines, comfort limits, and quality-of-experience preferences. Field trials corroborate this pattern in day-to-day use, showing that only a minority of users possess the technical skills to exploit advanced smart-home systems fully, and that the load shifting actually delivered remains limited despite the available capabilities [160]. Broader participation is therefore more likely when assistive automation hides this complexity behind intuitive interfaces and makes the achieved benefits explicit to the user [163,164,170], underscoring that interface design is as important as the underlying optimisation. At the same time, delegating every decision to the system may weaken the sense of involvement and control that keeps users engaged over time. Automated management is more likely to sustain participation when it preserves user autonomy, offering simple overrides and the possibility to withdraw at any time.

Flexibility, the subject of the second research question (RQ2), is defined, measured and valued differently by operators and by end-users, and this misalignment weighs on its practical delivery. DSOs frame flexibility in terms of voltage control, transformer loading, and congestion relief [40,41,59]; TSOs focus on balancing and frequency regulation [49]; and both procure it through markets whose minimum bid sizes often exclude individual households [49,116]. On the system side, the flexibility actually delivered during an activation event is measured against baselines whose accuracy determines the payment and sustains the participants' trust [127,128]. Users, in turn, experience flexibility as a change in daily routines, offered in exchange for lower bills [50] and bounded by the comfort limits set for each appliance [49,106]. Collective habits further reduce the response that can realistically be expected in certain periods of the day [63]. Pricing schemes therefore need to bridge the two views, and transparent baselines, predictable settlement rules and fair value sharing emerge as the main conditions for rewarding participants properly while keeping reasonable aggregator margins [128,141]. The experience of large programmes suggests that this alignment is achievable when rules are clear [126], but a pricing approach that operators, aggregators and households all consider fair remains to be consolidated.

User engagement with digital energy services, the focus of the third research question (RQ3), is driven mainly by everyday motivations, since users respond to clear and personalised information, tangible economic benefits, and services that respect their privacy and routines [120]. The timing, granularity and presentation of energy feedback strongly shape how users understand their consumption and how willing they are to change it [66]. Real-time feedback through apps or displays inside the home sustains awareness better than delayed billing [68,72], especially when consumption is broken down by appliance or room [67,70]. Nevertheless, cost is the prevailing driver of action, as users evaluate feedback in terms of financial rather than environmental benefits [73]. At the same time, daily routines and occupancy patterns limit the flexibility that households can actually offer [52,63]. This contrasts with engagement strategies built on sustainability arguments, since environmental claims perceived as vague or misleading undermine the very confidence they are meant to build. Communication is therefore more effective when it leads with verifiable savings and keeps environmental benefits as supporting information. AI-assisted interfaces may reduce

user effort and improve decision support [74,148], provided that transparency, user autonomy, privacy, and comfort are preserved.

Aggregator models and data-sharing practices, examined in the fourth research question (RQ4), condition how trust is built and how the revenues from flexibility services are shared with participating households [112,113,116]. Independent aggregators can trade household flexibility directly in wholesale markets [138,140], but must coordinate with network operators when many devices respond together [122,123]. Supplier-aggregators simplify participation yet may raise concerns about conflicts of interest, since the same actor sells energy and manages its reduction. Community-based schemes act on behalf of cooperatives or municipalities and build trust through local relationships, but the same local character keeps their portfolios small [118,119]. Taken together, these models reveal a trade-off between scale and trust, as the arrangements that generate trust are local and personal. At the same time, those that create market value depend on size and standardisation. Whatever the model, sustained trust depends on transparent measurement and verification, predictable settlement, clear communication of control actions, and robust data governance. Secure digital platforms, including blockchain and smart contracts, may support transparency and peer-to-peer exchange when appropriately designed and governed. Nevertheless, practical deployment requires addressing cybersecurity, interoperability, scalability, privacy, and regulatory challenges.

Finally, concerning the fifth research question (RQ5), energy communities take up digital services more readily when their members help to shape the rules and share the resulting benefits. Collective scheduling of appliances to maximise shared photovoltaic generation, with a fair allocation of the savings, illustrates how collective incentives translate into concrete participation [145]. Co-design practices, living labs and local champions deepen involvement [150–156], whereas solutions introduced without regard for local social and cultural practices limit the depth of engagement. Peer influence, through comparison with neighbours and gamified applications, can motivate behavioural change [153–156,159], but the same social mechanisms may exclude members with limited digital skills or confidence [2]. For this reason, communities need services that members with different levels of digital skills can actually use, together with a clear definition of who is responsible for managing the shared data. Without these conditions, participation concentrates among the most digitally confident members, and the community ends up reproducing the digital divide it could help to close. The experience of European pilots further indicates that climate, load profiles, tariff structures and social trust jointly shape outcomes [160,161], so results obtained in one context cannot be assumed to transfer directly to another.

Across the five questions, the evidence is comparatively strongest for deferrable appliances scheduled under explicit user constraints and deterministic mixed-integer formulations [41,48]. Thermostatically controllable and storage-based devices, together with stochastic and learning-based control, are promising but require broader field validation [49,50,58]. Clear feedback, user-defined preference and comfort settings, and simple override options are the most consistently supported engagement features [41,66]. Conversational interfaces are promising, although evidence on sustained engagement remains limited [74]. Independent aggregation has the clearest regulatory basis [137–140], while supplier-integrated models provide a direct contractual interface with customers [116]. Community-based aggregation remains promising but less extensively validated.

6. Concluding remarks

Digitalisation of residential energy systems is reconfiguring the relationship between households and electrical grids, turning consumers into active participants capable of providing flexibility services. Smart household appliances are the primary interface for delivering digital services, activating demand response, and achieving community-level optimisation.

