ORIGINAL RESEARCH **Open access**

Toward a Theory of Algorithmic Energy Flexibility: Demand Response, Consumer Agency, and Grid Stability

Lars Petersen[1*], Maja Jensen[1], Henrik Nielsen[2]

Abstract

The rise of automated demand response and distributed energy resources is reshaping how energy flexibility is produced and coordinated. Algorithmic systems increasingly mediate between grid needs and household energy consumption, raising fundamental questions about consumer agency and system stability. Existing research treats demand response optimization, consumer behavior, and grid stability as largely separate domains. As a result, the field lacks a unified theory explaining how algorithmic coordination of flexibility interacts with human agency and affects system-level outcomes. This article develops a theory of algorithmic energy flexibility that integrates demand response, consumer agency, and grid stability into a coherent conceptual account. The theory explains flexibility as a socio-technical phenomenon rather than merely a technical resource. The theory is constructed through conceptual synthesis and theoretical integration of literature from energy demand studies, socio-technical systems theory, behavioral science, and grid operations research. No empirical data are collected or analyzed. The theory proposes that algorithmic energy flexibility is shaped by three core constructs: the mode of algorithmic coordination, the degree and type of consumer agency preserved, and the temporal and spatial requirements of grid stability. These constructs interact through mechanisms of automation-alienation, agency-preserving design, and stability feedback, moderated by institutional trust, fairness perceptions, and market design. The theory provides a new lens for understanding why some algorithmic demand response programs succeed or fail, and it offers testable propositions for future empirical research. It also informs the design of flexibility mechanisms that are both technically effective and socially legitimate.

Keywords Demand response, Theory-building, Algorithmic energy flexibility, Consumer agency, Grid stability, Socio-technical systems

*Correspondence:
Lars Petersen
lars.petersen@dtu.dk
[1] Department of Intelligent Power Systems and Data Science, Faculty of Engineering, Technical University of Denmark, Lyngby, Denmark
[2] Department of AI for Wind Energy Forecasting, Faculty of Engineering, Aalborg University, Aalborg, Denmark

Introduction

Power systems are moving toward a flexibility-based operating paradigm in which distributed appliances, batteries, electric vehicles, heating systems, smart buildings, and behind-the-meter resources can be coordinated in response to changing grid conditions. Demand response research has increasingly emphasized automated control, machine learning, dynamic pricing, and distributed optimization as means of mobilizing flexible demand at scale [1]. This shift transforms consumers from passive users of electricity into participants whose everyday routines, devices, and preferences are algorithmically translated into grid services [2]. We propose that algorithmic energy flexibility should therefore be theorized as a socio-technical relation between automated coordination, consumer agency, and system stability.

This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License (CC BY-NC-SA 4.0), which permits non-commercial use, distribution, reproduction, and adaptation in any medium or format, provided that appropriate credit is given to the original author(s) and source, a link to the license is provided, and any changes made are indicated. Adapted material must be distributed under the same license.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

The theoretical gap arises because technical and social research streams often proceed in parallel rather than in integration. Engineering-oriented work commonly models demand response as an optimization problem involving load shifting, scheduling, or price-responsive control [3], while social research emphasizes consumer engagement, trust, autonomy, and the lived experience of smart energy technologies [4]. Energy justice scholarship further shows that automated flexibility can distribute benefits and burdens unevenly across households, especially when consumers differ in resources, literacy, housing conditions, and exposure to energy vulnerability [5]. A theory of algorithmic energy flexibility is needed because none of these perspectives alone explains how algorithmic coordination, consumer agency, and grid stability jointly shape demand response outcomes.

Existing conceptual approaches borrow selectively from behavioral economics, control theory, socio-technical studies, and market design, but they rarely specify the causal mechanisms linking automation design to consumer behavior and system reliability. Behavioral demand response research has examined how tariffs, incentives, and information complexity shape consumer response [6], while socio-technical accounts show that flexibility is embedded in domestic practices, routines, and institutional arrangements [7]. Grid-centered studies, by contrast, treat flexibility as a resource that can support balancing and integration of renewable generation [8]. The theory advanced here seeks to connect these strands by explaining how automation and agency co-produce stability outcomes under specific technical, institutional, and social conditions.

The objective of this article is to articulate a theory of algorithmic energy flexibility and define its core constructs, causal mechanisms, boundary conditions, and research propositions. This theory builds on work showing that automated demand response depends on communication infrastructures, metering systems, optimization models, and consumer enrollment arrangements [9]. It also draws from studies of algorithmic governance, which suggest that automated systems do not merely execute decisions but reshape authority, accountability, and participation [10]. The contribution is theoretical: algorithmic energy flexibility is conceptualized not as a neutral efficiency instrument but as a mediated form of demand-side coordination whose stability effects depend on how consumer agency is preserved, constrained, or displaced.

Background

The rise of algorithmic coordination in demand response

Demand response has evolved from manual conservation requests and simple time-of-use tariffs toward automated systems capable of coordinating distributed resources through software, sensors, aggregators, and platform-based control. Reinforcement learning approaches to dynamic pricing and home energy management illustrate how algorithms can learn consumption patterns, infer flexibility potential, and adjust device operation in response to price or grid signals [1]. Smart-grid-ready buildings and IoT-enabled energy systems further extend this logic by embedding demand response decisions in building management systems, connected appliances, and distributed energy platforms [3]. The rise of aggregators and virtual power plants therefore marks a shift from consumer-initiated response to algorithmically mediated flexibility dispatch, where grid stability depends increasingly on the reliability of automated coordination and the legitimacy of consumer participation.

