Ritter *et al. Energy Informatics* (2026) 9:59
https://doi.org/10.1186/s42162-026-00673-2

Energy Informatics

RESEARCH Open Access

Activating the electrical energy flexibility of residential thermal systems: an analysis of non-technical barriers in six countries

David Ritter[1,2*], Christoph Rohringer[3], Alireza Afshari[4], Manuel Andrés-Chicote[5], Pablo Hernandez-Cruz[6], Kaya Duenzen[2], Dierk Bauknecht[1,2] and Shady Attia[7]

*Correspondence:
David Ritter
d.ritter@oeko.de

Full list of author information is available at the end of the article

Abstract

Decentralised energy flexibility in electricity systems faces a range of non-technical barriers that constrain widespread implementation. This study focuses on flexibility from residential heat pumps (HP), especially in combination with thermally activated building systems (TABS). It provides a comparative analysis of regulatory, financial and stakeholder-related barriers in Austria, Belgium, Canada, Denmark, Germany and Spain. Besides these types of barriers, the cross-country analytical framework is structured around specific flexibility use cases and utilisation mechanisms, which are schemes and market structures through which end-users' flexibility can be activated. The analysis is based on expert consultations and a systematic review of scientific literature, offering insights into the multi-dimensional nature of the identified barriers. The findings highlight a significant disconnect between the technological availability of flexibility from residential heating systems and implementation. The main identified barriers are perceived high initial costs in combination with uncertain return on investments, insufficient awareness among end-users and professionals, reinforced by the insufficiently adopted regulatory setting. Insufficient regulatory consideration was identified, particularly for TABS, shortcomings in current energy policy frameworks were observed.

Keywords Decentralised flexibility, Heat pumps, Thermally activated building systems, Non-technical barriers, Sector coupling

Introduction and motivation

The importance of flexibility offered by decentralised heat pumps in the energy transition

The electricity system shows two main needs for energy flexibility: Firstly, it is necessary that generation and consumption are balanced at all times [1]; otherwise, the grid frequency exceeds tolerance ranges, and affected areas must be disconnected from the grid (as, for example, seen on the Iberian Peninsula in April 2025 [2]). Secondly, if there is a

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

risk of grid overload0F[1], the electricity flow through the power lines must be reduced, either by adjusting generation or consumption [1, 3].

Currently, mainly fossil power plants provide the therefore necessary system flexibility. But over the next few years, a global transition away from fossil-based energy production is essential to mitigate climate change [3]. Many countries have therefore set themselves net zero emission targets for 2050 or earlier [4, 5]. This decarbonisation requires a significant expansion of photovoltaic and wind power capacities [3, 6]. Unlike conventional fossil-fuelled systems, whereby electricity generation is adjusted to match demand, renewable energy (RE) systems must adapt to the variable and uncertain availability of wind and solar resources [7, 8]. With variable renewable energies (VRE) shares increasing, a broader and more diverse set of flexibility solutions is required [7]. Among these, long-term energy storage can bridge longer periods with low generation availability. In energy systems with high shares of RE, hydrogen-based technologies for storage, production, and electrification are expected to play a key role in bridging prolonged supply deficits [9–12]. But the production of hydrogen using electrolysers has very high energy losses [13]. As a result, alternative options should be used for short-term balancing needs. Besides battery storage, demand response (DR) (whereby industrial demand, electric vehicle charging or heat pump (HP) usage is shifted) is an option to provide flexibility to the energy system [14, 15].

Sector coupling technologies, like HPs, enable the utilisation of renewable electricity for heating and cooling to reduce associated emissions and often therefore form part of national decarbonisation strategies [16, 17]. This results in an increased need for solar and wind expansion, which entail higher flexibility needs. However, HPs could also provide flexibility to the system, buffering heat in thermal storages such as hot water tanks or thermally activated building systems (TABS) [18, 19]. This analysis places a special focus on TABS as it is a promising option for flexible thermal energy storage in buildings with a high degree of interaction with the indoor environmental quality. In the relevant literature, TABS is described as "active pipe-embedded structures in buildings" [19, 20]. They can be described as hydronic systems embedded in structural elements (floors, ceilings, or walls), typically water-carrying pipes cast into concrete slabs or screed. TABS store and release heat through the building's thermal mass. This differentiates TABS from indirectly activated building masses such as building walls heated indirectly by standard convection heaters and also from floor heating which has its pipes not embedded in the structural elements of a building but in the screed instead. On the one hand, TABS are a well-established, cost-competitive, and market-ready technical solution for heating and cooling in buildings [19]. TABS offer higher energy storage capacity on average (depending on the building typology) than purely convective heat dissipation system, and can store and slowly dissipate heat or cold for longer periods which makes it an attractive technology for flexibility [21, 22]. On the other hand, this option is rarely implemented due to a number of non-technical barriers relating to decentralised flexibility in general and TABS in particular.

A significant asymmetry exists between new construction and renovation contexts. In new buildings, TABS can be integrated during structural works at relatively low additional cost. In existing buildings, retrofitting TABS is often invasive, costly, and

[1] In the transmission grid the main problem is too high temperatures of the power lines, while in the distribution grid high electricity flows result in a drop of the voltage level.

sometimes structurally infeasible, requiring breaking up floors or ceilings to embed pipe systems. This retrofit barrier, combined with fragmented decision-making typical of multi-owner or condominium buildings, substantially limits TABS penetration in the existing stock [23]. Since the majority of the 2050 building stock already exists today, this constraint has significant implications for the long-term flexibility potential of TABS at scale [24].