This article has examined that landscape through a three-level conceptual framework covering appliance control at the *micro* level, user engagement at the *meso* level, and aggregator- and community-level intermediation at the *macro* level. By synthesising the scientific literature and recent European research projects, the review gathered the evidence needed to answer the five research questions on controllability, flexibility quantification, behavioural engagement, aggregator intermediation, and community sharing. These findings have practical implications for the actors involved in residential digital energy services. Policymakers should align flexibility procurement with consumer protection, interoperability, baseline, and settlement requirements. Aggregators should match appliance capabilities and user constraints to services with compatible activation and verification conditions. Energy communities should combine collective incentives with transparent governance and benefit allocation. Technology developers should prioritise understandable interfaces, comfort-preserving control, and simple override options.

There are some limitations of the analysis presented. On the one hand, the limitations referring to the research questions formulated in the article have been indicated in Table 11. On the other hand, the systematic literature review of review articles is based on the use of the Scopus database and the selection of keywords. Moreover, the selection of the projects has been limited to EU projects, with other examples from the UK and US. The findings reported for these projects and examples are intended as illustrative rather than exhaustive, and similar regulatory approaches may work differently in other markets and jurisdictions.

The *micro-meso-macro* framework provides a common structure for future research and pilot evaluation. The *micro* level addresses technical feasibility and appliance constraints, the *meso* level addresses user acceptance and comfort, and the *macro* level addresses aggregation, governance, and market implementation. The same structure can support policy analysis by separating appliance-level constraints from consumer-protection, data-governance, and market-design requirements.

Although digital technologies such as AI, blockchain, smart contracts, and automation offer significant opportunities to improve residential energy management, they should not be treated as general solutions. The reviewed evidence remains fragmented across appliance classifications, flexibility indicators, and validation settings. Most studies quantify theoretical or simulated flexibility, while evidence on realised flexibility, sustained participation, and comfort impacts is limited. Engagement mechanisms and community-based aggregation are mainly assessed in short-term pilots, and their scaling depends on interoperability, baseline and settlement rules, data governance, and regulation. Hence, further evidence is required on long-term effectiveness, user acceptance, and real-world scalability.

The reviewed evidence indicates that technical controllability is necessary but not sufficient for the effective uptake of residential digital energy services. Practical implementation requires the joint consideration of appliance constraints, user preferences, engagement mechanisms, aggregator arrangements, and data governance. Future research should compare realised flexibility, sustained participation, comfort impacts, baseline accuracy, benefit allocation, and regulatory scalability through long-term and context-specific pilots.

Declaration of competing interests

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.

Acknowledgement

This work was supported in part by the EU Horizon Europe Programme under GA ID: 101160614 (EU-DREAM Project; DOI: 10.3030/101160614), in part by COMPETE2030-FEDER-00883700 and FCT

(INVINCIBLE Project; DOI: 10.54499/2023.17788.ICDT), Portugal, in part by the Brazilian funding agency CNPq (National Council for Scientific and Technological Development) under the grant Process No. 404637/2024-8, and in part by FAPESB (Research Support Foundation of the State of Bahia), grant No. 2465/2025.

Data availability

No data was used for the research described in the article.

References

- [1] A. Wang, D.N. Mah, A systematic review on varieties, effectiveness and determinants of consumer engagement in the context of electricity market reforms from a European-Asian comparative perspective, *Renew. Sustain. Energy Rev.* 226 (2026) 116430.