Consumer agency in the energy literature

Consumer agency in energy systems refers not only to the ability to choose a tariff or enroll in a program but also to the capacity to understand, authorize, adjust, override, and contest energy-related decisions. Studies of residential demand response show that motivation, perceived control, trust, and practical convenience shape whether households accept flexibility programs and remain engaged over time [4]. Research on direct load control further suggests that consumers may accept automation when compensation, comfort protection, and decision authority are perceived as appropriate [11]. The theory therefore treats agency as multidimensional, spanning decisional autonomy, executive control, informational transparency, and procedural fairness rather than reducing participation to enrollment or behavioral compliance.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

Grid stability as a technical and institutional objective

Grid stability is commonly understood through technical requirements such as frequency regulation, voltage support, balancing, ramp management, and the reliable integration of variable renewable generation. Demand-side flexibility can support these objectives by shifting consumption, smoothing peaks, and enabling more responsive coordination between distributed resources and system needs [12]. However, stability is also institutional because the acceptable means of achieving it are shaped by market rules, compensation mechanisms, regulatory protections, and consumer obligations [13]. We therefore conceptualize grid stability as both a physical condition of the power system and a governance objective that depends on socially legitimate forms of flexibility mobilization.

Socio-technical perspectives on energy flexibility

Socio-technical perspectives challenge the assumption that flexibility is a purely technical property of devices or loads. Energy demand is organized through everyday practices, household routines, comfort expectations, gendered labor, work schedules, and social norms, which means that flexibility is co-produced by technologies and social arrangements [14]. Research on smart grids and domestic consumption shows that flexibility emerges when households, technologies, grid operators, and institutions negotiate what forms of consumption adjustment are acceptable or practical [2]. From this perspective, algorithmic energy flexibility must be understood as a mediated practice in which automated control interacts with lived routines, institutional expectations, and consumer interpretations.

Existing theoretical approaches and their limitations

Behavioral economics explains how consumers respond to price signals, incentives, information framing, and perceived tariff complexity, but it may understate how automation transforms the very conditions under which choices are made [3]. Control engineering explains how loads can be optimized and coordinated for system objectives, yet it often abstracts from trust, consent, fairness, and household heterogeneity [15]. Socio-technical theory explains how energy practices and institutions shape flexibility, but it has less often specified how algorithmic control modes produce distinct stability consequences [16]. Market design research offers important insight into incentives and participation structures, yet a dedicated theory is needed to explain how algorithmic coordination simultaneously reorganizes technical control, consumer agency, and grid stability.

Conceptual Foundations of the Theory

Defining algorithmic energy flexibility

Algorithmic energy flexibility can be defined as the capacity of a socio-technical energy system to modulate demand, storage, or distributed generation through automated algorithms that act on flexible resources in response to prices, constraints, forecasts, or grid needs. This definition builds on demand-side flexibility research showing that residential, commercial, industrial, and agricultural loads can provide different forms of temporal adjustment when supported by appropriate technologies and coordination mechanisms [8]. However, the concept also recognizes that flexibility is not merely latent in appliances or buildings; it is activated through consumer acceptance, institutional authorization, and the design of algorithmic decision rules [17]. We therefore propose that algorithmic energy flexibility is a relational capacity produced jointly by technical controllability, consumer agency, and institutional legitimacy.

Consumer agency as a multi-dimensional construct

Consumer agency is conceptualized here as a multidimensional construct composed of decisional autonomy, executive control, informational transparency, and procedural fairness. Decisional autonomy concerns whether consumers can choose participation terms, while executive control concerns whether they can override or adjust automated actions in real time. Informational transparency refers to whether consumers understand why an algorithm acts, and procedural

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

fairness concerns whether they can question, contest, or seek remedy for automated flexibility decisions. This conceptualization aligns with research showing that trust in demand-side management depends not only on automation level but also on interaction design, explanation, and perceived control [18].

Table 1 summarizes the principal dimensions of consumer agency and their implications for algorithmic flexibility governance.

Table 1. Dimensions of Consumer Agency in Algorithmic Energy Flexibility Systems

Dimension of consumer agency	Operational definition	Relevance to algorithmic flexibility	Potential risk when constrained
Decisional autonomy	Ability to choose participation terms and flexibility conditions	Supports legitimacy and voluntary enrollment	Consumers may perceive automation as coercive
Executive control	Ability to override or modify automated actions in real time	Maintains comfort protection and user confidence	Increased override resistance and disengagement
Informational transparency	Degree to which algorithmic decisions are understandable and explainable	Enhances trust in automated coordination	Opaque systems may weaken confidence and accountability
Procedural fairness	Availability of contestation, appeal, and remedy mechanisms	Strengthens institutional legitimacy and acceptance	Perceived injustice may reduce long-term participation
Participatory adaptability	Capacity for consumers to update preferences and routines over time	Enables durable alignment between algorithms and household practices	Static systems may become misaligned with evolving user needs

The stability-agency tension

The central theoretical tension is that maximizing short-term grid stability through pervasive automation may erode consumer agency, while maximizing agency through fully manual control may reduce the predictability and speed of flexibility response. Automated demand response can improve operational responsiveness by reducing reliance on moment-by-moment human action, but opaque or intrusive automation may weaken trust and trigger disengagement [19]. Conversely, highly voluntary or advisory systems may preserve consumer autonomy but deliver flexibility that is less reliable for fast balancing or congestion management [20]. The theory suggests that algorithmic energy flexibility becomes most stable when automation is designed to coordinate demand without making consumers feel excluded from decisions that affect comfort, cost, and household routines.