Therefore, this analysis focuses on the afore-mentioned issue in the context of activities in the International Energy Agency (IEA) Energy Storage Technology Collaboration Programme Task 43. This analysis centres on the flexible use of HPs installed at the building level, owned and operated by individual end-users. Centralised systems, like those integrated into district heating grids, are not considered here. Similarly, the interaction of decentralised thermal storage and purely thermal distribution grids falls outside the scope of our analysis.

Research gap addressed and aim of this study

The transition to sustainable energy systems has created growing research interest in operating building-integrated HPs [25–28], particularly when combined with Tables [19, 29, 30], as a source of DR. Existing literature has explored several aspects of this technology. A substantial body of literature has examined the technical barriers of HP integration [27, 31, 32], with some studies also touching on TABS as thermal storage systems [19]. Additionally, research has been conducted on the non-technical barriers of HP adoption, focusing on user acceptance [26, 31–33], policy frameworks [33–35] and economic viability [27, 36, 37] without intersecting TABS in energy system flexibility considerations [19, 38–40].

However, notable gaps remain, which are addressed in this analysis. Firstly, while some studies address use cases (UC) for flexibility individually or combine only a few of them, such as participating in the electricity markets [41–43], self-consumption [44–46], and optimisation of the coefficient of performance (COP) [25, 47, 48], electricity grid [46, 49–51] or balancing services [42, 52, 53], there is a lack of comprehensive, comparative analyses that cover the full spectrum of UC for HP flexibility, particularly when TABS are involved. Secondly, the literature rarely addresses how non-technical barriers to exploiting this flexibility vary across national contexts and across the different flexibility use cases. Moreover, existing classifications of barriers are fragmented and lack a coherent framework that integrates the various stakeholder, regulatory constraints, and financial aspects.

This analysis addresses these shortcomings by examining the following main research questions across six countries to cover a large geographical scope and reflect diverse climatic and regulatory contexts, namely Austria, Belgium, Canada, Denmark, Germany, and Spain, and by exploring how barriers differ across multiple flexibility UC, identifying both overarching barriers and context-specific perspectives:

– What non-technical barriers hinder the flexible use of decentralised heat pumps especially in combination with TABS, and how do these barriers differ across different countries and flexibility use cases?

With a specification to the three subsequent research question:

– How do existing regulatory frameworks affect the deployment and operation of residential thermal flexibility?
– Which stakeholders are involved and what are the associated barriers?
– What financial barriers limit the adoption of these flexibility solutions?

Methods

This study uses a mixed-methods approach, combining expert consultation through a structured questionnaire with a systematic literature review, to identify and analyse the non-technical barriers to decentralised thermal storage systems, particularly for TABS and HPs. This methodology was designed to gather insights from multiple countries and stakeholder perspectives. On this basis regulatory, stakeholder-related and financial barriers were identified. To contextualise the barriers, country profiles were developed for Austria, Belgium, Canada, Denmark, Germany, and Spain, using four indicators for flexibility needs and potential availability of HP flexibility. These are VRE share, HP penetration, HP market share, and smart meter deployment, plus the climatic conditions in the considered countries (Sect. "Country profile"). Furthermore, relevant UCs (Sect. "Identified use cases") and utilisation mechanisms (Sect. "Utilisation mechanisms Options to activate residential heat pump flexibility") were elaborated from the literature and interviews to structure and specify the identified barriers.

Expert consultation

As part of IEA Energy Storage Technology Collaboration Programme Task 43, a stakeholder questionnaire was developed to investigate non-technical barriers related to the integration of TABS as flexibility options in expert consultations. The design was developed in cooperation with the IEA task group and aimed to address identified research gaps, covering non-technical dimensions such as awareness, regulatory frameworks, financial implications, indoor comfort, public perception, and stakeholder collaboration. These categories were examined more closely to cover different aspects and nuances of non-technical barriers and answer the following research question: "What non-technical barriers hinder the flexible use of decentralised heat pumps especially in combination with TABS, and how do these barriers differ across different countries and flexibility use cases?".

Overall, the questionnaire combined qualitative and quantitative elements. It featured background information concerning the interviewee, 5-point Likert-scale assessments, in which experts rated the perceived relevance of barriers from "not relevant" to "highly relevant", and open-text sections, allowing both structured analysis and deeper insights. In addition to TABS-specific questions, the consultation also addressed decentralised heating flexibility more generally as the use of TABS as a flexibility option is not yet widespread, and all general barriers to decentralised heat flexibility must also be overcome for TABs.

Interviews were conducted across six countries (Austria, Belgium, Canada, Denmark, Germany, and Spain) to ensure broad geographical coverage and to capture diverse energy system contexts. Between 15 July 2024 and 7 April 2025, a total of 41 interviews (Austria: 6, Belgium: 6, Canada: 7, Germany: 9, Denmark: 7, Spain: 6) were completed. The participants came from a broad range of institutions, including research organisations, universities, ministries, system operators, design and construction firms, service

providers, and consultancies. The responses were entered into a shared data-process template and analysed thematically. Details on the questions asked, institutions participated, and their responses can be found in the supplementary material (see Chapter 7).