- [2] N. Stevanato, D. Fioriti, T. Ferrucci, L. Belloni, L. Rinaldi, D. Poli, E. Colombo, Data-driven analysis for the characterization of household appliance ownership and use in Sub-Saharan Africa, *Renew. Sustain. Energy Rev.* 212 (2025) 115396.
- [3] S. Hussain, C. Lai, U. Eicker, Flexibility: literature review on concepts, modeling, and provision method in smart grid, *Sustain. Energy Grids Netw.* 35 (2023) 101113.
- [4] H.H.H. Mousa, K. Mahmoud, M. Lehtonen, Recent developments of demand-side management towards flexible DER-rich power systems: a systematic review, *IET Gener., Transm. Distrib.* 18 (2024) 2259–2300.
- [5] K. Schmitt, R. Bhatta, M. Chamana, M. Murshed, I. Osman, S. Bayne, L. Canha, A review on active customers participation in smart grids, *J. Mod. Power Syst. Clean Energy* 11 (1) (2023) 3–16.
- [6] M.M. Shepherd, M. Salman, Demand flexibility: a review of quantification methods, models, and required data, *Appl. Sci.* 14 (23) (2024) 11276.
- [7] J. Shen, C. Jiang, B. Li, Controllable load management approaches in smart grids, *Energies* 8 (10) (2015) 11187–11202.
- [8] P.D.K. Manembu, A. Kewo, R. Bramstoft, P.S. Nielsen, A systematicity review on residential electricity load-shifting at the appliance level, *Energies* 16 (23) (2023) 7828.
- [9] H. Golmohamadi, S. Golestan, R. Sinha, B. Bak-Jensen, Demand-side flexibility in power systems, structure, opportunities, and objectives: a review for residential sector, *Energies* 17 (18) (2024) 4670.
- [10] T. Freire-Barceló, F. Martín-Martínez, Á. Sánchez-Miralles, A literature review of Explicit Demand flexibility providing energy services, *Elec. Power Syst. Res.* 209 (2022) 107953.
- [11] F. D'Etorre, M. Banaei, R. Ebrahimi, S. Ali Pourmousavi, E.M.V. Blomgren, J. Kowalski, Z. Bohdanowicz, B. Lopaciuk-Goncaryk, C. Biele, H. Madsen, Exploiting demand-side flexibility: state-of-the-art, open issues and social perspective, *Renew. Sustain. Energy Rev.* 165 (2022) 112605.
- [12] A.O. Ali, M.R. Elmarghany, M.M. Abdelsalam, M.N. Sabry, A.M. Hamed, Closed-loop home energy management system with renewable energy sources in a smart grid: a comprehensive review, *J. Energy Storage* 50 (2022) 104609.
- [13] E. Barabino, D. Fioriti, E. Guerrazzi, I. Mariuzzo, D. Poli, M. Raugi, E. Razaee, E. Schito, D. Thomopoulos, Energy Communities: a review on trends, energy system modelling, business models, and optimisation objectives, *Sustain. Energy Grids Netw.* 36 (2023) 101187.
- [14] S. Ahmed, A. Ali, A. Ciocia, A. D'Angola, Technological elements behind the renewable energy community: current status, existing gap, necessity, and future perspective—overview, *Energies* 17 (13) (2024) 3100.
- [15] E. Tsybina, C. Winstead, B. Ollis, M. Olama, T. Kuruganti, Demand response for frequency regulation: research continuity and knowledge gaps, *Renew. Sustain. Energy Rev.* 207 (2025) 114958.
- [16] S. Nema, V. Prakash, H. Pandžić, The role of thermostatically controlled loads in power system frequency management: a comprehensive review, *Sustain. Energy Grids Netw.* 42 (2025) 101680.
- [17] R. Lazdins, A. Gavrilovs, I. Antoskova, D. Mihaila, O. Borscevskis, A. Mutule, Synergy between demand flexibility and energy communities: a literature review, *Sustainability* 18 (4) (2026) 1858.
- [18] L. Chen, S.A. Salimon, Demand side management across residential, commercial, industrial, and agricultural sectors: global perspectives and case studies, *Renew. Sustain. Energy Rev.* 240 (2026) 117129.
- [19] C. Su, R. Fachrizal, J. Jurasz, A. Avelin, H. Li, Exploring demand side flexibility through aggregation of individual devices, *Renew. Sustain. Energy Rev.* 229 (2026) 116655.
- [20] X. Yang, T. Xu, T. Chen, Flexibility-based incentive program and aggregator operation strategy for distributed resources in energy community infrastructure, in: 2024 IEEE 2nd International Conference on Power Science and Technology (ICPST), 2024, pp. 1837–1842.
- [21] X. Yang, T. Chen, Y. Zhang, C. Gao, X. Yan, H. Hui, X. Ai, The optimal operation strategy of an energy community aggregator for heterogeneous distributed flexible resources, *IEEE Open Access Journal of Power and Energy* 12 (2025) 157–170.
- [22] S. Hussain, O. Alrumayh, R.P. Menon, C. Lai, U. Eicker, Novel incentive-based multi-level framework for flexibility provision in smart grids, *IEEE Trans. Smart Grid* 15 (2) (2024) 1594–1607.

