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Review



Beyond optimisation: Revisiting energy demand management

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ABSTRACT

Energy demand reduction (EDR) in households has re-emerged as a central pillar of climate and energy transition strategies in Europe and beyond. While energy efficiency has long dominated policy frameworks, growing evidence shows that efficiency alone is insufficient to achieve absolute reductions in energy consumption due to persistent rebound effects, lock-in dynamics, and equity concerns. This paper presents a systematic literature review of 137 studies published between 2004 and 2024, selected through a PRISMA-guided process with expert validation. The review adopts a structured, question-driven framework and a hybrid methodology combining AI-assisted analysis with expert synthesis. Three perspectives, energy efficiency, energy sufficiency, and behavioural change, are used as analytical lenses to identify complementarities and limitations in current EDR approaches. Findings indicate that effective EDR strategies require integrated technological, behavioural, and policy measures. Key enablers identified in the literature include fiscal incentives and digital technologies, while major barriers involve financial constraints, behavioural inertia, and fragmented governance. The reviewed studies further suggest that energy demand reductions of 37–61% may be achievable across different contexts and scenarios, although only through coordinated and systemic approaches. The review also highlights important co-benefits, including reduced energy poverty, improved health, greater energy independence, and enhanced energy security. However, EDR strategies may also generate rebound effects and unequal distributions of costs and benefits. Overall, the findings underline the importance of embedding EDR within justice-oriented and socially inclusive policy frameworks to support both climate mitigation and broader societal resilience.

1. Introduction

As Europe strives to meet its ambitious climate commitments, a unified and coordinated energy transition strategy remains elusive. Accelerating the energy transition offers a common opportunity for achieving long-term energy security, price stability, and enhanced resilience across the European Union (EU) in response to rising geopolitical tensions and environmental risks [1]. Over the past decades, the EU has developed a comprehensive policy framework to address energy demand and efficiency, including the Energy Efficiency Directive (EED), the Energy Performance of Buildings Directive (EPBD), Ecodesign and Energy Labelling regulations, as well as earlier instruments such as the National Energy Efficiency Action Plans (NEEAPs). More recently, these efforts have been complemented by the National Energy

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and Climate Plans (NECPs), aimed at strengthening coordination and aligning national actions with EU-wide targets. Despite this evolving and increasingly robust policy landscape, European countries continue to approach the transition with varied strategies, differing target ambitions, and uneven speeds of implementation [2].

1.1. Decarbonization pathways and the role of energy demand management

These strategies can be broadly grouped into three complementary dimensions of decarbonization: (i) transformation of energy supply systems, (ii) carbon mitigation and removal measures, and (iii) energy demand management (EDM). Across countries, approaches within (i) differ considerably. While some prioritize the expansion of renewable energy sources such as wind and solar, others rely on low-carbon alternatives like nuclear energy, which provide stable baseload capacity without direct CO_2 emissions, albeit at higher financial and operational costs [3]. Variation is equally evident within (ii), both in the types of solutions adopted and in their timing. Some countries emphasise nature-based solutions, such as enhancing carbon sinks through Land Use, Land-Use Change, and Forestry (LULUCF), while others invest in technological approaches, including engineered carbon removal methods like carbon capture and storage (CCS) [4]. These differences relate to both the solutions chosen and their timing, leading to divergent outcomes across countries, as delayed action may be politically or economically attractive in the short term but results in higher cumulative emissions [5]. By contrast, (iii) remains less clearly delineated within the overall transition. Although demand-side strategies are frequently discussed alongside supply-side and mitigation measures, their specific role is often not explicitly distinguished. This lack of clarity is reflected in national policy frameworks, where some countries rely primarily on carbon pricing, while others combine regulatory, market-based [6], and non-market-based instruments [7]. At the same time, despite longstanding policy efforts, energy demand in the EU is not consistently declining and is, in some sectors, increasing, driven by structural transformations such as the electrification of transport, the expansion of digital infrastructure (e.g. data centres), and growing electricity needs in emerging strategic sectors [8].

In this framework, the urgency of reducing energy consumption has been further amplified by the recent energy crisis following Russia's invasion of Ukraine, which reignited Europe's focus on cutting energy demand. Originally a response to the oil crises of the 1960s and 1970s, the concept of reducing overall energy consumption now emerges as a critical pathway to address the dual challenges of energy security and climate change [9]. Recent evidence, including the IPCC Sixth Assessment Report (AR6), highlights that demand-side measures are indispensable for achieving climate targets, as they directly reduce emissions while lowering the scale and cost of required supply-side and mitigation solutions [5]. In this context, Energy Demand Reduction (EDR), focused on optimizing energy use and curbing unnecessary consumption, has become a core element of Europe's broader EDM strategy, which also encompasses demand-side management practices [10]. Rather than representing an optional strategy, EDR should be understood as a central and equitable component of decarbonization, complementing and enabling supply-side and mitigation efforts. EDR is increasingly recognized as a vital strategy for achieving climate targets [11]. The International Renewable Energy Agency (IRENA) identifies EDR as one of six technological avenues for reducing emissions by 2050, estimating that 25% of the reduction will come directly from EDR efforts, achieved through reduced demand and efficiency improvements [12]. This aligns with a growing number of climate scenarios, such as the LIFE scenario in the European Commission's 2040 ex-ante assessment report [13], the "Road to Net Zero" from the Institut Rousseau [14], and the recent CLEVER scenario [15], all highlighting the need for EDR not only to reach targets but to do so affordably [13,16]. In addition to environmental and energy security benefits, reductions in energy consumption, whether achieved through absolute demand reduction or optimized use, provide substantial economic advantages [17]. Reducing energy demand allows households and businesses to lower energy costs, freeing up resources for other investments [18]. Moreover, lower energy demand reduces exposure to energy price volatility and supply disruptions, thereby contributing to greater economic stability, particularly in energy-import-dependent regions such as Europe [10].

1.2. Understanding and enacting energy demand reduction

As EDR gains prominence in the EU's policy agenda, this paper aims to provide a thorough review of recent advancements in the scientific and policy debate and deliver actionable insights for practitioners and policymakers, supporting effective EDR implementation with a specific focus on households. Given the rapid evolution and strategic importance of EDR across Europe, it is essential to keep knowledge in this field up to date, with particular emphasis on factors that drive successful implementation, including theoretical frameworks, underlying societal dynamics, and technological integration. This paper aims at answering the overarching research question: "What are the main drivers, frameworks, and strategies of energy demand reduction in households, and how can they be effectively and equitably implemented?". To this end, in accordance with EERA work on EDR [19], it adopts a combination of three analytical perspectives (efficiency, sufficiency and behavioural change) to scrutinize the literature in the field. And it provides a structured, question-driven framework for the analysis, inspired by methodological approaches designed to foster in-depth understanding through progressive inquiry [20].

In this paper, EDR is understood as a set of strategies aimed at lowering overall energy consumption by addressing both the level and the nature of energy demand. This includes not only direct demand-reducing approaches, such as behavioural change and energy sufficiency, but also energy efficiency measures, which influence overall demand trajectories by reducing the energy required to deliver services. While energy efficiency does not necessarily lead to absolute reductions in energy consumption [21], it remains a central component of the broader energy demand debate and is therefore included within the scope of this paper. This is particularly relevant in the EU policy context, where efficiency has long been prioritized as a primary lever for managing energy demand and interacts closely with behavioural and sufficiency-oriented measures.