Figure 1 presents the proposed theory of algorithmic energy flexibility, illustrating how coordination mode, consumer agency, and grid stability interact through automation–alienation, agency-preserving design, and stability-feedback mechanisms under specific institutional, social, and technological boundary conditions.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

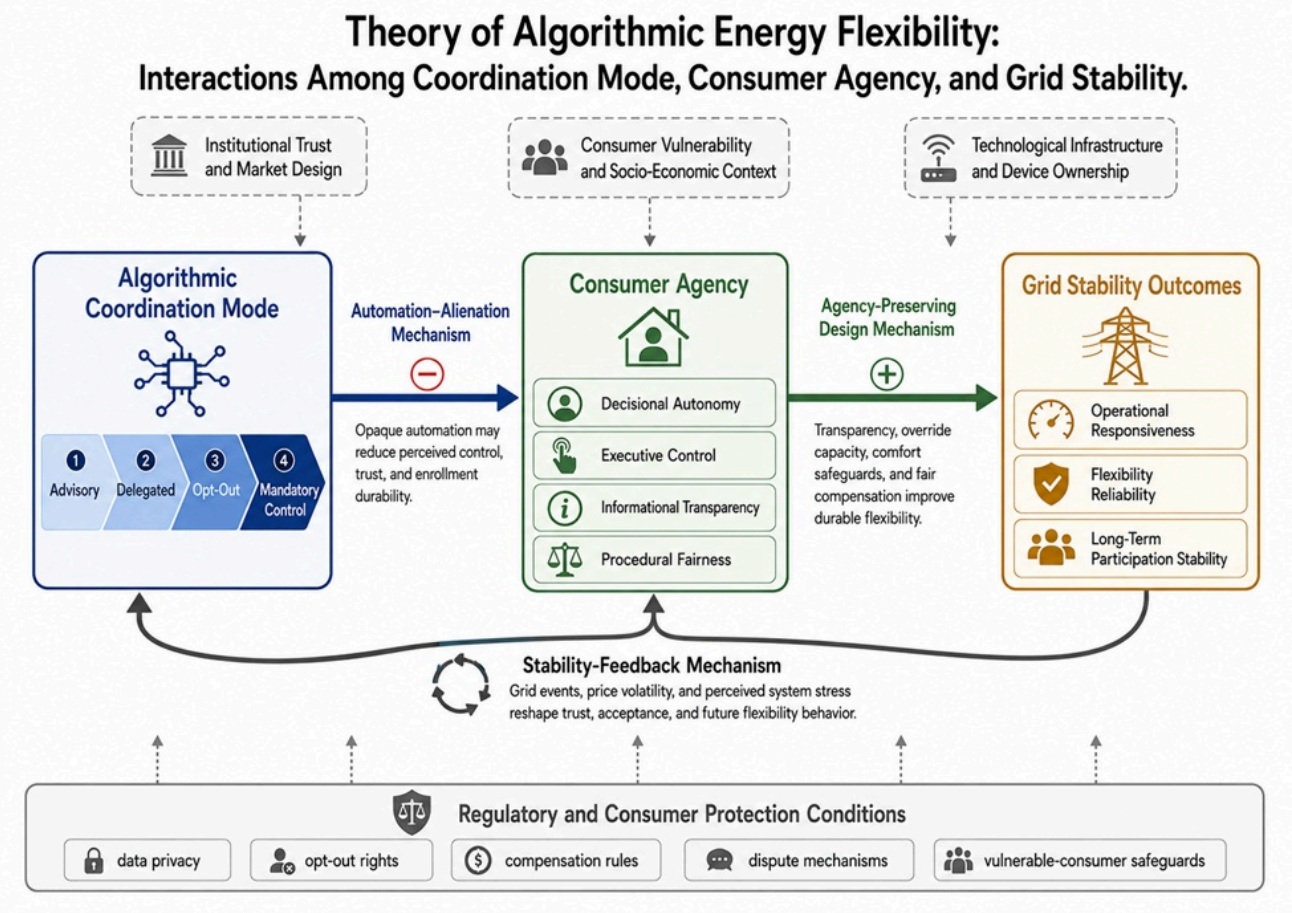


Figure 1. Theory of algorithmic energy flexibility: interactions among coordination mode, consumer agency, and grid stability

Core Theoretical Constructs and Relationships

Modes of algorithmic coordination

The first core construct is the mode of algorithmic coordination, which can be conceptualized along a continuum from advisory to delegated, opt-out, and mandatory control. In advisory modes, algorithms recommend consumption adjustments but consumers decide whether to act; in delegated modes, consumers pre-set preferences and allow automated execution within defined boundaries. In opt-out modes, automated response proceeds unless consumers intervene, while mandatory modes prioritize system requirements by limiting or eliminating consumer override. Research on automated home energy management and smart buildings suggests that these modes differ in their implications for predictability, convenience, comfort, and perceived autonomy [15].

Table 2 develops an analytical typology of algorithmic coordination modes, showing how each mode produces distinct trade-offs between consumer agency, operational predictability, and long-term flexibility legitimacy.