- [23] S. Dai, S.A. Mansouri, S. Huang, Y.Z. Alharthi, Y. Wu, L. Bagherzadeh, A multi-stage techno-economic model for harnessing flexibility from IoT-enabled appliances and smart charging systems: developing a competitive local flexibility market using Stackelberg game theory, *Appl. Energy* 373 (2024) 123868.
- [24] S. Yu, P. Mascherbauer, T. Haupt, K. Skorna, H. Rickmann, M. Kochanski, L. Kranzl, Modeling households' behavior, energy system operation, and interaction in the energy community, *Energy* 328 (2025) 136338.
- [25] S. Sareen, Digitalisation and social inclusion in multi-scalar smart energy transitions, *Energy Res. Social Sci.* 81 (2021) 102251.
- [26] J. Chambers, C. Robinson, M. Scott, Digitalisation without detriment: a research agenda for digital inclusion in the future energy system, *People, Place and Policy* 16 (2) (2022) 177–192.
- [27] R. Gupta, S. Zahiri, Enhancing user engagement in local energy initiatives using smart local energy engagement tools: a Meta Study, *Energies* 16 (7) (2023) 3037.
- [28] L.F. Cabeza, D. Ürgü Varsatz, D. Ürgü, A. Palacios, C. Barreneche, Household appliances penetration and ownership trends in residential buildings, *Renew. Sustain. Energy Rev.* 98 (2018) 1–8.
- [29] B. Hammi, S. Zeadally, R. Khatoun, J. Nebhen, Survey on smart homes: vulnerabilities, risks, and countermeasures, *Comput. Secur.* 117 (2022) 102677.
- [30] D. Russo, V. Miori, G. Tolomei, D. Belli, Home automation interoperability: two decades of lessons learned and future prospects into the development of IoT ecosystems, *Internet Things* 37 (2026) 101906.
- [31] Joint Research Centre of the European Commission (JRC), Code of Conduct on Energy Management Related Interoperability of Energy Smart Appliances, 1.0, December 2025.
- [32] A. Shuhaiber, W. Alkarbi, S. Almansoori, Trust in smart homes: the power of social influences and perceived risks, intelligent sustainable systems, in: *Lecture Notes in Networks and Systems*, vol 578, Springer, Singapore, January 2023.
- [33] G. Vardakis, G. Hatzivasilis, E. Koutsaki, N. Papadakis, Review of smart-home security using the internet of things, *Electronics* 13 (2024) 3343.
- [34] A. Savin, M.F. Nielsen, The data-driven home: towards a more coherent regulatory framework for smart homes in the European Union, *Inf. Commun. Technol. Law* 1–21 (2025).
- [35] H. Du, Q. Han, D. Yang, B. de Vries, T. van Houten, Data privacy and smart home energy appliances: a stated choice experiment, *Heliyon* 9 (11) (2023) e21448.
- [36] A.H.M. Aman, N. Shaari, Z.S. Attar Bashi, S. Iftikhar, S. Bawazeer, S.H. Osman, N. S. Hasan, A review of residential blockchain internet of Things energy systems: resources, storage and challenges, *Energy Rep.* 11 (2024) 1225–1241.
- [37] S. Behera, M. Khare, A survey on optimization strategies for energy storage and microgrid energy management in cyber-physical systems based microgrids, *Eng. Res. Express* 7 (4) (2025) 042303.
- [38] U. Waheed, S.A. Khan, M. Masud, H. Jamshed, T.A. Juman, N.U.R. Malik, Blockchain-based, dynamic attribute-based access control for smart home energy systems, *Energies* 18 (1973, 2025).
- [39] M. Umer, S. Sadiq, R.M. Alhebshi, M.F. Sabir, S. Alsulbai, A. Al Hejaili, M. Khayyat, A.A. Eshmawi, A. Mohamed, IoT based smart home automation using blockchain and deep learning models, *PeerJ Comput. Sci.* 9 (2023) e1332.
- [40] R. D'hulst, W. Labeeuw, B. Beusen, S. Claessens, G. Deconinck, K. Vanthournout, Demand response flexibility and flexibility potential of residential smart appliances, *Appl. Energy* 155 (2015) 79–90.
- [41] S. Althaher, P. Mancarella, J. Mutale, Automated demand response from home energy management system under dynamic pricing and power and comfort constraints, *IEEE Trans. Smart Grid* 6 (4) (2015) 1874–1883.
- [42] S. Zhai, Z. Wang, X. Yan, G. He, Appliance flexibility analysis considering user behavior in home energy management system using smart plugs, *IEEE Trans. Ind. Electron.* 66 (2) (2019) 1391–1401.
- [43] F. Elghitani, E. El-Saadany, Smoothing net load demand variations using residential demand management, *IEEE Trans. Ind. Inf.* 15 (1) (2019) 390–398.
- [44] C. Joe-Wong, S. Sen, S. Ha, M. Chiang, Optimized day-ahead pricing for smart grids with device-specific scheduling flexibility, *IEEE J. Sel. Area. Commun.* 30 (6) (2012) 1075–1085.
- [45] N. Ahmed, M. Levorato, G.P. Li, Residential consumer-centric demand side management, *IEEE Trans. Smart Grid* 9 (5) (2018) 4513–4524.
- [46] Y.H. Yang, W. Son, J.R. Woo, Shifting behavior, shaping grids: Appliance-level insights for targeted residential demand response, *Util. Policy* 101 (2026) 102233.
- [47] A. Mohsenian-Rad, V.W.S. Wong, J. Jatskevich, R. Schober, A. Leon-Garcia, Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid, *IEEE Trans. Smart Grid* 1 (3) (2010) 320–331.
- [48] N.G. Paterakis, O. Erdinc, A.G. Bakirtzis, J.P.S. Catalão, Optimal household appliances scheduling under day-ahead pricing and load-shaping demand response strategies, *IEEE Trans. Ind. Inf.* 11 (6) (2015) 1509–1519.
- [49] H. Khajeh, H. Firoozi, H. Laaksonen, Flexibility potential of a smart home to provide TSO-DSO-level services, *Elec. Power Syst. Res.* 205 (April 2022) 107767.
- [50] Z. Chen, L. Wu, Y. Fu, Real-time price-based demand response management for residential appliances via stochastic optimization and robust optimization, *IEEE Trans. Smart Grid* 3 (4) (2012) 1822–1831.
- [51] V. Pilloni, A. Floris, A. Meloni, L. Atzori, Smart home energy management including renewable sources: a QoE-driven approach, *IEEE Trans. Smart Grid* 9 (3) (2018) 2006–2017.
- [52] L. Hao, Y. Xu, Semisupervised learning-based occupancy estimation for real-time energy management using ambient data, *IEEE Internet Things J.* 10 (20) (2023) 18426–18437.