Literature review

Complementing the empirical component, a systematic literature review [54, 55] was conducted to map the existing body of literature on non-technical barriers for decentralised flexibility and TABS. The PRISMA methodological approach [56] was modified to guide the selection, screening and inclusion of resources (see Fig. 1). The search was performed in the Web of Science database and was supplemented by grey literature, including technical papers and policy reports, by snowball sampling of experts from the expert consultation and the IEA task group.

The query1F[2] used to gather the initial literature review body produced 350 items of peer-reviewed research. To complement the body of literature, snowball sampling was used to identify additional literature known to the authors and/or consulted experts. This resulted in 39 additional items of grey and peer-reviewed literature being identified. Literature focusing on (small-scale) batteries, electric vehicles, industrial demand response, or cybersecurity or focused on technical barriers were excluded. Additionally, literature from earlier than 2020 and literature that did not include the geographical scope of Austria, Belgium, Canada, Denmark, Germany, or Spain was excluded as well. After the screening process, 55 publications remained for analysis. These were analysed using a standardised data template structured in alignment with the questionnaire framework on stakeholder, regulatory, and financial barriers to ensure comparability between the two methodological steps.

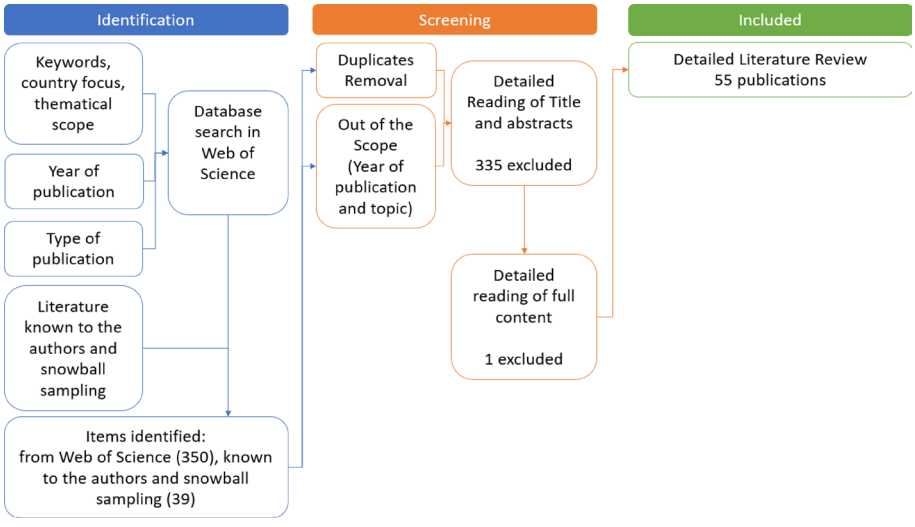

Fig. 1 Flow diagram of the systematic literature review methodology. Authors' own illustration

[2] "TS=("decentral* flexib*" OR "buildi* flexib*" OR "distribut* flexib*" OR "small* flexib*" OR "smart build*" OR "energ* flexib*"OR "electric* flexib*" OR "demand* flexib*" OR "load-shift*") AND TS=("challeng*" OR "barrier*" OR "constrain*" OR "restrain*") AND CU=(Germany OR Austria OR Denmark OR Canada OR Spain OR Belgium)".

Results

This chapter presents the findings from the literature and the expert consultation. In the first section, the country profiles provide the context for the conditions for utilising household heating systems as flexibility resources in the six countries included in the analysis. In the second section, the identified use cases and how flexibility from residential heat pumps could activated is described. These two sections are later used to discuss the findings.

Section "Regulatory landscape and barriers", "Stakeholders involved and related barriers" and "Financial incentives and barriers" present the current situation and barriers regarding decentralised flexibility exploitation, for regulatory, stakeholder and financial aspects respectively, particularly covering the use of TABS for flexibility purposes.

Country profile

The country profile depicts preconditions for residential heating flexibility in the six countries by four key indicators, namely VRE share in power generation, share of buildings with HPs, market share of HPs, and smart meter deployment. The four indicators are depicted as a percentage for 2023 in Fig. 2.

The share of VRE [56] can be taken as an indicator of the need of new flexibility options. It varies significantly across the countries studied. As visible in Fig. 2, Denmark led with 67% o electricity generation from VRE, primarily wind, followed by Spain (41%) nd Germany (39%),both of which rely on a mix of solar and wind. Belgium (28%)