Energy efficiency, the most well-known of these, refers to the ratio of useful energy output to the energy input required to perform a specific task or service [22]. It is a structured and widely referenced approach across EU legislation [23–25] that, by promoting the adoption of the Energy Efficiency 1st principle, prioritize energy efficiency "as the first fuel, that is a source of energy in its own right, in which the public and the private sectors can invest ahead of other more complex or costly energy sources ('save before you build')". However, definitions and interpretations of energy efficiency have evolved across academic disciplines and policy contexts. Some studies focus on technical performance and energy-efficient technologies [22], while others raise concerns about measuring energy inputs and outputs in different contexts and the "energy efficiency gap" or the discrepancy between theoretical and actual energy savings [18]. Further debate surrounds the relationship between energy efficiency and economic growth, with diverse views on how efficiency improvements affect growth and innovation [26]. In addition to energy efficiency, there has been a gradual shift toward better understanding behavioural change, driven by public authorities and academics seeking to understand consumer behaviour and energy-saving practices [18,27]. Behavioural change involves a multi-stage process, influencing individuals' attitudes, behaviours, and choices [28,29]. It considers intentions, habits, situational factors, and the conditions under which individuals operate [30], as well as social norms, cultural conventions, and shared consumer practices [31]. Factors such as activity location, duration, coordination, and appliance use

are key to understanding energy consumption behaviours [31]. Addressing these factors requires a multidisciplinary approach that considers the socio-material constitution of energy demand, cultural contexts, and everyday life [32]. The concept of energy sufficiency, advocating the avoidance of unnecessary energy demand while maintaining human well-being [5] is also gaining traction [33]. With some countries cautiously introducing policies to reduce baseline demand [34], the definition of energy sufficiency has evolved, reflecting the recognition that efficiency measures alone may not achieve consumption reduction goals [35]. Energy sufficiency is generally understood as a strategy to limit and reduce the input of energy while ensuring adequate services for basic needs [36,37]. However, what constitutes "sufficient" energy remains contested in the literature, with no uniform definition. Interpretations vary from those emphasizing access to a minimum level of energy services associated with basic needs, to broader perspectives that frame sufficiency in terms of enabling a dignified standard of living, social participation, and well-being, particularly in high-income contexts [36,38,39]. These differing views are reflected in approaches that emphasise frugal lifestyles and reduced material consumption [40], as well as those focusing on wider lifestyle changes and cultural shifts [41,42]. While sufficiency is often associated with lifestyle changes, it differs from behavioural change in that it explicitly targets absolute reductions in energy demand through structural, social, or regulatory measures, rather than focusing solely on individual decision-making processes.

1.3. Aim and structure of the paper

The analysis is organized around ten guiding questions, identified through a structured consultation with an expert group on EDR (see Methodology). These questions progress from foundational concepts to applied perspectives, linking EDR to related domains. To support this analysis, a dedicated knowledge base was developed by combining AI-driven tools with expert knowledge. The paper concludes by synthesizing the main findings, identifying knowledge gaps and implementation challenges, outlining directions for future research, and highlighting key policy implications, with the aim of advancing both conceptual understanding and practical application of EDR.

2. Methodology

2.1. AI-supported systematic literature review (SLR)

The systematic literature review was conducted to examine EDR through the lens of three complementary perspectives: energy efficiency, energy sufficiency, and behavioural change. This focus is the result of joint research by the authors of this paper who produced the EERA 2023 Flagship report on EDR [19]. Experts were selected within the EERA consortium based on their recognized experience in the field and consolidated at an international Conference in Padova in October 2023 [43]. The methodology adopts a collaborative approach, combining expert knowledge from EDR specialists with advanced AI tools to streamline and enhance the review process. Compared to fully manual reviews, AI tools enabled faster screening of large volumes of literature, supported the prioritization of relevant papers, and facilitated the identification of thematic connections across studies. In this way, AI primarily improved the efficiency and consistency of the review process, rather than replacing expert judgment. This combined approach responds to a growing usage of natural language-based tools, particularly large language models (LLM), which are reshaping academic research, though not without potential biases [44]. To address this, the paper integrates AI tools with expert judgment in a transparent bibliometric systematic literature review [45]. More specifically, AI tools were used at two stages: during the title and abstract screening phase, where they supported the prioritization of papers based on relevance, and during the synthesis phase, where a context-aware generative AI system (Petal) was used to generate preliminary responses to the guiding research questions based exclusively on the selected knowledge base. The selection of the literature included in the review (knowledge base) followed the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; [46]). All AI-generated outputs were treated as intermediate analytical support. They were systematically reviewed, validated, and rewritten by the authors, who retained full responsibility for the interpretation, synthesis, and final wording of the manuscript. No text generated by AI tools was included without substantial human revision.

2.2. Information source and search strategy

The literature was sourced from the Web of Science database (Clarivate), which was selected for its comprehensive coverage of high-quality academic publications. A total of four separate searches were carried out, each corresponding to a different theoretical perspective within the framework of this review. A supplementary search was conducted for the sufficiency perspective, which, due to its nuanced nature and less established presence in the literature, required additional scrutiny. The search strings were formulated to target the reduction of energy demand through the three different perspectives.

1. Energy Efficiency Perspective: ((TS = ("energy demand")) AND TS = (reduc*)) AND TS = (efficien*)
2. Behavioural Change Perspective: ((TS = ("energy demand")) AND TS = (reduc*)) AND TS = (behavio*)
3. Sufficiency Perspective:
   a. ((TS = ("energy demand")) AND TS = (reduc*)) AND TS = (sufficien*)
   b. ((TS = (energy)) AND TS = (degrowth OR de-growth))

Filters were applied to include peer-reviewed articles, review articles, and book chapters published from January 1, 2004, to May 25, 2024.

2.3. Eligibility criteria

After the initial filtering through the database, additional selection criteria were established to refine the pool of studies. The process unfolded in two stages: first, a screening of titles and abstracts, followed by a full-text screening. While the primary focus was on European countries, studies from other contexts were included where they provided relevant insights for the energy demand reduction context and were considered transferable to similar socio-economic conditions. Given the focus of the paper is on EDR in households, studies were also excluded when their topics were outside the scope of residential energy use, such as those dealing primarily with industrial or transport sectors. Disciplinary irrelevance was another criterion for exclusion, with papers outside the fields of social sciences and humanities (SSH), environmental sciences, or economics being omitted. In addition, works published in predatory journals, as identified in Beall's list of potential predatory journals and publishers, based on criteria such as editorial overlap, misleading practices, and mission incongruence were excluded [47]. Finally, during the full-text screening stage, reviewers applied all these criteria in detail, retaining only those studies that demonstrated a robust and clearly defined methodology suitable for replication.

2.4. Selection process

The paper selection process was carried out by a team of 10 researchers, organized into 3 groups based on their expertise, with each group focusing on one of the three perspectives: Energy Efficiency, Behavioural change, and Sufficiency. The final body of papers is therefore the result of 3 separate selection processes, each following the same selection criteria. The platform Hubmeta [48], a web-based data entry

system for Systematic Review, was employed to assist the paper selection process. The platform also provided AI assistance at the state of title and abstract screening by analysing the selection patterns of the researchers and prioritizing papers for the review accordingly. During the full-text screening process, the multiple researchers independently reviewed each paper to ensure a rigorous and impartial selection. The resulting set of selected articles constituted the "Knowledge Base" (See Fig. 1).

2.5. Results of the selection process

From an initial pool of 5987 records, most of the articles were excluded during the title and abstract screening phase. In the Efficiency category, 4430 records were identified. After deduplication, 4428 remained, of which 331 were excluded during the initial screening. Among the 97 full-text articles assessed, 34 were excluded, resulting in 63 studies included in the final analysis. For Behavioural Change, 1017 records were screened. Following deduplication (1015 records), 903 were excluded based on title and abstract, and 41 more after full-text review, leaving 71 studies for inclusion. In the Sufficiency category, 536 records were screened, with 505 excluded during initial screening and 8 following full-text review, resulting in 23 included studies. In total, 157 studies were selected across all categories. After removing duplicates, mostly overlaps between Efficiency and Behavioural Change, the final number of unique studies included in the analysis was 137. The complete list of papers included in the final knowledge base, also indicating the papers selected across multiple categories, can be consulted in Table S1, supplemental materials. Fig. 2 provides a breakdown of the papers selected across multiple categories, reflecting the filtering applied at various stages of the review process.