- [53] I.Y. Joo, D.H. Choi, Optimal household appliance scheduling considering consumer's electricity bill target, *IEEE Trans. Consum. Electron.* 63 (1) (2017) 19–27.
- [54] J. Li, L. Luo, J. Chen, S. Wei, B. Li, Evaluation of load-side flexibility supply capability considering source-load interaction in power system operation, *Sustain. Energy Grids Netw.* 45 (2026) 102132.
- [55] A. Shahid, R. Ahmadihangar, A. Rosin, T. Korötko, Forecasting demand-side flexibility of a household with dynamic consumer behavior analysis, *2024 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE)*, Dubrovnik, Croatia, 2024, pp. 1–5.
- [56] R. El Abed, A. Hammoud, M. El-Gohary, B. Taher, Recent optimization methods and techniques in residential home energy management systems, *Results Eng.* 29 (2026) 108974.
- [57] L. Mendicino, D. Menniti, A. Pinnarelli, N. Sorrentino, P. Vizza, C. Alberti, F. Dura, DSO flexibility market framework for renewable energy community of nanogrids, *Energies* 14 (12) (2021) 3460.
- [58] Y. Zhang, R. Lin, Z. Mei, M. Lyu, H. Jiang, Y. Xue, J. Zhang, D.W. Gao, Interior-point policy optimization based multi-agent deep reinforcement learning method for secure home energy management under various uncertainties, *Appl. Energy* 376 (2024) 124155.
- [59] M. Premkumar, S. Ravichandran, A.O. Hourani, T.A.H. Alghamdi, Optimizing residential flexibility for sustainable energy management in distribution networks, *Energy Rep.* 12 (2024) 4696–4716.
- [60] M. Collotta, G. Pau, A novel energy management approach for smart homes using bluetooth low energy, *IEEE J. Sel. Area. Commun.* 33 (12) (2015) 2988–2996.
- [61] J.H. Hong, D.Y. Hong, L.H. Yao, L.C. Fu, A demand side management with appliance controllability analysis in smart home, in: *2020 International Conference on Smart Grids and Energy Systems (SGES)*, 2020, pp. 556–561.
- [62] S. Welikala, C. Dinesh, M.P.B. Ekanayake, R.I. Godaliyadda, J. Ekanayake, Incorporating appliance usage patterns for non-intrusive load monitoring and load forecasting, *IEEE Trans. Smart Grid* 10 (1) (2019) 448–461.
- [63] I.A. Sajjad, G. Chicco, R. Napoli, Definitions of demand flexibility for aggregate residential loads, *IEEE Trans* 7 (6) (2016) 2633–2643, *on Smart Grid*.
- [64] H. Poulter, M.C. Brisbois, Governing flexibility: trust, time and agency in automated demand-side flexibility, *Energy Policy* 206 (2025) 114806.
- [65] G. Chicco, G. Mustafayeva, R. Occhiuto, A. Russo, Survey-assisted time-domain characterization of the power patterns of the main household appliances, *Energies* 19 (2026) 1014.
- [66] R. Agarwal, M. Garg, D. Tejaswini, V. Garg, P. Srivastava, J. Mathur, R. Gupta, A review of residential energy feedback studies, *Energy Build.* 290 (2023) 113071.
- [67] S. Loizidis, F. Kourougianni, A.V. Olympios, A. Kyprianou, G.E. Georghiou, Disaggregation of household energy consumption with principal component analysis and sparse filtering, *Energy Rep.* 15 (2026) 108894.
- [68] A. Kendel, N. Lazaric, K. Maréchal, What do people 'learn by looking' at direct feedback on their energy consumption? Results of a field study in southern France, *Energy Policy* 108 (2017) 593–605.
- [69] S. D'Oca, S.P. Corgnati, T. Buso, Smart meters and energy savings in Italy: determining the effectiveness of persuasive communication in dwellings, *Energy Res. Social Sci.* 3 (2014) 131–142.
- [70] D. Bonino, F. Corno, L. De Russis, Home energy consumption feedback: a user survey, *Energy Build.* 47 (2012) 383–393.
- [71] J. Li, J. Du, B. Chen, Reasoning energy saving behaviors of air conditioner users considering wellness and climate change concerns, *Energy Build.* 347 (2025) 116387.
- [72] R. Kerr, M. Tondro, Residential Feedback Devices and Programs: Opportunities for Natural Gas. Technical Report NREL/TP-5500-55481, National Renewable Energy Laboratory (NREL), Building America Partnership for Improved Residential Construction, December 2012.
- [73] K. Buchanan, R. Russo, B. Anderson, Feeding back about eco-feedback: how do consumers use and respond to energy monitors? *Energy Policy* 73 (2014) 138–146.
- [74] M. Sanguinetti, M. Atzori, Conversational agents for energy awareness and efficiency: a survey, *Electronics* 13 (2) (2024).
- [75] B. Karlin, R. Ford, C. Squiers, Energy feedback technology: a review and taxonomy of products and platforms, *Energy Effic.* 7 (3) (2014) 377–399.
- [76] M. Ali, A. Safdarian, M. Lehtonen, Demand response potential of residential HVAC loads considering users preferences, in: *IEEE PES Innovative Smart Grid Technologies, Europe*, 2014, pp. 1–6.
- [77] R. Jovanovic, A. Boushelham, I.S. Bayram, Residential demand response scheduling with consideration of consumer preferences, *Appl. Sci.* 6 (1) (2016).
- [78] N. Javaid, I. Ullah, M. Akbar, A. Iqbal, F.A. Khan, N. Alrajeh, M.S. Alabed, An intelligent load management system with renewable energy integration for smart homes, *IEEE Access* 5 (2017) 13587–13600.
- [79] Y. Ji, E. Buechler, R. Rajagopal, Data-driven load modeling and forecasting of residential appliances, *IEEE Trans. Smart Grid* 11 (3) (2020) 2652–2661.
- [80] E. Heylen, D. Papadaskalopoulos, I. Konstantelos, G. Strbac, Dynamic modelling of consumers' inconvenience associated with demand flexibility potentials, *Sustain. Energy Grids Netw.* 21 (2020) 100298.
- [81] X. Kou, Y. Du, F. Li, H. Pulgar-Painemal, H. Zandi, J. Dong, M.M. Olama, Model-based and data-driven HVAC control strategies for residential demand response, *IEEE Open Access Journal of Power and Energy* 8 (2021) 186–197.
- [82] H.T. Dinh, K.H. Lee, D. Kim, Supervised-learning-based hour-ahead demand response for a behavior-based home energy management system approximating MILP optimization, *Appl. Energy* 321 (2022) 119382.