Table 2. Analytical Typology of Algorithmic Coordination Modes and Their Agency–Stability Trade-Offs

Algorithmic coordination mode	Core decision logic	Dominant agency preserved	Dominant agency constrained	Expected grid-stability advantage	Principal stability risk	Theoretical interpretation

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

Advisory coordination	Algorithms recommend actions, but consumers decide whether and when to respond.	High decisional autonomy; high executive control.	Low automation convenience; higher cognitive burden.	Supports voluntary participation and perceived legitimacy.	Flexibility response may be slow, fragmented, or unreliable during fast system events.	Agency is preserved mainly through human discretion, but stability depends on active interpretation and behavioral follow-through.
Delegated coordination	Consumers pre-authorize automated action within defined comfort, cost, timing, or device boundaries.	Decisional autonomy through preference-setting; procedural control through authorization.	Some real-time executive control is transferred to algorithms.	Balances predictable response with consumer legitimacy.	Poorly designed preferences or unclear boundaries may produce mistrust or overrides.	The most theoretically stable mode when delegation is transparent, reversible, and aligned with household routines.
Opt-out coordination	Automated response occurs by default unless consumers intervene.	Residual executive control through opt-out or override.	Decisional autonomy may be weakened by default enrollment or low salience.	Increases speed, scale, and predictability of flexibility dispatch.	May generate alienation if consumers experience automation as hidden, intrusive, or difficult to contest.	Stability gains are strong in the short term but depend on whether consumers view default automation as legitimate.
Mandatory control	System requirements override household discretion during defined conditions.	Minimal agency, usually limited to prior consent or regulatory protection.	Executive control, decisional autonomy, and procedural fairness may be severely constrained.	Provides highly predictable response during emergencies or critical grid constraints.	High risk of resistance, distrust, inequitable burden, or political contestation.	Technically powerful but socially fragile unless narrowly bounded, justified, compensated, and regulated.

Dimensions of consumer agency

The second core construct is the degree and type of consumer agency preserved under each coordination mode. Advisory systems may preserve decisional autonomy but impose cognitive burden, especially when tariffs or signals are complex [6]. Delegated systems may preserve agency more effectively when consumers can define comfort, cost, timing, and override preferences in advance [21]. Mandatory or highly opaque systems may deliver more predictable flexibility in the short term, but the theory proposes that they risk weakening procedural fairness and informational transparency, particularly where consumers cannot understand or challenge automated actions [22].

Feedback loops with grid stability

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

The third core construct is grid stability feedback, understood as the dynamic relationship between algorithmic decisions, consumer reactions, and system outcomes. Consumers may comply with automated actions, override them, disengage from programs, shift consumption strategically, or adapt routines in ways that either strengthen or weaken flexibility reliability. Traditional engineering models often treat consumer response as an input parameter, but socio-technical research suggests that reactions evolve through experience, trust, perceived fairness, and institutional learning [23]. We therefore propose that grid stability is partly endogenous to consumer interpretations of algorithmic coordination rather than only a technical result of control performance.

Mechanisms Linking Demand Response, Agency, and Stability

The automation-alienation mechanism

The automation-alienation mechanism proposes that high levels of opaque automation can reduce consumer understanding, perceived autonomy, and willingness to remain enrolled in flexibility programs. When consumers experience algorithmic actions as intrusive, unexplained, or misaligned with household routines, they may interpret demand response as a loss of control rather than a contribution to collective grid stability [7]. This alienation can weaken long-term flexibility reliability because consumers may override devices, disable automation, reject future enrollment, or distrust aggregators and energy providers. Under this mechanism, short-term gains in predictable load control may be offset by longer-term erosion of participation legitimacy.

The agency-preserving design mechanism

The agency-preserving design mechanism proposes that transparent explanations, granular control, fair compensation, and meaningful override options can sustain trust while allowing algorithms to coordinate flexible resources. Consumer preference studies indicate that willingness to participate in demand response depends on motivators such as financial value, comfort protection, environmental contribution, and perceived fairness [11]. Smart charging research similarly suggests that user integration matters because flexibility services depend on aligning automated control with mobility needs, expectations, and routines [21]. The theory therefore suggests that agency-preserving design can increase both short-term operational effectiveness and long-term stability by making automated flexibility socially acceptable.

The stability-feedback mechanism

The stability-feedback mechanism explains how grid events, price volatility, or perceived system stress can reshape consumer attitudes toward algorithmic flexibility. During periods of instability or high renewable variability, consumers may temporarily accept stronger automation if it is framed as necessary for reliability, affordability, or collective resilience [12]. However, if such automation is experienced as unfair, poorly explained, or disproportionately burdensome, it may reduce trust in market institutions and accelerate disengagement once the immediate crisis passes [5]. The theory therefore proposes that stability events generate reinforcing or balancing feedback loops depending on whether consumers interpret algorithmic intervention as legitimate coordination or coercive control.

Boundary Conditions and Moderating Factors

Institutional trust and energy market design

The theory suggests that the effects of algorithmic coordination on consumer agency and grid stability are moderated by institutional trust and energy market design. In regulated systems, consumers may interpret automated demand response as part of a public reliability obligation, whereas in liberalized markets they may view it through the lens of supplier incentives, data control, and contractual risk. Research on barriers and enablers of demand response shows that participation depends on institutional arrangements as much as technical feasibility [24]. We therefore propose that

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

algorithmic flexibility is more likely to preserve agency and support stability when market rules make responsibilities, compensation, and consumer protections visible and credible.