2.6. Synthesis methods and expert-guided validation

Once the knowledge base was established, a set of ten guiding questions was defined by the experts to structure the synthesis of the selected literature. Inspired by Galvin & Sunikka-Blank, 2017 [20], the guiding questions follow a progressive analytical logic. Questions 1–3 primarily address conceptual foundations, theoretical perspectives, and governance approaches to EDR. Questions 4–8 focus more directly on implementation challenges, including barriers, social and economic implications, justice dimensions, and rebound effects. Finally, Questions 9–10 examine future EDR pathways, scenario development, and remaining research and policy gaps. This question-driven approach was selected to address the interdisciplinary and fragmented nature of EDR, which spans engineering, economics, behavioural sciences, and policy studies [20]. The questions were developed through an expert consultation process involving the EDR expert group. This process combined insights emerging from the initial literature screening, identification of recurring conceptual gaps and policy-relevant issues, and iterative refinement through expert discussion. The analysis of the knowledge base to find responses to the nine questions was conducted with the assistance of Petal (Petal.org), a context-aware generative AI system, which was exclusively trained on the selected knowledge base composed by the 137 papers selected. The initial responses generated by the Petal AI tool were used by the research team to formulate follow-up queries and identify additional relevant literature. All Petal-generated outputs were used as input to support the authors' analysis and were critically reviewed, refined, and fully rewritten. The final text presented in the manuscript reflects the authors' own interpretation and synthesis and does not reproduce any direct outputs from the AI system. This hybrid methodology also explains why not all of the 137 selected papers were included in the final synthesis, despite forming part of the knowledge base.

3. Results – Nine questions and responses around EDR

3.1. Which are the key themes and concepts studied in EDR?

Fig. 3 presents a keyword co-occurrence network from the knowledge base generated with VOSviewer [49]. The analysis is based on 89 keywords which met the minimum threshold of 3 occurrences and reveals 7 clusters of terms, from which 5 can be seen as major: Cluster 1, displayed in red, reflects research focused on optimizing technical systems, improving building performance, and identifying policy levers to encourage the adoption of energy-efficient technologies, often through modelling and empirical assessment. Cluster 2 (purple) comprises policy design, evaluation, and systemic implications, including critiques of policy effectiveness, rebound effects and regulatory limitations. Cluster 3 (green) reflects a research stream concentrated on the behavioural and societal aspects of energy consumption, sustainability goals, and social factors influencing energy practices. Cluster 4 (blue) links research around decision-making dynamics at the individual and group levels,

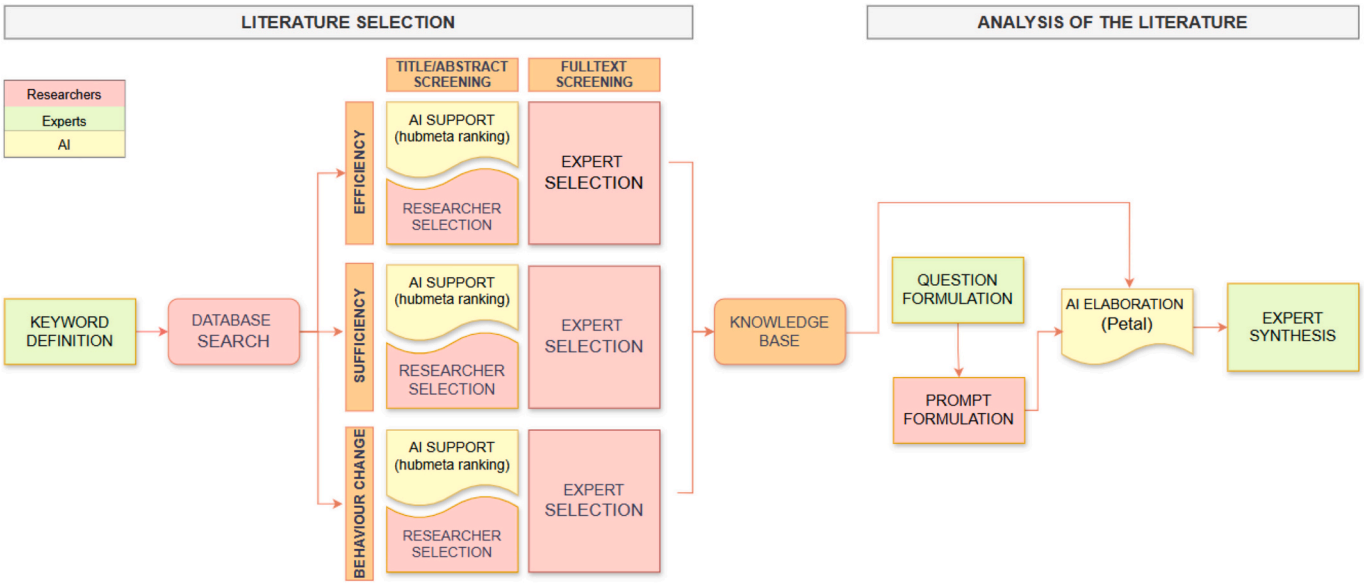


Fig. 1. Overview of the workflow for the systematic literature review, outlining the different stages of the process and the interaction of researcher, expert, and AI input.

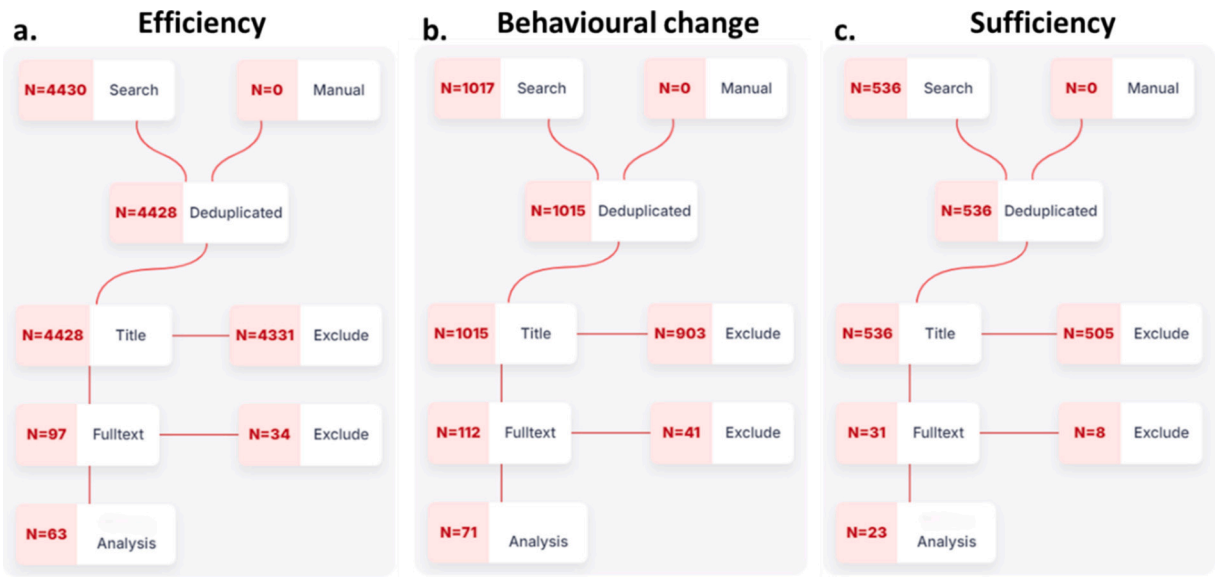


Fig. 2. PRISMA chart – outline of the selection of papers in the category efficiency (a), behavioural change (b) and sufficiency (c). Source: Hubmeta.