- [83] A.A. Amer, K. Shaban, A.M. Massoud, DRL-HEMS: deep reinforcement learning agent for demand response in home energy management systems considering customers and operators perspectives, *IEEE Trans. Smart Grid* 14 (1) (2023) 239–250.
- [84] S. Feng, M. Cucuzzella, T. Bouman, L. Steg, J.M.A. Scherpen, An integrated human–cyber–physical framework for control of microgrids, *IEEE Trans. Smart Grid* 14 (5) (2023) 3388–3400.
- [85] N. Aguiar, A. Dubey, V. Gupta, Pricing demand-side flexibility with noisy consumers: Mean-variance trade-offs, *IEEE Trans. Power Syst.* 38 (2) (2023) 1151–1161.
- [86] V. Kaisermayer, D. Muschick, M. Horn, G. Schweiger, T. Schwengler, M. Mörth, R. Heimrath, T. Mach, M. Herzlieb, M. Gölls, Predictive building energy management with user feedback in the loop, *Smart Energy* 16 (2024) 100164.
- [87] H. Saberi, C. Zhang, Z.Y. Dong, A multi-agent deep constrained q-learning method for smart building energy management under uncertainties, *IEEE Trans. Smart Grid* 15 (5) (2024) 4649–4661.
- [88] J. Aldahmashi, X. Ma, Real-time energy management in smart homes through deep reinforcement learning, *IEEE Access* 12 (2024) 43155–43172.
- [89] P. Saroha, G. Singh, U.K. Lilhore, S. Simaiya, M. Khan, R. Alroobaea, M. Alsafyani, H. Alsufyani, Dynamic appliance scheduling and energy management in smart homes using adaptive reinforcement learning techniques, *Sci. Rep.* 15 (1) (2025) 24594.
- [90] F. Teng, Y. Gao, J. Wang, W. Zhang, M. Wu, K. Zhuo, Innovative cost allocation and energy management in off-grid microgrids via Stackelberg game, *IEEE Trans. Autom. Sci. Eng.* 22 (2025) 21387–21399.
- [91] M. Baldini, A. Trivella, J.W. Wente, The impact of socioeconomic and behavioural factors for purchasing energy efficient household appliances: a case study for Denmark, *Energy Policy* 120 (2018) 503–513.
- [92] A. Sridhar, S. Honkapuro, F. Ruiz, J. Stoklasa, S. Annala, A. Wolff, A. Rautiainen, Toward residential flexibility—Consumer willingness to enroll household loads in demand response, *Appl. Energy* 342 (2023) 121204.
- [93] G.W. Hart, Nonintrusive appliance load monitoring, *Proc. IEEE* 80 (12) (1992) 1870–1891.
- [94] Z. Yan, M. Nardello, D. Brunelli, H. Wen, Reproducible non-intrusive load monitoring: a survey of open-source methods and practical challenges, *Renew. Sustain. Energy Rev.* 226 (2026) 116255.
- [95] M.R. Herrmann, E. Costanza, D.P. Brumby, et al., Exploring domestic energy consumption feedback through interactive annotation, *Energy Effic.* 14 (2021) 90.
- [96] Q. Wang, Identifying consumer behavior patterns from massive user transaction data based on data mining techniques, in: Z. Xu, S. Alrabae, O. Loyola-González, N.H. Ab Rahman (Eds.), *Cyber Security Intelligence and Analytics (CSIA 2024)*, Volume 1351 of *Lecture Notes in Networks and Systems*, Springer, Cham, 2025.
- [97] H.J. Kim, M.K. Kim, New customized bidirectional real-time pricing mechanism for demand response in predictive home energy management system, *IEEE Internet Things J.* 11 (14) (2024) 24497–24510.
- [98] P.O. Fanger, *Thermal Comfort: Analysis and Applications in Environmental Engineering*, McGraw Hill, 1970.
- [99] L. Jiang, J. Li, Y. Zheng, The impact of thermal comfort requirements on household heating energy consumption, *J. Build. Eng.* 90 (2024) 109426.
- [100] Y. Zhang, Z. Mei, H. Jiang, Y. Xue, W.W. Chen, J. Zhang, W. Gao, A parallel PPO-based federated transfer reinforcement learning method for multiple home energy management via cross-domain adaption, *IEEE Trans. Ind. Inf.* (2025) 1–12.
- [101] L. Xiong, Y. Tang, K. Bhattacharya, M.Y. Chow, F.F. Qian, Offline deep reinforcement learning-based home energy management systems with heterogeneous EV charging load models, *IEEE Trans. Circuits Syst. I Regul. Pap.* (2025) 1–11.
- [102] G. Binini, J. Munda, O. Popoola, An iterative approach to large-scale decentralised optimised demand response considering user comfort. E-Prime - Advances in Electrical Engineering, Electronics and Energy, 2025 101145.
- [103] M. Cho, T. Honda, Demand management for an electrified apartment building with a photovoltaic power source and battery energy storage system, *IEEE Access* 12 (2024) 142784–142798.
- [104] B. Han, Y. Zahraoui, M. Mubin, S. Mekhilef, M. Seyedmahmoudian, A. Stojcevski, Home energy management systems: a review of the concept, architecture, and scheduling strategies, *IEEE Access* 11 (2023) 19999–20025.
- [105] M.T. Nowbandegani, M.S. Nazar, M. Shafie-Khah, J.P.S. Catalão, Demand response program integrated with electrical energy storage systems for residential consumers, *IEEE Syst. J.* 16 (3) (2022) 4313–4324.
- [106] O. Aliç, Ü.B. Filik, A multi-objective home energy management system for explicit cost-comfort analysis considering appliance category-based discomfort models and demand response programs, *Energy Build.* 240 (2021) 110868.
- [107] L. Xiong, Y. Tang, C. Liu, S. Mao, K. Meng, Z. Dong, F. Qian, A home energy management approach using decoupling value and policy in reinforcement learning, *Frontiers of Information Technology & Electronic Engineering* 24 (9) (2023) 1261–1272.
- [108] M.S. Javadi, M. Gough, M. Lotfi, A. Esmaeel Nezhad, S.F. Santos, J.P.S. Catalão, Optimal self-scheduling of home energy management system in the presence of photovoltaic power generation and batteries, *Energy* 210 (2020) 118568.
- [109] K. Shantanu, N.K. Choudhary, N. Singh, K. Kumar, Demand response for residential appliances using multi-agent reinforcement learning with price and solar power uncertainty, *Energy Rep.* 14 (2025) 3725–3737.
- [110] C.A. Correa-Florez, A. Michiorri, G. Kariniotakis, Optimal participation of residential aggregators in energy and local flexibility markets, *IEEE Trans. Smart Grid* 11 (2) (March 2020) 1644–1656.