Consumer vulnerability and socio-economic context

Consumer vulnerability moderates the agency-stability relationship because households differ in their ability to understand, negotiate, and absorb algorithmic flexibility decisions. The energy flexibility divide shows that flexibility opportunities may not be equally available to all households, especially when participation depends on home ownership, controllable devices, digital literacy, or financial capacity [25]. Automated demand response can therefore create unequal exposure to discomfort, price risk, or loss of control if vulnerable consumers have fewer alternatives. We propose that algorithmic coordination strengthens stability most legitimately when it accounts for socio-economic constraints rather than assuming that all consumers can exercise agency in the same way.

Technological infrastructure and device ownership

Technological infrastructure moderates the applicability of algorithmic energy flexibility because automated coordination depends on smart meters, interoperable devices, reliable communication networks, and controllable distributed resources. Machine learning-based demand response schemes for IoT-enabled smart buildings illustrate how flexibility depends on embedded sensors, connected platforms, and device-level control capacity [26]. However, device ownership also matters because renters, apartment residents, and consumers using shared heating or charging infrastructure may lack direct authority over the assets being controlled. The theory therefore suggests that algorithmic flexibility is strongest where technical controllability and consumer authority over devices are aligned.

Regulatory frameworks and consumer protection

Regulatory frameworks define the legal and procedural boundaries within which algorithmic flexibility can operate. Algorithmic governance research shows that automated decision systems reshape accountability by relocating decision authority into technical rules, platforms, and institutional procedures [10]. In the energy domain, consumer protections such as mandatory opt-outs, data privacy safeguards, compensation floors, and dispute mechanisms can determine whether automation is interpreted as legitimate coordination or coercive intervention [22]. We therefore propose that regulation moderates the agency-stability relationship by defining which forms of algorithmic control are acceptable, contestable, and accountable.

Theoretical Propositions and Research Implications

Propositions on algorithmic coordination and agency

The theory generates propositions about how different coordination modes affect consumer agency and stability. We propose that advisory coordination preserves higher decisional autonomy but yields less predictable flexibility because response remains dependent on active consumer interpretation and action, a pattern consistent with research on tariff complexity and informed decision-making [17]. We also propose that opt-out coordination produces higher short-term stability because it reduces response delay, but it may erode long-term agency if consumers perceive automation as opaque or difficult to override. Delegated coordination is expected to produce the most stable balance when consumers can predefine preferences and algorithms operate within those authorized boundaries.

Propositions on agency-preserving design and stability

The theory further proposes that agency-preserving design can convert consumer autonomy from a constraint on grid stability into a source of durable flexibility. Transparent explanations, easy override, comfort safeguards, and fair compensation should increase trust in automated demand response, especially where consumers perceive automation as serving both household and system interests [18]. Demand response research on residential willingness to enroll

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

suggests that participation is more likely when consumers see clear benefits and manageable risks [20]. We therefore propose that agency-preserving design improves long-term stability by reducing alienation, preventing withdrawal, and supporting repeated participation.

Propositions on feedback loops and dynamic behavior

The theory proposes that algorithmic flexibility produces dynamic feedback loops in which consumer experience alters future flexibility reliability. Stability crises, price spikes, or renewable variability may temporarily increase acceptance of automation, but this acceptance may decline if consumers later perceive that burdens were unfairly distributed or poorly explained [5]. Reinforcement learning approaches to demand response show that algorithmic systems can adapt to consumption patterns, yet the theory suggests that such adaptation must also account for evolving trust, fatigue, and resistance [27]. Future research should test whether stability feedback is reinforcing when consumers experience automation as legitimate and balancing when they experience it as intrusive or inequitable.

Methodological implications for future research

The theory implies that future empirical research should move beyond one-time measures of enrollment, load reduction, or technical performance. Longitudinal studies are needed to examine whether consumer trust, override behavior, and perceived fairness change as households accumulate experience with automated demand response [4]. Mixed methods can capture both measurable response patterns and the meanings consumers attach to automated control, while socio-technical modeling can represent interactions among devices, institutions, markets, and household practices [16]. Future empirical research should test whether the proposed mechanisms operate differently across housing types, market structures, device ecosystems, and vulnerability contexts.

Table 3 consolidates the theory into a testable analytical matrix by linking each proposed mechanism to moderators, observable indicators, and falsifiable research propositions.

Table 3. Theoretical Consolidation Matrix: Mechanisms, Moderators, Propositions, and Empirical Indicators

Theoretical mechanism	Core causal claim	Key moderators	Observable empirical indicators	Falsifiable proposition	Analytical contribution
Automation–alienation mechanism	Opaque or intrusive automation reduces perceived control, trust, and willingness to remain enrolled.	Institutional trust; transparency rules; consumer vulnerability; device ownership.	Override frequency; program withdrawal; trust decline; complaints; reduced willingness to re-enroll.	Programs with lower transparency and weaker override capacity will show higher disengagement over time, even when short-term load reduction is technically effective.	Explains why technically optimized demand response may fail socially or lose durability.
Agency-preserving design mechanism	Transparent explanations, granular control, fair compensation, and comfort safeguards convert agency into a	Market design; compensation adequacy; digital literacy; household flexibility capacity.	Sustained enrollment; lower override rates; higher satisfaction; greater perceived fairness; repeated participation.	Delegated systems with clear preference-setting and easy override will produce more durable participation	Reframes consumer agency as a stabilizing resource rather than an obstacle to optimization.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