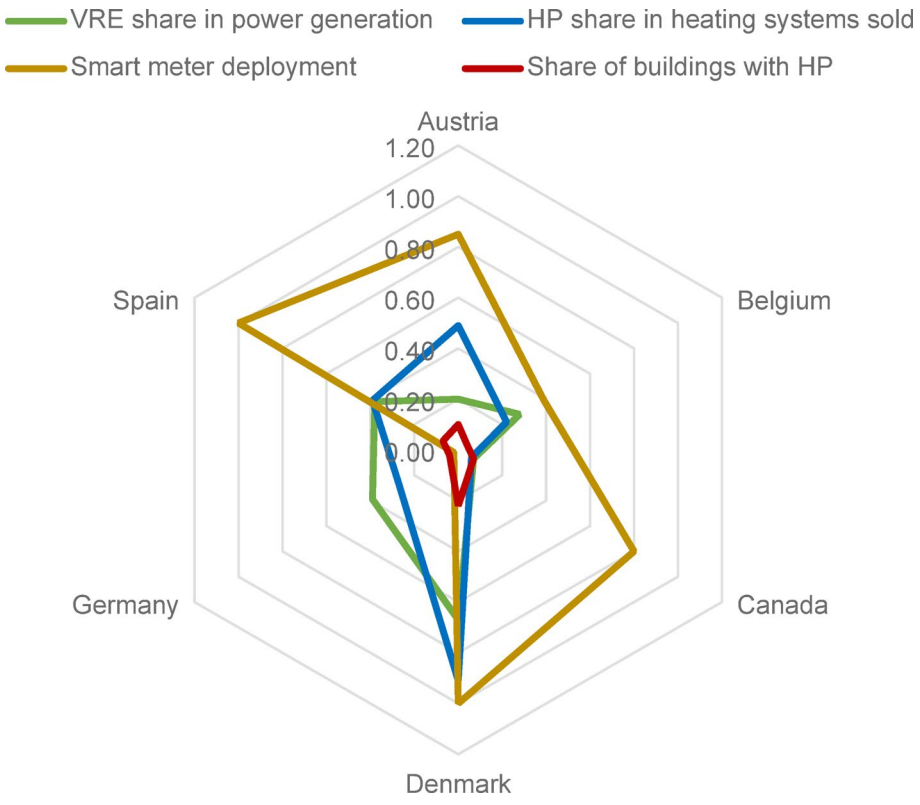

Fig. 2 Current assessment of four key parameters to access the preconditions for residential heating flexibility in the countries as a percentage for 2023. Authors' own illustration, data sources: [57–64]

nd Austria (20%) resent more moderate shares, while Canada reported the lowest VRE share at just 7%, ue to its reliance on hydro, nuclear, and fossil-based generation. A future outlook predicts an increase of all countries' VRE shares by 2030 significantly [56]. Denmark may reach 86%, Germny 70% and Sain 58%, reflcting ambitious decarbonisation targets. Belgium may reach 51%, Austia 34% and Cnada only 13%.

The share of buildings with HPs [57] is a key indicator of HP flexibility potential in the building sector. Denmark leads with 22% o buildings equipped with HP, followed by Austria (10%) nd Canada and Spain (both 7%).Germany and Belgium lag behind, showing only a 4% pnetration. Market share data [57] for new heating system installations further illustrates adoption trends. HPs accounted for 91% of ne systems in Denmark, reflecting its frontrunner position among these six countries in electrified heating. Austria also shows a strong uptake (49%), wit Spain (39%) and ermany (27%) follwing at a moderate level. Belgium is found to be in an earlier phase of market adoption with 22%. The hare of buildings with HPs in Canada currently amounts to 6% [58] indiating a very slow market development. Overall, while adoption levels differ, all countries are trending toward greater heat electrification. It is worth noting that HP penetration rates remain very low across all studied countries, with even the leading country (Denmark) showing only 22% of buildigs equipped with HPs. This significantly constrains the near-term flexibility potential of the HP-TABS combination studied here, since flexibility mechanisms can only be activated where HPs are already installed. Increasing HP deployment is therefore a prerequisite for scaling up residential thermal flexibility.

Smart meter deployment is essential for enabling household-level flexibility. However, their implementation is not a guarantee for flexibility provided to the system as the flexible devices, i.e. HPs, have to be ready for flexible use providing an opportunity to store heat or implementing a battery, so that demand could be shifted [59]. Denmark and Spain have already reached almost full coverage in households [60]. Austria follows closely with a coverage of 85% in 203, aiming for 95% by th end of 2024 [61]. In Belgium, implementation varies regionally due to its federal structure; however, the weighted average across Belgium lies at 39% [62]. Canada as around 80% smart meter cverage and aims to reach 94% by 2029 [63]. Gerany presents the slowest roll-out, with only 2% coverage in 2023 [64] However, from 2025 onwards, smart meters became mandatory for households consuming over 6,000 kWh annually; Germany is aiming for 95% by 2030 [65].

These differences reflect variations in policy priorities, digital infrastructure and the pace of regulatory development, all of which directly impact the scalability and responsiveness for household-based flexibility solutions.

In addition to assessing key indicators for residential flexibility use, this section also considers the climatic differences between the analysed countries to contextualise how varying climate conditions influence the role of heat pumps in meeting heating and cooling demands. Based on the ASHRAE classification system [66], the selected countries cover both colder and warmer climate types. This classification is based on heating and cooling degree-days, humidity and a modified Koeppen-Geiger system to categorise regions into 9 climate zones (0: the hottest to 8: the coldest) with 3 moisture regimes (A: moist, B: dry, C: marine). The selected countries fall into the following zones: Austria – 5 A/7, Belgium – 4 A/5A, Canada – 7/8, Denmark – 5 A, Germany – 5 A. Some countries like Spain [67], exhibit significant regional variation – 3 A/3B/4A/4 C. These

climatic conditions shape whether HPs are primarily used for heating, cooling or both. In colder climates (e.g. Austria and Canada), HPs are mainly for heating, though cooling use is rising as summer heat peaks. In warmer regions (e.g. parts of Spain), HPs already serve year-round comfort needs, with a strong emphasis on cooling during the summer period. Climate change is altering the amount of heating and cooling degree days. This increases the relevance of TABS, which offers an efficient and energy flexible solution that can meet both demands with one system. In warmer zones, this also aligns with PV self-consumption as cooling demand coincides with solar generation.