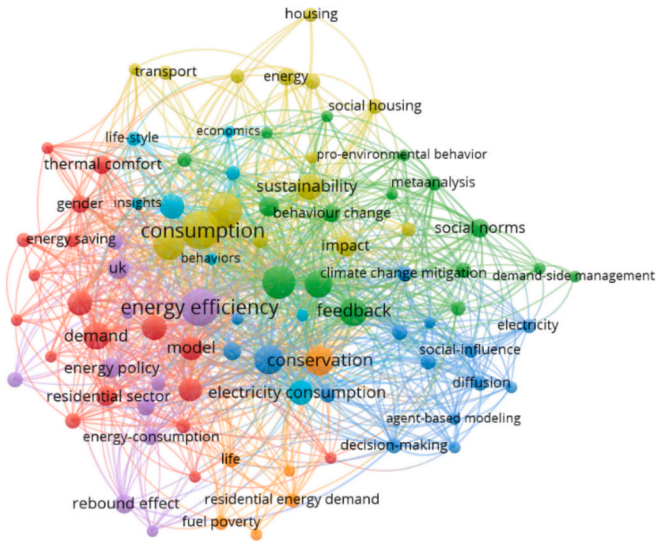


Fig. 3. Keyword network from the final selection of papers (137), generated using VOSviewer. Note: Larger nodes reflect higher frequency of term occurrence, proximity reflects higher co-occurrence.

while Cluster 5 (yellow) engages with the built environment, covering residential energy use and mobility systems. Central terms such as *energy efficiency*, *consumption*, *policy*, *behaviour*, *conservation*, and *sustainability* are prominent across clusters. The dense network of interconnections, especially around bridging terms like *conservation* and *sustainability*, illustrates the cross-cutting nature of EDR research. It also highlights how boundaries between technical, behavioural, and societal domains are increasingly blurred.

3.2. What are the main theoretical frameworks for understanding EDR

Table 1 provides a summary of the main conceptual and analytical frameworks emerging from the systematic literature review. The table highlights the conceptual plurality behind EDR, combining behavioural, socio-cultural, techno-economic and transition-oriented perspectives. Across the literature, reductions in energy demand cannot be explained solely through technological efficiency improvements or individual decision-making. Behavioural economics, practice theory, and the energy cultures framework foreground the cognitive, normative, material, and routine-based dimensions of energy demand, thereby challenging narrow rational-choice assumptions. Meanwhile, demand-response approaches, hybrid modelling, and efficiency-oriented pathways provide important system-level and techno-economic insights, although they may risk instrumentalising demand as a variable to be optimized rather than as a socially constituted phenomenon. Diffusion of innovations theory and socio-technical transition perspectives situate EDR within broader processes of socio-technical change, institutional adaptation, and systemic reconfiguration [50,51]. (See Table 2.)

Together, these frameworks demonstrate that EDR cannot be reduced to a single disciplinary perspective. Instead, the literature increasingly treats technological optimisation, behavioural dynamics, social practices, governance structures, and broader societal transformations as interdependent dimensions of energy demand reduction.

A large body of research focuses on improving energy use through technological innovation and policy mechanisms, emphasizing optimisation, efficiency improvements, and the deployment of low-carbon systems [18]. These approaches often rely on frameworks such as Hybrid Modelling [53], Energy Efficiency Gap Theory [54], and Efficiency Pathways [55], which incorporate economic constraints, investment barriers, and renewable energy substitution strategies. At the same time, the literature highlights that technological improvements alone do not necessarily result in proportional reductions in overall energy consumption [56]. This perspective often overlooks behavioural side effects such as the rebound effect [52,57,58], situations in which efficiency improvements trigger behavioural or systemic responses that partially offset the expected energy savings [44], as well as free-riding behaviour, whereby individuals or actors benefit from collective energy-saving efforts without actively contributing to them [15]. These limitations have led scholars to argue that technological and efficiency-oriented approaches need to be complemented by broader socio-cultural and structural transformations in patterns of energy use and consumption. Accordingly, a growing stream of literature emphasizes the social, cultural, and structural dimensions of energy demand. Studies focusing on sufficiency and consumption practices argue that reducing overall demand requires addressing social norms, lifestyles, material expectations, and structural patterns of overconsumption [36,41,59–61]. These approaches often advocate measures targeting housing size, material use, mobility patterns, and resource allocation, while also raising questions around fairness, inequality, and acceptable levels of consumption

Table 1
Theoretical frameworks emerging from the SLR on EDR.

Theoretical frameworks	Description	References
A). TFs emerging from AI tools		
Behavioural economics	Focuses on how cognitive biases and decision-making heuristics influence energy-related behaviours. Key mechanisms include nudges, social comparisons, and feedback systems. These non-price interventions have been highlighted as effective	[18,27–32,37,65–67,71]
Demand response	Involves managing and controlling flexible energy consumption on the demand side to improve the stability of renewable energy systems addressing the challenges of intermittency and uncertainty in energy supply	[74,75]
Efficiency path for energy	Advocates a holistic approach to reducing energy consumption by prioritizing the use of best available technologies and substituting carbon-intensive energy with renewable sources	[52,55–58]
Energy cultures framework	Examines the interplay between cognitive norms, material culture and energy practices to better understand consumer behaviour and promote smarter resource use for sustainability	[36,59–61,69,70,76,77]
Energy efficiency gap theory	Addresses the complex relationship between efficiency and actual demand reduction by showing that improvements in energy efficiency may not lead to proportional decreases in energy consumption due to shift in consumption patterns	[54]
Hybrid modelling	Combines technological details from bottom-up models with economic insights from top-down models, offering a comprehensive evaluation of EDR	[53]
Practice theory	Emphasizes the role of social practices, interactions and governance in EDR highlighting the co-evolution of technology with social behaviours and routines as essential for effective energy management	[37,68,71]
Problem framing	Focuses on how societal issues are defined, shaping the solutions proposed to address them. It emphasizes how different actors influence the dominant narratives guiding the strategies used in initiatives like sustainable energy consumption	[68,72,73]
B). Included after experts' validation		
Diffusion of innovations theory	Explains the process by which new technologies or behaviours spread through social networks in stages. It has been applied to understand the adoption of energy-efficient technologies and feedback devices	[50]
Socio-technical transition	Considers transitions as long-term changes in how societal functions are fulfilled, involving technology, user practices, regulation and cultural meaning and argue that EDR requires broader socio-technical reconfiguration	[51,73,164]
Sufficiency frameworks	Focus on corridors of sustainable consumption, reducing total energy use or redistributing over- to under-consuming populations	[11,36,38,39,59–61,108]

Table 2
Effective EDR strategies identified (grouped by domain of intervention).

Domain	EDR Strategies	Number of mentions
(i) Technological innovation	Energy-efficient technologies	19
	Smart meters and real-time feedback	17
	Building insulation and design	15
	Energy-efficient appliances	9
	Building retrofitting	8
	Renewable energy integration	7
	Technological advancements in energy systems	6
	Efficiency improvements in devices and appliances	6
	Improving vehicle fuel efficiency	5
	Total	92
(ii) Behavioural and informational instruments	Information campaigns and education	13
	Feedback and social comparison	12
	Occupant behavioural changes	10
	Community and social practices	9
	Incentives for energy-saving behaviours	7
	Social and behavioural science integration	5
	Total	56
(iii) Regulatory instruments	Regulations and standards	12
	Building codes and energy performance standards	7
	Reducing heating and cooling demand (via standards)	7
	Total	26
(iv) Financial, fiscal and price-based instruments	Subsidies and taxes (including carbon taxes)	10
	Incentives for energy-saving behaviours (financial)	7
	Real-time pricing	5
	Total	22
(v) Market-based and system-level instruments	Dynamic pricing and demand control	11
	Demand-side management	7
	Total	18
(vi) Strategy objectives/ policy outcomes	Promoting energy conservation	8
	Reducing heating and cooling demand	7
	Energy sufficiency strategies	6
	Eco-sufficiency strategies	5
	Promoting smaller, more sustainable housing	5
	Total	31
(vii) Sectoral/domain specific strategies	Transportation strategies (including promoting energy-efficient vehicles)	8
	Improving housing stock energy efficiency	7
	Encouraging public transportation and cycling	6
	Total	21
(viii) Integrated cross-cutting approaches	Holistic and integrated approaches (combining policies, technologies, etc.)	6
	Other strategies (energy audits, labelling, DRPs, heat pumps, etc.)	5
	Total	11

Note: The domains of intervention are adapted from Bertoldi (2022) [36]. Category totals are not mutually exclusive and cannot be aggregated across domains.