	source of durable flexibility.			than opaque opt-out systems.	
Stability-feedback mechanism	Grid events, price volatility, and perceived system stress reshape future acceptance of algorithmic intervention.	Crisis framing; burden distribution; public communication; regulatory legitimacy.	Changed trust after grid events; altered acceptance of automation; post-event enrollment changes; perceived fairness of intervention.	Acceptance of stronger automation will increase after system stress only when interventions are perceived as fair, necessary, and well explained.	Makes grid stability endogenous to consumer interpretation and institutional legitimacy.
Flexibility-divide mechanism	Unequal access to controllable devices, ownership rights, digital literacy, and financial capacity creates uneven agency and uneven exposure to risk.	Housing tenure; income; appliance ownership; energy vulnerability; access to smart infrastructure.	Differential enrollment; unequal compensation; discomfort exposure; inability to override; exclusion from flexibility markets.	Vulnerable or infrastructure-poor households will experience lower agency and fewer benefits from algorithmic flexibility unless protections are built into program design.	Extends the theory from average consumer response to distributive and justice-sensitive analysis.
Regulatory-legitimacy mechanism	Consumer protections and accountability structures determine whether algorithmic control is interpreted as coordination or coercion.	Data privacy standards; opt-out rights; dispute mechanisms; compensation floors; public-service obligations.	Consumer complaints; regulatory disputes; perceived accountability; trust in aggregators; acceptance of automated control.	Algorithmic demand response programs with stronger procedural protections will sustain higher legitimacy and lower resistance across repeated interventions.	Links technical flexibility governance to accountability, contestability, and institutional trust.

Practical and Policy Implications of The Theory

Designing algorithmic flexibility for agency and stability

For demand response platforms, aggregators, and smart home systems, the theory implies that flexibility design should not treat consumer agency as an obstacle to optimization. Instead, agency should be built into algorithmic systems through preference-setting tools, transparent explanations, controllable automation levels, and reliable override functions. Automated demand response reviews show that metering, communication, and optimization infrastructures are necessary but insufficient without mechanisms that support consumer participation and acceptance [9]. The practical implication is that technically efficient flexibility systems may fail over time if they do not also preserve meaningful forms of household control and understanding. **Figure 2** illustrates how demand response and smart home flexibility systems can preserve consumer agency while maintaining grid stability through preference control, explainability, adjustable automation, and override capacity.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

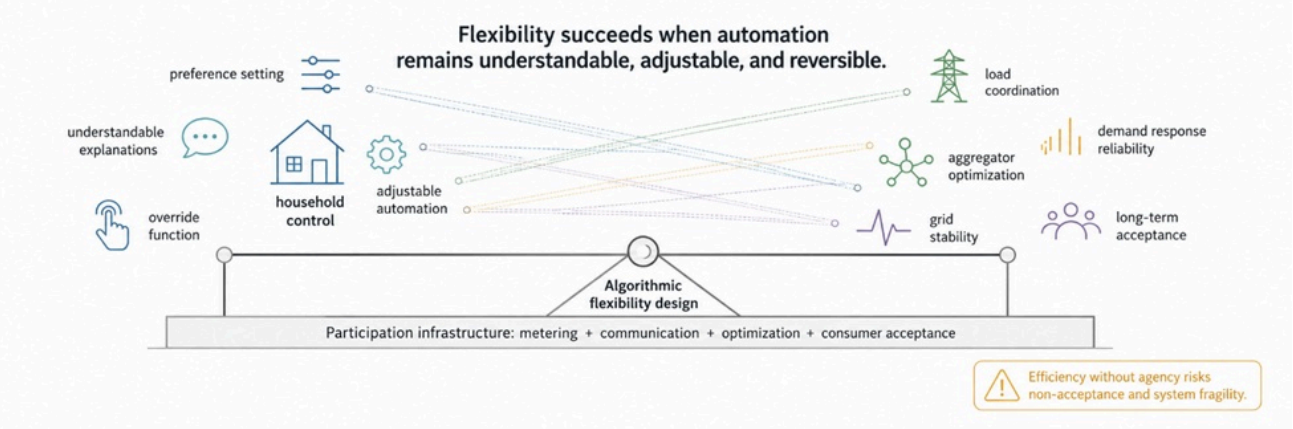


Figure 2. Algorithmic Flexibility as a Stability–Agency Design Balance

Regulatory safeguards and consumer empowerment

For policymakers, the theory suggests that algorithmic flexibility programs should be evaluated not only by their grid contribution but also by their effects on consumer agency, fairness, and vulnerability. Demand-side technological and social innovation research highlights that decarbonization pathways require attention to both technical transformation and social acceptance [28]. Inclusive innovation research similarly indicates that smart local energy systems must account for participation, justice, and institutional legitimacy rather than assuming that innovation benefits are automatically shared [29]. Policy measures such as transparency standards, dynamic consent mechanisms, agency impact assessments, and protection for vulnerable consumers would therefore strengthen both legitimacy and stability.