Utilising flexibility from decentralised heat pumps

Identified use cases

There are different needs for flexibility in the energy system. This section structures the flexible use of residential heat pumps around two key analytical concepts. First, use cases (UCs) describe the different needs and purposes for which flexibility is provided to the energy system,- such as grid stabilisation, market participation, or self-consumption. Second, utilisation mechanisms are the practical schemes through which end-user flexibility is activated, such as variable tariffs or direct load control. These two concepts are treated in separate subchapters because they operate at different levels: UCs define the system-level objective, while utilisation mechanisms define how that objective is operationalised. Based on Amann et al. [68], the following use cases (UC) for flexibility were considered for further analysis: electricity market, electricity grid, balancing services, self-consumption and device optimisation. However, following the interview with M. Kuehnbach [69], the considered UCs were extended by device optimisation to reflect on the trade-off between flexibility and efficiency. The following Table 1 elaborates UCs relevant for flexibility from HPs, their objective from a system perspective and how the flexibility is used to achieve the objectives.

In general, the different UCs compete for the available flexibility of the HPs as flexibility can be allocated to only one application at a time [70, 71]. Nevertheless, a combination of UCs is possible if their requirements are staggered at different times or can be prioritised. This could increase the incomes for flexibility. Prioritisation can be based on financial attractiveness or regulatory requirements, e.g. regulated direct load control (see Sect. " Utilisation mechanisms: Options to activate residential heat pump flexibility").

Table 1 Definition of use cases bases on on [68, 69]

Use cases	System objectives	Use of flexibility
Electricity market	Avoidance of extreme electricity prices and RE curtailment	Shift demand to low-price periods
Electricity grid	Avoidance of grid overload and reduction or postponement of grid expansion in distribution or transmission grid	Avoidance of local peaks from demand or generation
Balancing services	Balance of demand and supply to stabilise grid frequency within seconds or minutes depending on the frequency control type	Demand reduction when frequency too low and vice versa
Self-consumption	This deviates from system perspective focus on increase of individual or collective self-consumption (e.g. by energy sharing)	Shift demand to periods with high local generation (e.g. from rooftop PV)
Device optimisation	(1) Maximise efficiency through optimal management of operating periods, setpoints and part load performance (2) Reduce HP size and device on/off cycling	(1) Shift demand to hours with the most favourable outdoor temperature (2) More steady operation of HP

Importantly, the financially most attractive UC is not necessarily the most favourable for the electricity system. For example, maximising PV self-consumption is economically appealing for end-users but does not necessarily align with system needs, such as reducing peak load and thereby minimising grid expansion needs. An additional aspect is that UCs can have conflicting demands, which must be taken into account when designing incentive signals. For example, if grid-related aspects are not considered when implementing variable electricity tariffs, it may result in grid overloads.

Another critical consideration is the potential trade-off between flexibility and efficiency. For example, while using a heat storage for the *device optimisation* UC whereby the electricity demand is flattened – often by extending operation over longer periods to improve efficiency, providing flexibility in response to external signals may require temporarily generating higher output temperatures to charge the thermal storage system. This reduces the heat pump's COP and may necessitate the installation of larger, more expensive units or additional direct current heater, using electricity less efficient.

Utilisation mechanisms: options to activate residential heat pump flexibility

From the analysed literature and questionnaires, we identified four utilisation mechanisms through which the flexibilisation of heat pump demand could be incentivised and end-users could participate in one or multiple flexibility UCs: variable tariffs, active market participation, regulated direct load control, and local optimisation. Regarding the target actors: variable tariffs and local optimisation are generally accessible to individual households without an aggregator. Active market participation, however, typically requires aggregation due to minimum trading volumes and market access thresholds, meaning that a single household generally cannot participate directly. This creates a structural disadvantage for the residential sector compared to industrial actors, which can offer larger and more predictable flexibility volumes. These mechanisms vary in their level of maturity. Some are already used in the countries studied, while others remain in an experimental stage (see Table 2).

Variable tariffs are an option for activating flexibility for grid support or electricity market participation. These tariffs link price components, such as grid charges and procurement costs, to the status of the grid or wholesale market prices. There are various implementation options, from predetermined time windows2F[3] for time-of-use tariffs to dynamic tariffs that follow the hourly electricity price, reflecting actual market

Table 2 Regulatory framework for decentralised flexibility per country6F

Country	Aggregator regulation	Variable tariffs	Regulated direct load control	Flexibility markets	EPC recognises flexibility	TABS -specific policy
Austria	-	✓ (voluntary)	✖	✖	✖	✖
Belgium	-	✖	✖	under development	✖	✖
Canada	✖	✖	pilots	pilots	✖	✖
Denmark	✓ (since 2020)	✓ (mandatory)	✓ (for large systems)	under development	✖	✖
Germany	Partial (high entry)	✓ (mandatory 2025)	✓ (for DSOs)	pilots	✖	✖
Spain	✖	✓ (Basic time of use)	✖	pilots	✖	✖

[3] For example set for the course of the day or seasonally.

conditions. Their development is difficult to predict for customers and may increase their electricity bill. An additional potential barrier with variable tariffs is that its effect is difficult to predict. Depending on participation rates, the activated flexibility can be below that which is needed while very high participation rates may lead to the overfulfilment of requirements, so-called overshoots, potentially requiring additional balancing measures [72].