[38,39]. The debate includes both voluntary approaches centred on lifestyle changes [42,63] and more interventionist perspectives advocating stronger regulatory measures such as zoning laws, consumption caps, or restrictions on resource-intensive activities [36,62,64].

Another important strand of literature focuses on the behavioural and social dynamics shaping energy use. Drawing from psychology, behavioural economics, and social sciences, these frameworks examine how habits, routines, perceptions, social norms, and contextual factors influence energy consumption [32,65–67]. Behavioural economics, strongly influenced by the work of Kahneman and Thaler [78,79], highlights mechanisms such as nudges, feedback systems, social comparison, and cognitive biases. However, several studies stress that energy demand cannot be fully understood as the outcome of individual choices alone. Broader frameworks such as practice theory [37,68,71], socio-technical transitions [72,73], problem framing [68], energy cultures [76,77], and demand-response approaches [74,75] instead conceptualise energy demand as embedded within infrastructures, institutions, technologies, and socially shared practices. These perspectives emphasise that energy transitions involve not only technological substitution, but also deeper transformations in governance systems, societal expectations, and everyday life [68,80,81].

3.3. Which strategies most effectively contribute to achieve EDR?

The selected studies were analysed to identify the strategies most frequently associated with effective EDR. The identified strategies were organized into eight broad domains of intervention capturing the main approaches to EDR discussed across the reviewed literature [see 36].

At the technological level, the adoption of energy-efficient technologies emerges as the most frequently cited strategy for reducing energy demand. These include energy-efficient appliances [23,82–85], smart energy management systems [86–88], and building-related measures such as insulation, envelope optimisation, and retrofitting [67,77,92,93]. Smart energy systems rely particularly on the deployment of sensors and real-time feedback mechanisms [19,28], which can either provide information directly to occupants [89,90] or be integrated into automated control systems [91]. Combined with broader system improvements, such as heat pumps and efficient HVAC technologies, these measures can significantly reduce energy consumption without compromising living standards [67,93].

Behavioural and informational instruments constitute the second most frequently identified group of effective EDR strategies. Studies consistently highlight the role of feedback mechanisms, social comparison, behavioural incentives, and changes in occupant practices in shaping energy consumption patterns [94]. These approaches often draw on behavioural economics principles, including nudging, goal-setting, and moral suasion [32,35,66,95], supported by real-time energy feedback systems [90,96,97]. Information campaigns and energy education further support these interventions by increasing awareness and reducing resistance to behavioural change [98,99]. More broadly, the integration of social and behavioural sciences contributes to the design of context-sensitive and psychologically informed programmes [94,100,101].

Regulatory, financial, and market-based instruments collectively shape the broader policy environment for EDR. Regulatory measures such as building codes, appliance standards, and energy labelling establish the framework within which demand reduction can be achieved [102]. Financial instruments, including subsidies, carbon taxes, and innovative financing schemes [103], create incentives for the adoption of low-energy solutions. At the same time, market-based instruments such as real-time pricing, dynamic tariffs, and demand-side management schemes encourage load shifting, energy conservation, and greater system flexibility [96,102,104–107].

The literature also highlights a growing emphasis on sufficiency-oriented approaches aimed at reducing overall energy demand through changes in consumption patterns and living arrangements. These include measures promoting energy conservation, lower heating and cooling demand, and broader energy sufficiency and eco-sufficiency strategies [38,108]. For example, initiatives encouraging multifunctional use of rooms or smaller living spaces have demonstrated tangible reductions in household energy use [41]. Similarly, behavioural guidelines related to indoor temperature settings and thermal comfort adjustments can reduce heating and cooling demand while maintaining occupant well-being [109].

Finally, sector-specific and integrated approaches reinforce the need for systemic and coordinated action. Strategies targeting transport and housing, combined with integrated approaches that link technologies, behavioural interventions, and policy instruments, demonstrate that effective EDR depends on coordination across multiple domains rather than isolated measures. Governments therefore play a central role in orchestrating these policy, regulatory, and economic levers across sectors [85]. Importantly, policy instruments do not map exclusively onto either efficiency or sufficiency perspectives. Depending on their design, scope, and level of ambition, measures such as carbon taxes, energy efficiency standards, and demand-side management schemes can support both energy efficiency improvements and broader reductions in overall energy demand.

3.4. What are the most common barriers and enablers for EDR?

At the consumer level, energy demand is constrained by economic, behavioural, and political factors [18]. Economic constraints, such as low return on investment (ROI) and high ongoing operational costs, can discourage further investment [28,103,110]. This is particularly pronounced for lower-income households, which frequently lack access to necessary financing mechanisms, thereby limiting their ability to invest in these innovations [111]. The rebound effect, where efficiency gains may lead to higher consumption, undermines the intended demand reductions [112], serving as a critical behavioural barrier. Moreover, behavioural inertia and psychological biases, including status quo bias, prevent individuals from changing long-established consumption habits, even when new, more cost-effective alternatives are available [37,113,114]. On the policy side, the complexity of energy markets and lack of policy coherence can undermine the effectiveness of EDR efforts and disadvantaging lower-income groups who cannot afford energy-efficient technologies [111]. Holistic approaches to EDR and sustainable consumption are considered most effective [115], as they account for the social, material, and contextual dimensions of everyday energy use. Enablers of EDR, such as subsidies, low-interest loans, and tax incentives, help to counteract the financial constraints by reducing economic barriers [111]. Additionally, technological innovations such as smart meters, real-time feedback, and dynamic pricing practices enable consumers to reduce their energy consumption [105]. Such innovations also facilitate behavioural interventions including nudging techniques to maximize the effectiveness of the technology [94]. Finally, regulatory support through mechanisms like energy performance standards, building codes, and appliance labelling further enhances EDR by setting clear benchmarks for energy efficiency [102]. These frameworks are particularly crucial in Europe, where they not only promote transparency and comparability for consumers but also incentivize manufacturers and building developers to innovate and improve energy performance [36].

3.5. Which are the main social, economic and environmental implications of EDR?

EDR has the potential to improve public health, reduce fuel poverty, and generate broader societal co-benefits related to equity, well-being, and energy security [72,81,85,116]. These impacts can influence both individual and collective decision-making by affecting energy consumption patterns and household energy costs, thereby contributing to the alleviation of energy poverty [117,118]. The relationship between

behaviour and social expectations is reciprocal [72], meaning that EDR is shaped by existing social norms while simultaneously contributing to the emergence of new norms and practices related to energy conservation. Increased societal awareness of energy consumption and more positive attitudes toward conservation may further support the adoption of energy-saving behaviours and practices necessary for achieving EDR [70,119,120]. Energy communities can reinforce these dynamics by creating spaces that encourage collective engagement in energy-saving practices and sustainable lifestyles [120], thereby contributing to broader social welfare outcomes [121]. Some studies also suggest that reduced expenditure on energy-intensive consumption may allow households to redirect resources toward higher-order needs associated with well-being and self-actualisation [40].

At the same time, potential drawbacks of EDR measures have also been identified. Sufficiency-oriented lifestyles may face social resistance, particularly where they are perceived as conflicting with economic growth objectives or established consumption patterns [122]. This challenges overly optimistic assumptions regarding the effectiveness of behavioural interventions alone. Nevertheless, EDR can generate measurable economic benefits for households and firms, including reduced energy bills, net savings, increased productivity, and enhanced energy security [84]. The extent to which these benefits are realised depends significantly on levels of knowledge, motivation, and engagement in energy-efficient practices [30].

EDR may also strengthen energy security by reducing dependence on external energy sources and limiting exposure to geopolitical risks and supply disruptions [123–125]. However, some studies question the extent of these benefits and highlight the possibility of unintended negative externalities [121].