Recent scholarship further reinforces the importance of integrating explainability, adaptive coordination, and participatory governance into algorithmic flexibility systems. Research on explainable artificial intelligence in smart grids suggests that transparency-enhancing interfaces can improve user trust and facilitate more informed participation in automated energy management systems, particularly when consumers are asked to delegate operational decisions to algorithms [30]. In parallel, studies of transactive energy coordination indicate that decentralized flexibility markets depend not only on optimization efficiency but also on interoperable governance structures capable of balancing consumer preferences with grid reliability objectives [31]. Emerging evidence from human-centered energy informatics research additionally shows that algorithmic flexibility programs are more likely to sustain long-term engagement when users perceive system recommendations as understandable, negotiable, and aligned with everyday routines rather than purely system-centric control imperatives [32].

Evaluation Strategy for the Theory

Theoretical coherence and explanatory power

The theory should first be evaluated for internal coherence, parsimony, and explanatory power. It is coherent if the constructs of algorithmic coordination, consumer agency, and grid stability remain analytically distinct while explaining their interdependence. It is parsimonious if it explains variations in demand response outcomes without reducing them solely to technology, incentives, or behavior, a limitation identified across demand response and smart grid literatures [24]. Its explanatory power lies in accounting for why technically sound flexibility programs may fail when agency is undermined, and why socially legitimate programs may produce more durable stability contributions.

Falsifiability and empirical testability

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

The theory is formulated to be falsifiable because its propositions specify expected relationships among automation mode, agency preservation, consumer response, and stability outcomes. Surveys could test whether transparency and override capacity predict trust and sustained participation, while qualitative case studies could examine how households interpret algorithmic control in different socio-economic settings [11]. Experiments or agent-based models could assess whether advisory, delegated, opt-out, and mandatory coordination modes generate different patterns of compliance, override, or disengagement under simulated market conditions [27]. Future empirical research should test whether agency-preserving design produces more stable participation trajectories than opaque automation.

Practical relevance and stakeholder resonance

The theory should also be evaluated by its practical relevance for grid operators, aggregators, policymakers, technology designers, and consumer advocates. For grid operators, it explains why reliable flexibility depends not only on device controllability but also on consumer trust and institutional legitimacy. For technology designers, it clarifies why interaction design and automation levels shape acceptance of demand-side management [18]. For consumer advocates and regulators, it provides language for assessing whether algorithmic demand response empowers households or shifts system risk onto consumers with limited ability to respond.

Limitations

Conceptual novelty and the risk of overgeneralization

The theory is conceptually novel and therefore risks overgeneralizing across diverse energy systems, cultures, housing contexts, and regulatory environments. Research on social acceptability in demand management shows that consumer responses may vary across countries, institutional settings, and public expectations about energy systems [23]. The theory should therefore be treated as a starting point for empirical confrontation rather than a universal explanation. Future work should refine the proposed mechanisms by testing where the agency-stability tension is strongest, weakest, or transformed by local conditions.

Scope boundaries and disciplinary limitations

The theory focuses primarily on residential and small commercial demand response, where consumer agency, household routines, and device-level automation are especially salient. It may apply less directly to industrial flexibility, wholesale market dynamics, or large-scale balancing resources where organizational decision-making and contractual structures differ substantially. Research on sectoral demand-side flexibility shows that residential, industrial, commercial, and agricultural flexibility resources vary in controllability, incentives, and operational constraints [8]. The theory is therefore best understood as a socio-technical account of algorithmically mediated end-use flexibility rather than a complete theory of all flexibility markets.

Conclusion

This article has developed a theory of algorithmic energy flexibility that conceptualizes demand response as a socio-technical phenomenon linking automated coordination, consumer agency, and grid stability. The theory explains flexibility not merely as a technical resource but as a mediated capacity shaped by devices, algorithms, consumers, institutions, and market rules.

The theory's integrative ambition is to bridge technical optimization and social science concerns in a single conceptual account. It helps explain why some demand response programs may succeed technically but struggle socially, while others may preserve consumer legitimacy yet provide less predictable flexibility for system operation.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

The key mechanisms of automation-alienation, agency-preserving design, and stability feedback clarify how algorithmic systems can either strengthen or undermine durable demand response participation. The propositions suggest that flexibility systems should be designed to preserve meaningful agency while delivering reliable coordination for grid stability.

Future research should test, refine, and extend this theory through interdisciplinary collaboration among energy engineers, social scientists, policymakers, behavioral researchers, and consumer advocates. Such work is necessary to ensure that algorithmic energy flexibility serves both system needs and human values.

Acknowledgements

None

Conflict of interest

None

Financial support

None

Ethics statement

None

Received: 25 Oct 2022 Revised: 30 Dec 2022 Accepted: 16 Jan 2023
Published online: 15 November 2023

Rights and permissions

Open Access The author(s) retain copyright. This article is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. It may be shared and adapted for non-commercial purposes with appropriate attribution, an indication of changes, and distribution of adaptations under the same license. Third-party material may be subject to separate terms identified in its credit line. View the license at https://creativecommons.org/licenses/by-nc-sa/4.0/.

References

1. Lu R, Hong SH, Zhang X. A dynamic pricing demand response algorithm for smart grid: reinforcement learning approach. Appl Energy. 2018;220:220-30.

2. Smale R, Van Vliet B, Spaargaren G. When social practices meet smart grids: flexibility, grid management, and domestic consumption in The Netherlands. Energy Res Soc Sci. 2017;34:132-40.

3. Pallonetto F, De Rosa M, Milano F, Finn DP. Demand response algorithms for smart-grid ready residential buildings using machine learning models. Appl Energy. 2019;239:1265-82.

4. Parrish B, Heptonstall P, Gross R, Sovacool BK. A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response. Energy Policy. 2020;138:111221.