An alternative approach to mitigate such effects is *active market participation*, which can offer more coordinated flexibility deployment. Participating in electricity, balancing, redispatch or (local or national) flexibility markets allow end-users to offer flexibility in response to market needs. Due to minimum trading volumes3F[4] and market access restrictions, in most cases aggregation is required to pool multiple small-scale units into a virtual power plant. In this sense, various studies address the flexibility potential of building clusters [73, 74], and highlight the need to clearly define the role of market aggregators [75] who trade energy and flexibility or flexibility service providers who focus on the technical control of the devices distributed energy. Although the involvement of aggregators leads to revenue sharing, it enables participation in multiple UCs and additionally the sale of surplus electricity [76]. Flexibility markets designed to procure distributed flexibility for DSOs and TSOs or intraday markets also offer a platform to combine several of the UCs described in Table 1 but are still under development in the countries considered or are being tested in pilots and research projects.

Under the concept of *regulated direct load control*, grid operators are granted the authority to temporarily curtail or shift the operation of residential HPs or similar devices [77]. Currently, this approach has been implemented for residential HPs only in Germany, and is subject to regulatory conditions defined in § 14a German Federal Energy Industry Act (EnWG) [78], including requirements for minimum residual load, intervention duration, frequency and triggering criteria4F[5]. This approach is highly efficient and targeted as flexibility is activated only when necessary and to the precise extent required, eliminating the risk of overshooting [79, 80]. In Germany, DSOs are no longer permitted to deny grid connection for HPs as participation in direct load control can be a connection criterion [78]. However, the approach may reduce user acceptance if conditions for interventions are unclear [80, 81]. Nevertheless, it incentivises the installation of technical enablers, such as thermal storage or controllable HPs, that can also support other flexibility UCs [39, 68, 82, 83].

Local optimisation focuses on increasing self-consumption and/or operational efficiency at the individual or collective level. This includes individual or collective self-consumption (e.g. aligning HP operation with PV generation) or COP optimisation (e.g. operating the HP during ambient conditions favourable to performance). Individual optimisation strategies are straightforward to implement and require little technical infrastructure and no external communication. Collective self-consumption schemes are more complex, often subject to regulatory limitations and economic viability constraints, which vary across the countries considered (see Sect. "Financial incentives and barriers"). Notably, PV self-consumption is especially relevant when paired with cooling loads as both cooling demand and solar irradiance typically peak at the same time. In this sense, the literature acknowledges the role of local environments (such as energy

[4] Typically, 1 MW so residential HPs are too small, even for Nord Pool's Intraday Flexibility Market with 0.1 MW.

[5] Load control is only allowed when local grid congestion is imminent or occurring.

communities) as catalysts for the deployment of aggregation and energy sharing models. These offer opportunities for both users and flexibility tenders [82, 83].

Regulatory landscape and barriers

Overview of the regulatory landscape

Across the six countries examined, the regulatory landscape for decentralised thermal flexibility remains highly uneven and is shaped by varying interpretations within the European Union of the EU Energy Performance of Buildings Directive [84], Renewable Energy Directive [85] and the degree of market liberalisation. Some national policies show notable progress in certain areas, varying significantly between the identified UCs and utilisation mechanisms for decentralised flexibility.

Denmark stands out for embedding flexibility into its energy policy. Since recognising aggregators legally in 2020, Denmark has become a testbed for commercial flexibility offerings. Within the so-called Market Model 3.0 the market role of aggregators was improved5F[6] and balancing services are restructured until the end of 2026 to make them more accessible for small-scale flexibility [86]. Additionally, the country has achieved near-universal smart meter coverage and mandatory dynamic pricing, establishing a strong foundation for commercial flexibility services [60].

Germany's framework is more fragmented. While dynamic tariffs became mandatory in 2025, aggregator participation is still constrained by high entry barriers and compliance burdens [87]. The roll-out of smart meters shows the lowest level among all analysed countries. The § 14a EnWG allows DSOs to curtail HP loads over 4.2 kW, providing a regulatory route for direct load control. However, implementation of flexibility markets remains in pilot phases, still lacking implementation into the regulation and system.

Austria, an early mover in energy sharing, offers reduced grid fees for electricity produced and consumed in a collectively local way and thereby incentivises the utilisation mechanism of Local Optimisation. However, Austria lacks supportive regulation for other DR approaches. Notably, TABS are mandatory for new office buildings in Vienna [88].

In Belgium, the roll-out of smart meters is improving, and collective self-consumption is legally supported. However, thermal storage value is not considered in energy performance certificates (EPCs) [89] and the implementation of dynamic pricing remains uncommon. Elia's Flex Market does exist but is limited to a narrow set of technologies such as batteries and electric vehicles [90].