Given the continuing short-term dependence of modern economies on fossil fuels, EDR remains essential for reducing greenhouse gas emissions and other environmental pollutants [126]. In addition to lowering emissions, reductions in energy demand can decrease the need for expanding energy infrastructure and associated resource use [85,124,127]. Although technological efficiency improvements are necessary, the literature increasingly emphasizes that only holistic approaches combining technological, behavioural, and structural dimensions are likely to avoid rebound effects at the broader economic level [84,124,125,128].

3.6. Which factors influence the role of citizens and households in EDR?

Citizens and households are significant contributors to energy consumption and carbon emissions, and their actions can have a substantial impact on energy demand reduction [30,66,67,84,112,119,127,129,130]. Both the actions and their impacts are shaped by various factors, which can be grouped into three main categories: technologies, socio-economic conditions, and policy interventions [28,67,84,112,127]. Smart technologies can foster and facilitate energy savings, while the adoption of energy-efficient appliances and renewable energy sources by households helps reduce energy demand and advance sustainability goals [101,131]. However, income, demographics, awareness and social values highly affect individuals' and households' energy-related decisions and lifestyles [84,132]. Socio-economic factors like personal capability, income, education, and employment [133] play a major role in energy behaviour and are recognized as a critical step in reducing energy demand in households [94]. Individual awareness, attitudes, environmental and social values, and lifestyle choices, are crucial for initiating and maintaining energy-saving behaviours [30,134]. Social influences such as peer behaviour, social expectations, and leadership also play a significant role in encouraging the action [132]. Moreover, these behaviours are strongly influenced by lifecycle-related factors such as marital status, household size, and composition.

On the policy side, a variety of interventions, such as fiscal instruments, market mechanisms, regulatory policies, technological innovation programs, as well as research and development policies are crucial to reduce energy demand [84]. Policy interventions should adopt a holistic and systemic perspective by supporting building regulations, infrastructure and technology adoption through behavioural nudges and social motivation [27,68,72,81,89,135]. But citizens and households cannot drive energy demand reduction alone. Sufficiency policies like stricter efficiency laws must be prioritized to prevent energy demand rebound at the individual level [36,122,136,137].

3.7. How does EDR impact the just energy transition, and vice versa?

The just energy transition is a shift from fossil-fuel dependence to a low-carbon, climate-resilient, and sustainable system while equitably distributing its costs and benefits. From a justice perspective, EDR has to be accompanied by strategies for social inclusion, poverty alleviation, and intergenerational fairness [108]. This includes ensuring affordable access to basic energy services for all, including vulnerable groups, providing these communities with decision-making power, and respecting universal rights to decent living standards [138]. Reducing demand creates space for easing energy poverty, and ensuring fairer resource distribution [6,40,139]. As an example, Norway's stringent building codes exemplify how demand reduction can align with justice outcomes [140]. Energy-efficient technologies can optimize energy use and reduce household consumption, contributing to sustainable energy strategies [84,134].

At the same time, justice-related concerns reveal the multidimensional challenges of equitable EDR strategies. Efficiency improvements requiring high upfront investments, such as retrofits or advanced technologies, may disproportionately benefit wealthier households while excluding lower-income groups [141–144]. Similarly, unequal access to digital technologies can reinforce disparities in the uptake of efficiency measures. Policies that fail to address these issues risk undermining both equity and public acceptance. Integrating sufficiency, efficiency, and justice within a shared framework enables EDR to function as a redistributive strategy, where reduced consumption among affluent groups can help secure access to essential energy services for under-consuming populations. In this sense, sufficiency extends beyond reducing energy demand and becomes linked to broader questions of equity and well-being. Although sufficiency approaches are increasingly recognized, efficiency continues to dominate policy and practice due to its compatibility with techno-economic models and narratives of productivity and competitiveness [57]. However, sufficiency-oriented perspectives challenge growth-based assumptions and open space for alternative approaches to employment, taxation, and macroeconomic organisation. The 2022 IPCC report similarly argues that achieving human well-being within planetary boundaries requires moving beyond growth-driven throughput and adopting alternative frameworks such as capabilities-based or doughnut models [5].

Nevertheless, tensions between EDR and just transition objectives remain. In some contexts, improving equity may require maintaining or even expanding energy use in underserved regions, potentially conflicting with reduction targets. Moreover, efficiency-centred transitions may contribute to new forms of extractivism, whereby the expansion of renewable energy infrastructures imposes social and environmental burdens on resource-rich but economically disadvantaged countries. These tensions underline the importance of carefully balancing sufficiency, efficiency, and equity within EDR policies [145–148].

3.8. What are the potential side effects of EDR interventions?

As discussed in Q3.5, EDR can generate a wide range of co-benefits, including improvements in health, environmental quality, energy security, social welfare, and economic resilience [17]. However, interventions aimed at reducing energy consumption may also produce unintended consequences, most notably rebound effects [149,150].

Rebound effects occur when efficiency gains or sufficiency measures trigger behavioural, economic, or systemic responses that partially or

fully offset expected energy savings. These effects are commonly classified as direct, indirect, or economy-wide [151–153]. Direct rebounds occur when efficiency improvements increase the use of a service (e.g., higher heating use after insulation upgrades), while indirect rebounds arise when financial savings are redirected toward other energy-intensive goods or activities. Economy-wide rebounds result from broader structural changes in prices, productivity, and consumption patterns across the economy [154]. The magnitude of rebound effects may vary widely, ranging from more than 100% in cases of "backfire" to below −100% in cases of negative rebound [101,127,151,155]. More common are partial rebounds (0–100%), also referred to as the Jevons paradox or take-back effect [131]. Zero rebound implies the full realization of projected savings, while negative rebounds occur when actual savings exceed expectations [156]. These dynamics demonstrate that efficiency improvements do not translate into proportional reductions in final energy consumption per se.

Research on energy sufficiency further challenges the assumption that increasing energy consumption necessarily improves well-being. Sufficiency measures, such as reducing private car use, may lower household expenditures and increase disposable income, which can subsequently be spent on other energy-intensive activities, including long-distance travel [157]. Behavioural research also highlights mechanisms such as "moral self-licensing", whereby individuals feel justified in consuming more after making environmentally responsible choices [158,159]. These dynamics underscore again the importance of systemic approaches capable of addressing unintended consequences across multiple domains [136].

Policy instruments including resource pricing, regulation, and incentives for voluntary restraint can help reduce rebound effects [26,136]. Complementary measures such as sustainability communication, education, and green marketing may further counteract behavioural rebounds and moral licensing [26]. At a broader level, strong sustainability approaches emphasise reshaping societal understandings of material needs, consumption norms, and human–nature relationships [136]. Capturing efficiency gains for reinvestment in natural capital or environmental initiatives provides an additional pathway for limiting rebounds [131,161]. The literature also questions policy approaches that rely primarily on assumptions of rational consumer optimisation, arguing instead that energy use is strongly shaped by infrastructures, regulations, and urban systems. Consequently, policies targeting energy-intensive sectors, construction practices, and spatial planning are often considered more effective than household-level incentives alone [162]. Measures such as limiting unnecessary construction, reducing embodied energy in buildings, or curbing resource-intensive development can support more durable reductions in energy demand. From this perspective, sufficiency-oriented policies should complement (and in some cases precede) efficiency measures to prevent rebound effects from undermining expected savings [163].

3.9. What are the projected future scenarios for EDR, and what role do different strategies play in these?

Future scenarios to achieve EDR targets encompass a range of strategies, including technological, behavioural, and structural changes. As for technological interventions, a study in Japan for reducing greenhouse gas emissions by 80% in 2050 indicates that energy demand can be cut by 37% [85]. From a behavioural perspective, a study in the UK suggests that a ~ 50% reduction in energy demand is possible while improving social outcomes, via shifting consumption toward less intensive forms while reducing the need for energy [138]. A study on the Swedish residential building stock indicates that an integrated scenario combining technological, behavioural, and structural changes can result in a 61% reduction in heat energy demand by 2050 [164].