5. Calver P, Simcock N. Demand response and energy justice: a critical overview of ethical risks and opportunities within digital, decentralised, and decarbonised futures. Energy Policy. 2021;151:112198.

6. Layer P, Feurer S, Jochem P. Perceived price complexity of dynamic energy tariffs: an investigation of antecedents and consequences. Energy Policy. 2017;106:244-54.

7. Torriti J, Yunusov T. It's only a matter of time: flexibility, activities and time of use tariffs in the United Kingdom. Energy Res Soc Sci. 2020;69:101697.

8. Golmohamadi H. Demand-side flexibility in power systems: a survey of residential, industrial, commercial, and agricultural sectors. Sustainability. 2022;14(13):7916.

9. Tiwari A, Pindoriya NM. Automated demand response in smart distribution grid: a review on metering infrastructure, communication technology and optimization models. Electr Power Syst Res. 2022;206:107835.

10. Gritsenko D, Wood M. Algorithmic governance: a modes of governance approach. Regul Gov. 2022;16(1):45-62.

11. Sridhar A, Honkapuro S, Ruiz F, Stoklasa J, Annala S, Wolff A, et al. Residential consumer preferences to demand response: analysis of different motivators to enroll in direct load control demand response. Energy Policy. 2023;173:113420.

12. Panda S, Mohanty S, Rout PK, Sahu BK, Parida SM, Samanta IS, et al. A comprehensive review on demand side management and market design for renewable energy support and integration. Energy Rep. 2023;10:2228-50.

13. Rohde F, Hielscher S. Smart grids and institutional change: emerging contestations between organisations over smart energy transitions. Energy Res Soc Sci. 2021;74:101974.

14. Martin R. Energy housekeeping: intersections of gender, domestic labour and technologies. Build Cities. 2022;3(1):554-69.

15. Lu R, Hong SH, Yu M. Demand response for home energy management using reinforcement learning and artificial neural network. IEEE Trans Smart Grid. 2019;10(6):6629-39.

16. Piano SL, Smith ST. Energy demand and its temporal flexibility: approaches, criticalities and ways forward. Renew Sustain Energy Rev. 2022;160:112249.

17. El Gohary F, Nordin M, Juslin P, Bartusch C. Getting the signal: do electricity users meet the preconditions for making informed decisions on demand response? Energy Res Soc Sci. 2023;100:103119.

18. Diamond L, Mirnig A, Fröhlich P. Encouraging trust in demand-side management via interaction design: an automation level based trust framework. Energies. 2023;16(5):2393.

19. Hussain M, Gao Y. A review of demand response in an efficient smart grid environment. Electr J. 2018;31(5):55-63.

20. Sridhar A, Honkapuro S, Ruiz F, Stoklasa J, Annala S, Wolff A, et al. Toward residential flexibility—consumer willingness to enroll household loads in demand response. Appl Energy. 2023;342:121204.

21. Baumgartner N, Weyer K, Eckmann L, Fichtner W. How to integrate users into smart charging—a critical and systematic review. Energy Res Soc Sci. 2023;100:103113.

22. Noorman M, Espinosa Apráez B, Lavrijssen S. AI and energy justice. Energies. 2023;16(5):2110.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press

23. Gleue M, Unterberg J, Löschel A, Grünewald P. Does demand-side flexibility reduce emissions? Exploring the social acceptability of demand management in Germany and Great Britain. Energy Res Soc Sci. 2021;82:102290.

24. Good N, Ellis KA, Mancarella P. Review and classification of barriers and enablers of demand response in the smart grid. Renew Sustain Energy Rev. 2017;72:57-72.

25. Savelli I, Morstyn T. The energy flexibility divide: an analysis of whether energy flexibility could help reduce deprivation in Great Britain. Energy Res Soc Sci. 2023;100:103083.

26. Balakumar P, Vinopraba T, Chandrasekaran KJ. Machine learning based demand response scheme for IoT enabled PV integrated smart building. Sustain Cities Soc. 2023;89:104260.

27. Wan Y, Qin J, Yu X, Yang T, Kang Y. Price-based residential demand response management in smart grids: a reinforcement learning-based approach. IEEE/CAA J Autom Sin. 2021;9(1):123-34.

28. Khanna NZ, Zhang J, Lu H, Feng W, Johnson-Wang M, Zhou N. Conceptualizing demand-side technological and social innovations in modeling pathways to carbon neutrality. Energy Res Soc Sci. 2023;100:103115.

29. Smith A, Contreras GA, Brisbois MC, Lacey-Barnacle M, Sovacool BK. Inclusive innovation in just transitions: the case of smart local energy systems in the UK. Environ Innov Soc Transit. 2023;47:100719.

30. Ozdemir G, Kuzlu M, Sarp S, Catak FO, Dimd BD, Cali U. The role of explainable artificial intelligence (XAI) in smart grids. In: Big data application in power systems. Elsevier Science; 2024. p. 349-70.

31. Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E. Peer-to-peer and community-based markets: a comprehensive review. Renew Sustain Energy Rev. 2019;104:367-78.

32. He R, Jin J, Qiu X, Zhang C, Yan J. Rural residents' climate change perceptions, personal experiences, and purchase intention-behavior gap in energy-saving refrigeration appliances in Southwest China. Environ Impact Assess Rev. 2023;98:106967.

© 2023 The Author(s). | Published by Institute of Smart Energy Systems Press