Spain has widespread time-of-use tariffs (three periods). These are not exclusively aligned with renewable generation profiles from the daily market – they are also indexed to future market prices, system adjustment services and other costs [91]. The Nominated Energy Market Operator in the Iberian Peninsula, OMIE, has several pilot projects underway for the development and implementation of local flexibility markets in the country [92]. Moreover, mechanisms for decentralised flexibility participation into electricity markets as well as the role of key stakeholders (e.g. aggregators) are still underregulated. There is a balancing service (Servicio de Respuesta Activa de la Demanda) in place for individual consumers and retailers with a minimum bid size of 1 MW [93].

[6] Especially providing flexibility to the system without having the balancing responsibility.

National pilot legislation is pending approval to define the conditions for retailing, aggregation and consumer protection in the electricity sector [94].

Canada presents an additional layer of complexity due to its fragmented market structure. Electricity regulation falls under provincial jurisdiction, resulting in significant discrepancies across regions. Only Ontario and Alberta operate liberalised electricity markets with the potential for DR integration. The other provinces continue to rely on vertically integrated monopolies with limited access for third-party aggregators [95]. In Canada, regulated direct load control and flexibility markets are being tested in some regional pilots.

Table 2 summarises the regulatory frameworks by country, evaluating aggregator regulation, variable tariffs, direct load control, flexibility markets, EPC flexibility recognition and the presence of TABS-related policy[7].

Regulatory barriers

Despite the technical maturity of HPs and TABS, their participation in electricity markets and grid services remains limited due to policy blind spots. One critical barrier is the lack of recognition for TABS in energy performance assessments. EPCs across all countries rely on steady-state modelling and disregard dynamic thermal behaviour, which prevents TABS from being rewarded for their flexibility potential. To address this regulatory blind spot, two concrete adaptations are recommended. First, EPC methodologies should be updated to incorporate dynamic thermal performance indicators, such as the building's ability to shift loads over time, rather than relying exclusively on steady-state energy demand metrics. Second, subsidy programmes should be redesigned to reward demonstrated flexibility performance, for example by linking HP installation subsidies to certification that the system is flex-ready and capable of participating in at least one use case [89].

Another barrier is the lack of application of dynamic tariffs. Only a few countries, such as Denmark and Austria, have made significant progress toward enabling variable electricity pricing linked to the actual market price fluctuation. In Germany the implementation of dynamic tariffs has just begun. In Belgium and Canada, consumers lack exposure to time-varying prices, weakening incentives to shift load or exploit building inertia.

Aggregator-based participation also remains restricted. While Denmark leads with a clear legal framework, other countries like Germany impose substantial regulatory and technical hurdles, including high minimum capacity thresholds for market participation [87]. Without stronger regulatory support and simplified aggregation rules, it is difficult for HP and TABS systems to provide their flexibility to markets.

Similarly, the grid operators' ability to control load is differently shaped. § 14a of the German Energy Industry Act (EnWG) [78] provides DSOs the right to curtail residential HPs under specific conditions, which is unique among the countries analysed. Denmark's direct control is reserved for district heating networks and does not extend to small-scale buildings or TABS. In Canada, only a few DSOs are testing similar capabilities.

Finally, local optimisation approaches, such as self-consumption schemes and energy sharing, are more widespread but insufficiently integrated with grid-level services and thereby seen critically by some DSOs [83, 96]. Eicke et al. [97] also showed that in the

[7] A tick mark denotes an established and operational mechanism, while an X denotes its absence. Partial or transitional states are described with short labels such as "pilots", "voluntary", or "under development".

case of Germany self-consumption (with batteries) is financially highly attractive due to grid fee and tax exemptions, while showing almost no benefits for system costs (combination of generation costs and grid reliefs). Austria and Belgium support collective self-consumption, but these programs are primarily financial in nature and lack mechanisms to reward load-shifting behaviour.

In summary, existing frameworks are piecemeal and often overlook the multi-service potential of building-based thermal flexibility. As shown in Table 2, no country has yet implemented policy instruments specifically tailored to TABS, and most fall short in providing a coherent, multi-layered regulatory structure that enables decentralised participation across use cases and utilisation mechanisms.

Stakeholders involved and related barriers

Identification of relevant stakeholders

The literature review and the analysis of the expert consultations reveal a complex stakeholder framework. This is reflected in Fig. 3, which shows a schematic overview of the electricity system.

Governments and policymakers [74, 75, 81–83, 96, 98–106] make up the first layer of the stakeholder framework and play a central role by shaping the adoption of decentralised technologies through policies, incentives, and regulations promoting energy efficiency, renewable integration, and grid flexibility.

The second layer in Fig. 3 shows a classical supply chain, with plant operators [79, 83, 98, 105–107] managing mainly large-scale conventional and renewable power plants, operators of distribution grids (DSO) and transmission grids (TSO) [73–75, 79, 81–83, 98–101, 103–105, 108–111]. DSOs benefit from flexibility to manage grid congestion, while TSOs have an additional responsibility for load balancing, and maintaining stability.