Wiese et al., 2024 show how accounting for sufficiency allows to achieve on average 46% EDR in Europe [165]. Sufficiency in addition to efficiency and renewable energy measures is essential in the heating sector for achieving the climate targets [137]. At the same time dissemination of information and guidance for behaviour are crucial for ensuring societal acceptance of demand reduction strategies [67,84]. Taken together, these studies suggest that substantial reductions in energy demand, on the order of approximately 37–61%, are technically and socially achievable. However, these estimates are derived from heterogeneous modelling approaches, assumptions, and sectoral scopes, and should therefore be interpreted as indicative of the overall magnitude of achievable reductions rather than as directly comparable or precise quantitative benchmarks. Yet, holistic approaches to EDR, integrating technological, behavioural, and structural strategies, and related scenarios, are largely missing. EDR policies should remain flexible to accommodate geopolitical and technological uncertainties [134]. Zhang et al. (2025) indicate "energy demand science" as a multidisciplinary field and report that energy demand can be reduced by up to 40% by 2050 through lifestyle adjustments, urbanization, and innovative technologies [166].

A key conflicting perspective in EDR is the debate between green growth and post-growth approaches. Green growth proponents argue that efficiency improvements, electrification, and circular economy strategies can enable economic growth while reducing energy use [167]. However, post-growth advocates pointing to historical data show that absolute decoupling remains insufficient at the scale required for climate goals. Relying solely on efficiency and technological improvements is unlikely to deliver the necessary reductions in energy demand. Without addressing the structural drivers of energy consumption, economic growth imperatives, urban expansion, and material throughput, EDR strategies will remain limited in impact.

3.10. Which are the areas in the literature that need further study for a deeper understanding of EDR?

Further research is needed on behavioural interventions, as research on their effectiveness and potential gaps remains limited and uneven [66]. There is a growing interest in how energy norms are shaped, including the role of online discussion forums and digital environments in influencing debates on energy use and, in turn, consumption habits [70]. There is also a lack of comprehensive research on societal preferences for energy-efficient behaviours, particularly concerning how lifestyle choices and energy sufficiency measures interact, and how different societal groups respond to such measures [63]. Policy design requires further attention, especially in understanding the barriers to implementing policies aimed at energy efficiency and demand reduction, as well as their distributional impacts, particularly in sectors such as residential heating. More broadly, sustainability transitions in energy use need to be studied through the lens of socially shared and institutionalised energy consumption patterns, calling for new frameworks and problem-framing approaches to accelerate these transitions [68].

In addition, forecasting energy demand has emerged as a critical area of research, driven by the need for accurate predictions and improved methodologies, including the use of AI [168]. Further research is also needed to address the divide between those advocating for technological efficiency improvements and those promoting sufficiency-based approaches. While efficiency-oriented perspectives emphasise innovation and electrification, sufficiency-oriented approaches highlight that, without direct demand reduction policies, efficiency gains may lead to rebound effects and increased energy consumption.

A particularly relevant gap concerns the energy embodied in goods and services, which involves substantial energy use during production, transportation, and distribution across global supply chains. Everyday items such as clothing, electronics, or processed foods carry hidden energy costs that significantly contribute to overall energy demand. Overlooking these components leaves a gap in fully understanding energy demand and its reduction [23]. Addressing this requires a more holistic approach to behavioural change that goes beyond traditional energy services and considers the entire consumption set of individuals,

encompassing all goods and services they use [82]. This also relates to the growing attention on "non-energy" policies, such as those in education, health, land use, or trade, which, although not explicitly designed to affect energy systems, nonetheless shape energy demand in significant and often overlooked ways [106]. Such policies remain largely invisible in mainstream energy governance despite their substantial indirect impacts on energy systems [103,135,169].

4. Conclusions and policy implications

This review highlights the increasing central role of energy demand reduction (EDR) within climate and energy transitions. Across the literature, EDR emerges as a multidimensional challenge that cannot be addressed through technological solutions alone, but instead requires the interaction of governance, infrastructures, behavioural dynamics, social practices, market structures, and broader societal objectives. The findings show that meaningful and lasting reductions in energy demand depend on integrated approaches combining technological innovation, behavioural adaptation, regulatory and financial instruments, and broader structural changes across sectors and governance levels. The review also identifies several important implementation challenges and tensions. These include rebound effects and behavioural spillovers, unequal access to energy-efficient solutions, fragmented governance frameworks, limited integration of sufficiency perspectives, and broader tensions between growth-oriented economic models and long-term demand reduction objectives. At the same time, the literature increasingly highlights the wider co-benefits of EDR, including improved energy security, affordability, resilience, public health, and social well-being. Table X synthesizes the main cross-cutting insights emerging from the review and their associated strategic policy directions. Together, these findings suggest that EDR should be understood not only as a climate mitigation strategy, but as a broader socio-technical transition agenda requiring coordinated action across policy domains, infrastructures, institutions, and everyday consumption practices. Table 3 synthesizes the main cross-cutting insights emerging from the review and their associated strategic policy directions. Overall, the evidence indicates that the most effective EDR pathways combine technological innovation (e.g. retrofits, smart systems, and efficient appliances), behavioural interventions (e.g. feedback mechanisms, social comparison, and nudging), and policy or economic instruments such as standards, subsidies, and carbon pricing. However, the effectiveness of these measures remains strongly conditioned by governance coherence, access to financing, social acceptance, and distributional impacts, particularly for lower-income households. Rebound effects, whether direct, indirect, or economy-wide, further complicate the achievement of absolute reductions in energy demand, while sufficiency-oriented measures may also trigger unintended behavioural responses through reallocated consumption or moral licensing. These dynamics highlight the need for more integrated modelling approaches capable of capturing behavioural responses, systemic interactions, and distributional implications over time.

Despite these challenges, the literature reviewed suggests that substantial reductions in energy demand are both technically and socially achievable when technological, behavioural, and structural strategies are combined. Scenario-based studies indicate potential reductions ranging from approximately 37% to 61%, depending on the sectoral scope, modelling assumptions, and degree of structural change considered. These include reductions of 37% in Japan [85], around 50% in the United Kingdom [10], up to 61% in heat demand in Sweden [164], and approximately 46% across Europe when sufficiency measures are integrated into scenarios [15]. Together, these studies underline the importance of context, scale, long-term policy coordination, and structural societal change in enabling ambitious EDR pathways.

Some additional themes emerge more indirectly from the review and deserve further attention in future research and policy discussions. While EU energy efficiency instruments have progressively strengthened

Table 3
Cross-cutting insights emerging from the review, linking the guiding research questions with the main strategic policy directions identified across the literature on energy demand reduction (EDR).

Cross-cutting insight from the review	Related question(s)	Strategic policy direction
Effective EDR requires cross-sector coordination and integrated governance approaches	Q1, Q2, Q3, Q6, Q10	EDR strategies should coordinate energy, housing, transport, urban planning, and social policies through coherent long-term frameworks combining technological, behavioural, sufficiency-oriented, and financial measures.
The review highlights the continued dominance of efficiency approaches and the limited integration of sufficiency perspectives	Q2, Q3, Q7, Q8, Q9, Q10	Greater integration of sufficiency within EDR strategies is needed, particularly through measures addressing excessive consumption, material demand, and rebound effects alongside efficiency improvements.
Growth-oriented economic logics may conflict with long-term EDR objectives	Q7, Q8, Q9	Complementing GDP-oriented approaches with well-being, sufficiency, and resource-use indicators could better align economic policy with long-term sustainability and demand reduction goals.
Large-scale deployment of energy-efficient technologies remains a central pillar of EDR	Q3, Q4, Q6, Q9	Accelerating retrofits, efficient appliances, smart systems, and ambitious building standards remains essential, while ensuring accessibility across income groups.
EDR generates multiple co-benefits beyond climate mitigation	Q5, Q6, Q7, Q9	Framing EDR as a strategy that also supports energy security, affordability, resilience, public health, and social well-being could strengthen policy support and implementation.
Collective and community-based approaches can strengthen EDR in decentralized energy systems	Q3, Q5, Q6, Q9	Community-based initiatives such as energy communities, collective retrofits, local demand-response schemes, and neighbourhood-level governance can strengthen participation, flexibility, and social acceptance.
Reducing energy demand can lower pressures on infrastructures and material resources	Q5, Q7, Q9, Q10	EDR should also be recognized as a strategy to reduce pressures on grids, generation capacity, storage systems, construction materials, and critical minerals.
EDR policies raise important social vulnerability and global justice considerations	Q4, Q5, Q6, Q7, Q9, Q10	Social inclusiveness, affordability, imported emissions, resource extraction, and unequal global impacts of energy transitions need to be more systematically integrated into EDR policy design.
Rebound effects and behavioural responses remain major risks for effective EDR	Q2, Q4, Q8, Q9, Q10	Rebound effects, consumption spillovers, and behavioural dynamics should be systematically incorporated into EDR policy design, evaluation, and scenario modelling.
Future EDR pathways depend on behavioural adaptation and societal acceptance	Q3, Q5, Q6, Q7, Q9, Q10	Future EDR pathways should be understood not only as technically feasible, but also as socially and politically conditional, requiring trust, participation, and long-term societal acceptance.