- [111] S. Talari, M. Shafie-Khah, N. Mahmoudi, P. Siano, W. Wei, J.P.S. Catalão, Optimal management of demand response aggregators considering customers' preferences within distribution networks, *IET Gener., Transm. Distrib.* 14 (23) (October 2020) 5571–5579.
- [112] C. Heinrich, C. Ziras, A.L.A. Syri, H.W. Bindner, Ecogrid 2.0: a large-scale field trial of a local flexibility market, *Appl. Energy* 261 (March 2020) 114399.
- [113] S. Burger, J.P. Chaves-Ávila, C. Battle, I.J. Pérez-Arriaga, A review of the value of aggregators in electricity systems, *Renew. Sustain. Energy Rev.* 77 (September 2017) 395–405.
- [114] L. Zhang, Y. Tang, T. Zhou, C. Tang, H. Liang, J. Zhang, Research on flexible smart home appliance load participating in demand side response based on power direct control technology, *Energy Rep.* 8 (4) (2022) 424–434.
- [115] C. Su, R. Fachrizal, J. Jurasz, A. Avelin, H. Li, Exploring demand side flexibility through aggregation of individual devices, *Renew. Sustain. Energy Rev.* 229 (2026) 116655.
- [116] Ö. Okur, P. Heijnen, Z. Lukszo, Aggregator's business models in residential and service sectors: a review of operational and financial aspects, *Renew. Sustain. Energy Rev.* 139 (April 2021) 110702.
- [117] J. Cano-Martínez, A. Quijano-López, V. Fuster-Roig, A scoping review of flexibility markets in the power sector: models, mechanisms, and business perspectives, *Energies* 18 (19) (2025) 5213.
- [118] T. Schittekatte, L. Meeus, Flexibility markets: Q&A with project pioneers, *Util. Policy* 63 (April 2020) 101017.
- [119] I. Lampropoulos, M. van den Broek, E. van der Hoofd, K. Hommes, W. van Sark, A system perspective to the deployment of flexibility through aggregator companies in the Netherlands, *Energy Policy* 118 (July 2018) 534–551.
- [120] P. Grünewald, T. Reisch, The trust gap: social perceptions of privacy data for energy services in the United Kingdom, *Energy Res. Social Sci.* 68 (October 2020) 101534.
- [121] S. Pelka, S. Preuß, J. Stute, E. Chappin, L. de Vries, One service fits all? Insights on demand response dilemmas of differently equipped households in Germany, *Energy Res. Social Sci.* 112 (June 2024) 103517.
- [122] X. Jin, Q. Wu, H. Jia, Local flexibility markets: literature review on concepts, models and clearing methods, *Appl. Energy* 261 (March 2020) 114387.
- [123] S. Potenciano Menci, O. Valarezo, Decoding design characteristics of local flexibility markets for congestion management with a multilayered taxonomy, *Appl. Energy* 357 (March 2024) 122203.
- [124] C. Edmunds, S. Galloway, I. Elders, W. Bukhsh, R. Telford, Design of a DSO-TSO balancing market coordination scheme for decentralised energy, *IET Gener., Transm. Distrib.* 14 (5) (January 2020) 707–718.
- [125] G. Xu, S. Song, Y. Li, Y. Lu, Y. Zhao, L. Zhang, F. Wang, Z. Song, Application of deep reinforcement learning in electricity demand response market: demand response decision-making of load aggregator, *MethodsX* 12 (June 2024) 102735.
- [126] National Energy System Operator (NESO), Demand Flexibility Service Delivers Electricity to Power 10 Million Households, May 2023. (Accessed 5 May 2026).
- [127] J. Granderson, S. Fernandes, E. Crowe, M. Sharma, D. Jump, D. Johnson, Accuracy of hourly energy predictions for demand flexibility applications, *Energy Build.* 295 (September 2023) 113297.
- [128] ENTSO-E (European Network of Transmission System Operators for Electricity), DSO Entity and ENTSO-E Submit Joint Network Code on Demand Response, May 2024. (Accessed 5 May 2026).
- [129] F. Martín-Martínez, J. Boal, A. Sánchez-Mirallas, C. Becker Robles, R. Rodríguez-Vilches, Technical deployment of aggregator business models, *Heliyon* 10 (9) (May 2024) e30101.
- [130] UK Power Networks & LCP Delta, Project Harmony: Improving Coordination in GB Flexibility Markets, 2025. (Accessed 5 May 2026).
- [131] Siemens Industry, Inc, Enrolling with a Demand Response Aggregator, 2011. (Accessed 5 May 2026).
- [132] P. Olivella-Rosell, E. Bullich-Massagué, M. Aragüés-Penalba, A. Sumper, S. Ø. Ottesen, J.A. Vidal-Clos, R. Villafañila-Robles, Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources, *Appl. Energy* 210 (January 2018) 881–895.
- [133] UK Power Networks (Operations) Limited, Flexibility Services Procurement Statement: Standard Licence Condition 31E Reporting Requirement 2022-23, July 2022. (Accessed 5 May 2026).
- [134] UK Power Networks (Operations) Limited, Flexibility Dispatch Framework Report, November 2023. (Accessed 5 May 2026).
- [135] UK Power Networks (Operations) Limited, Flexibility Services Procurement Statement: Standard Licence Condition 31E Reporting Requirement, March 2024 (April 2024–March 2025), March 2024. Issued 28. (Accessed 5 May 2026).
- [136] UK Power Networks (Operations) Limited, Flexibility Dispatches Dataset, 2023. (Accessed 5 May 2026).
- [137] Federal Energy Regulatory Commission, FERC Order No. 2222: Fact Sheet, September 2020. (Accessed 5 May 2026).
- [138] European Parliament and the Council of the European Union, Directive (EU) 2019/944 of the European Parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending directive 2012/27/EU (recast), 2019, *Official Journal L158* (2019) 125–199, 05-5-2026.
- [139] Office of Gas and Electricity Markets (Ofgem), Decision to Approve BSC Modification P473: “Correcting Inconsistencies in the P415 Legal Text”, September 2024. (Accessed 5 May 2026).
- [140] Elexon Ltd, Virtual Lead Parties to Offer Services in the Wholesale Electricity Market, October 2023. Last updated 06 October 2023. (Accessed 5 May 2026).
- [141] ENTSO-E (European Network of Transmission System Operators for Electricity), System Flexibility Needs for the Energy Transition, 2024. (Accessed 5 May 2026).

- [142] H. Khajeh, R. Zheng, H. Firoozi, H. Laaksonen, M. Shafie-Khah, Role of smart homes and smart communities in flexibility provision, in: H. Haes Alhelou, E. Heydarian-Forushani, P. Siano (Eds.), *Flexibility in Electric Power Distribution Networks*, CRC Press, 2021, pp. 21–40, chapter in.
- [143] S. Pelekis, A. Pipergias, E. Karakolis, S. Mouzakitis, F. Santori, M. Ghoreishi, D. Askounis, Targeted demand response for flexible energy communities using clustering techniques, *Sustain. Energy Grids Netw.* 36 (December 2023) 101134.
- [144] C. Piselli, G. Salvadori, L. Diciotti, F. Fantozzi, A.L. Pisello, Assessing users' willingness-to-engagement towards net zero energy communities in Italy, *Renew. Sustain. Energy Rev.* 152 (December 2021) 111627.
- [145] F. Conte, F. Silvestro, A. Vinci, A.R. Di Fazio, Optimal coordination and discount allocation in residential renewable energy communities with smart home appliances, in: 2023 IEEE Belgrade PowerTech, IEEE, June 2023, pp. 1–8.
- [146] R. Sepehrzad, M. Yadav, G.C. Lazaroiu, I.I. Avramidis, I.B. Benitez, M. Di Somma, C. Papadimitriou, H. Mirsaedi, A. Hassankashi, N. Krami, A. Javed, P. Siano, A critical overview of local energy communities: State-of-the-art, real-life applications & challenges and tackling the academia-industry gap, *Renew. Sustain. Energy Rev.* 226 (2026) 116165.
- [147] G. Graditi, A. Buonanno, M. Caliano, M. Di Somma, M. Valenti, *Machine Learning Applications for Renewable-based Energy Systems*, Springer International Publishing, Cham, 2023, pp. 177–198.
- [148] R.H. Jensen, V.V. Jensen, R.C. Smith, Energy communities: pervasive technologies and collective futures, *IEEE Pervasive Comput.* 23 (2) (April 2024) 45–55.
- [149] F. Fernandes, H. Morais, Z. Vale, Near real-time management of appliances, distributed generation and electric vehicles for demand response participation, *Integrated Comput. Aided Eng.* 29 (3) (June 2022) 313–332.
- [150] ACCEPT Project Consortium, European Project H2020: ACCEPT. Grant Agreement No. 957781, 2021. (Accessed 5 May 2026).
- [151] DEDALUS Project Consortium, European Project Horizon Europe: DEDALUS. Grant Agreement No. 101103998, 2023. (Accessed 5 May 2026).
- [152] ENERSHARE Project Consortium, European Project Horizon Europe: ENERSHARE. Grant Agreement No. 101069831, 2022. (Accessed 5 May 2026).
- [153] ENPOWER Project Consortium, European Project Horizon Europe: ENPOWER. Grant Agreement No. 101096354, 2023. (Accessed 5 May 2026).
- [154] LIGHTNESS Project Consortium, European Project H2020: LIGHTNESS. Grant Agreement No. 953020, 2020. (Accessed 5 May 2026).
- [155] OMEGA-X Project Consortium, European Project Horizon Europe: OMEGA-X. Grant Agreement No. 101069287, 2022. (Accessed 5 May 2026).
- [156] PRELUDE Project Consortium, European Project H2020: PRELUDE. Grant Agreement No. 958345, 2020. (Accessed 5 May 2026).
- [157] BRIGHT Project Consortium, European project H2020: BRIGHT. Grant agreement No. (2020) 957816. (Accessed 5 May 2026).
- [158] DATACELLAR Project Consortium, European Project Horizon Europe: DATACELLAR. Grant Agreement No. 101069694, 2022. (Accessed 5 May 2026).
- [159] DIGITISE Project Consortium, European Project Horizon Europe: DIGITISE. Grant Agreement No. 101160671, 2024. (Accessed 5 May 2026).
- [160] M. Vindegg, T.E. Julsrud, Digitised demand response in practice: the role of digital housekeeping for smart energy technologies, *Energy Effic.* 18 (1) (2025) 1–19.
- [161] P. Staudt, B. Richter, Empirical case study of a digitally enabled energy community with prosumers and P2P trading, *Energy Sustain. Soc.* 15 (3) (2025) 1–20.
- [162] REDREAM Project Consortium, European Project H2020: REDREAM. Grant Agreement No. 957837, 2020. (Accessed 5 May 2026).
- [163] SENDER Project Consortium, European Project H2020: SENDER. Grant Agreement No. 957755, 2020. (Accessed 5 May 2026).
- [164] IFLEX Project Consortium, European Project H2020: Iflex. Grant Agreement No. 957670, 2020. (Accessed 5 May 2026).
- [165] InterConnect Project Consortium, European Project H2020: Interconnect. Grant Agreement No. 857237, 2019. (Accessed 5 May 2026).
- [166] FLEXGRID Project Consortium, European Project H2020: FLEXGRID. Grant Agreement No. 863876, 2019. (Accessed 5 May 2026).
- [167] I-ENERGY Project Consortium, European project H2020: I-ENERGY. Grant agreement No. 101016508, 2021. (Accessed 5 May 2026).
- [168] PLATOON Project Consortium, European Project H2020: PLATOON. Grant Agreement No. 872592, 2020. (Accessed 5 May 2026).
- [169] EDDIE Project Consortium, European Project Horizon Europe: EDDIE. Grant Agreement No. 101069510, 2023. (Accessed 5 May 2026).
- [170] Eco-Bot Project Consortium, European Project H2020: Eco-Bot. Grant Agreement No. 767625, 2017. (Accessed 5 May 2026).
- [171] OPENTUNITY Project Consortium, European Project Horizon Europe: OPENTUNITY. Grant Agreement No. 101096333, 2023. (Accessed 5 May 2026).