regulatory standards, supported technological innovation, and embedded the "Energy Efficiency First" principle across sectors, recent trends show that overall energy demand in the EU is not consistently declining and is, in some sectors, increasing. This increase is partly driven by structural transformations associated with the transition itself, including transport electrification, the expansion of digital infrastructures such as data centres, and rising electricity demand in emerging strategic sectors. This reveals a broader paradox whereby decarbonization efforts may simultaneously place upward pressure on energy demand, further reinforcing the importance of comprehensive EDR strategies. In this context, the current geopolitical situation also reinforces the strategic importance of EDR beyond climate mitigation alone. Reducing energy demand can strengthen energy security, reduce import dependency, increase resilience to external shocks, and support European strategic autonomy. At the same time, the review suggests an increasing mismatch between nationally driven energy policies and the growing cross-border nature of electricity systems, flexibility markets, and infrastructure interdependence in Europe. This points to the need for stronger multilevel governance and coordination between national and EU-level policy frameworks.

Finally, while sufficiency is increasingly recognized as an important pillar of EDR, the review also highlights the lack of clear implementation pathways, governance mechanisms, and monitoring approaches for translating sufficiency principles into operational policy frameworks. Further work is therefore needed on policy-readiness criteria, sector-specific implementation instruments, political feasibility, public acceptance, and metrics for assessing sufficiency-oriented policies. Overall, advancing EDR research will require integrated modelling and scenario development, improved data and methods, and more robust evaluation of interventions over time, including their heterogeneity and persistence, as well as a stronger integration of justice and equity considerations (see Fig. 4).

5. Limitations

This review adopted a hybrid methodology combining AI-assisted screening with expert validation. The use of Petal (petal.org) facilitated the identification, prioritization, and synthesis of relevant studies, while all AI-generated outputs were critically reviewed and refined by the authors and EDR experts. Nevertheless, AI-supported reviews may reflect biases linked to training data, prioritization algorithms, and question framing, raising challenges for replicability and exhaustive coverage. These methodological choices also shaped the final synthesis: although the knowledge base comprised 137 studies, only the most relevant contributions to the guiding research questions were ultimately discussed in depth. While this question-driven approach enabled a focused analysis of core themes, some secondary findings may have been overlooked. In addition, both the EDR literature and AI tools used in this review are evolving rapidly, meaning that some findings may require future updating. Despite these limitations, the review provides a coherent and policy-relevant synthesis intended to clarify concepts, identify research gaps, and support future research, policy design, and cross-sector collaboration on energy demand reduction.

CRediT authorship contribution statement

G. Borragán: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Data

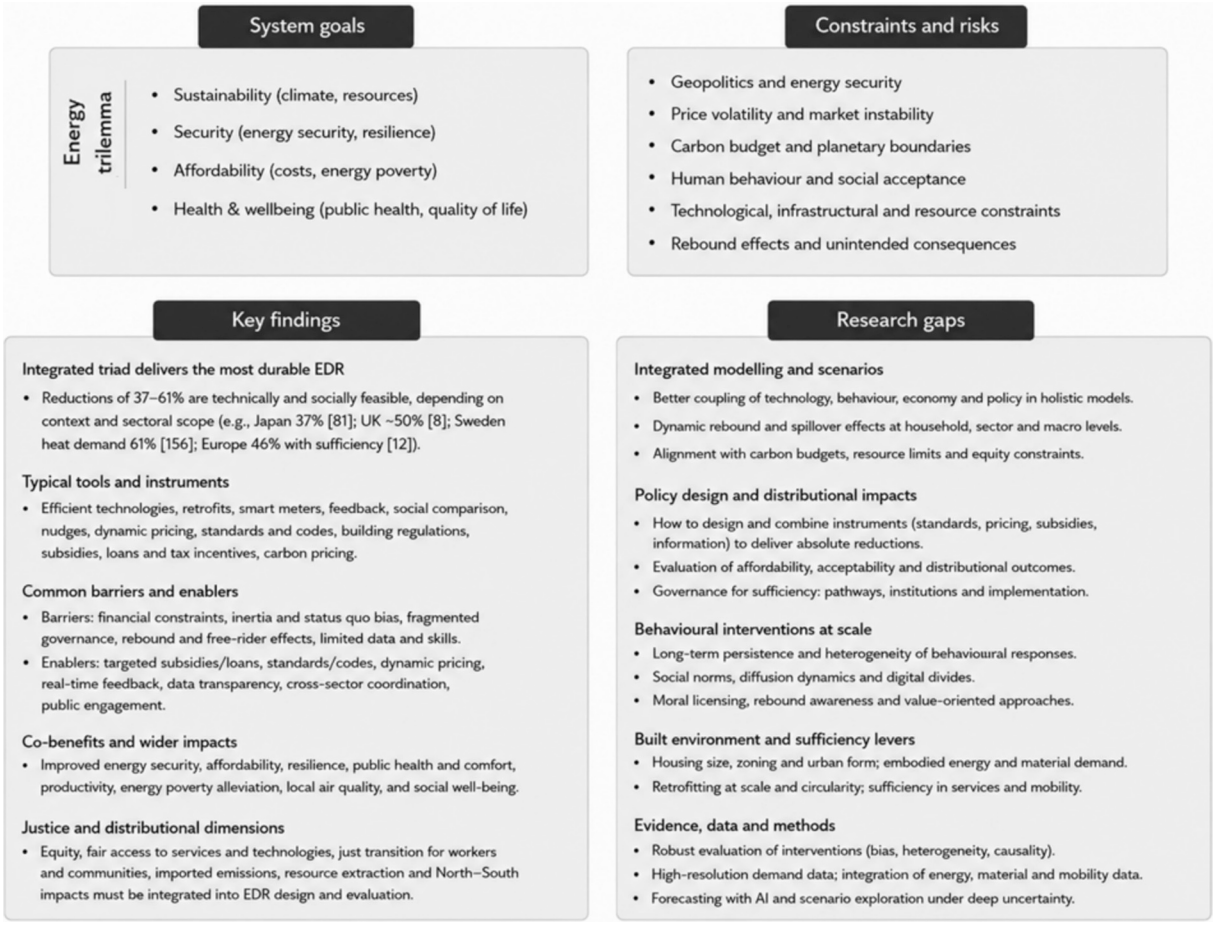


Fig. 4. Conceptual synthesis of the review, summarizing the main system goals, constraints, key findings, and future research priorities for Energy Demand Reduction (EDR).

curation, Conceptualization. **M. Paier:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **J. Verheyen:** Writing – review & editing, Validation. **E. Annunziata:** Data curation. **E. Biresselioglu:** Data curation. **G. Calis:** Data curation. **C. Franceschinis:** Data curation. **T. Koljonen:** Data curation. **P. Pisciella:** Data curation. **Ayşen Sivrikaya:** Data curation. **W.R. Poganietz:** Data curation. **M. Thiene:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **A. Sciullo:** Writing – review & editing, Writing – original draft, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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