Market operators [74, 99] coordinate markets and their participants and play a key role by enabling energy flexibility trading across various markets, including wholesale, balancing, ancillary services, and local markets. Finally, energy retailers [74, 75, 79, 82,

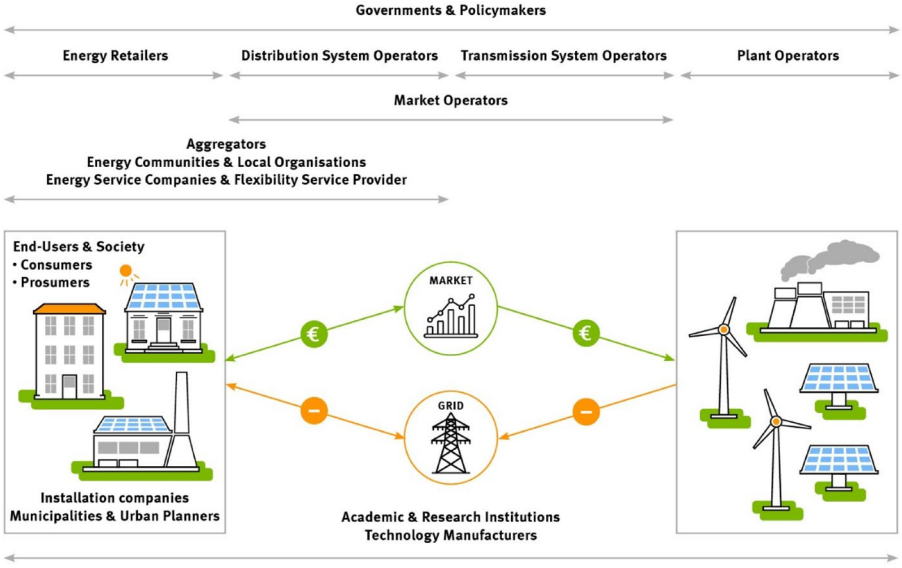

Fig. 3 Schematic summary of the decentralised flexibility stakeholder framework.Source: Authors' own

96, 99, 101, 102, 112] buy energy from producers and sell it to consumers, fostering energy flexibility through dynamic pricing.

Aggregators [73, 75, 83, 99, 109, 111, 112] play a key role in aligning the interests of end-users and the electricity system. By managing clusters of buildings, they deliver flexibility services to DSOs and TSOs and enable consumer participation in markets. Energy communities and local organisations [74, 82, 83, 99], composed of consumers, prosumers, and distributed generators, collectively manage energy generation and consumption. Energy service companies (ESCOs) and flexibility service providers [74, 75, 79, 82, 99, 101, 102, 112] contribute by offering dynamic tariffs and managing renewable energy and flexibility services for communities and end-users.

End-users are widely recognised as essential stakeholders in distributed energy flexibility and can gain financial benefits by engaging in use cases like self-consumption and heat pump optimisation [75, 79, 81, 83, 96, 98–113]. They can be categorised as consumers who provide demand-side flexibility, and prosumers who both consume and generate energy through on-site renewable systems, becoming active participants in the energy system [75, 99, 101]. End-users also form part of society, a broader stakeholder group vital to flexibility deployment. Installation companies are an essential stakeholder in realising flexible residential heating systems. This is because they are not only responsible for planning and installing the systems, but are also one of the main consultants for end-user questions. Municipalities represent public interests and help drive energy flexibility initiatives. Urban planners and building constructors, through early-stage district design, also influence the integration of decentralised energy technologies. In combination, these actors are instrumental in enabling and supporting the widespread adoption of flexibility mechanisms [82, 98, 102, 107, 113].

Academic and research institutions [73, 81, 82, 98, 99, 101, 102, 104, 106] contribute by developing and testing new technologies and business models. Meanwhile, manufacturers of flexibility-related technologies [74, 81, 82, 96, 98, 101, 102, 104, 106, 108, 111] support implementation by producing smart devices, control systems, and communication infrastructure essential for decentralised energy flexibility.

The stakeholders identified above have been found to be common in the selected countries. However, there are some specific nuances between countries that should be noted. Austria is characterised by a solid technical and regulatory approach, but also by a conservative stance toward decentralisation. Austrian DSOs face significant barriers in implementing flexibility markets at the low-voltage level due to the nature of their non-meshed grid structures. Instead of local markets, operating at higher voltage levels (above 110 kV) is considered more viable. In Austria, energy communities benefit from reduced grid charges (depending on the connected grid levels). In Denmark [74, 81, 82], aggregators play a highly relevant technical and strategic role in enabling small consumers to participate in energy flexibility markets. They are actively involved in pilot projects, especially in the thermal sector (e.g. HP control). Finally, Canada is the most unique country in terms of its stakeholder environment. Its federal organisation [73, 82, 83] represents a barrier to the nationwide coordinate and standardise the implementation of decentralised flexibility nationally, particularly with regard to regulation and the participation of stakeholders such as energy retailers, aggregators and DSOs.

Stakeholder-related barriers

The successful implementation of flexibility mechanisms relies heavily on the acceptance and participation of end-users and society. The relevant literature highlights a widespread lack of awareness and understanding of these mechanisms and their benefits, which is seen as a key barrier across many countries [34, 75, 83, 84, 97, 99, 106, 107, 113–115]. This knowledge gap limits public willingness to engage, posing a major obstacle to wider adoption. Expert consultations confirm that misconceptions are common, though some Danish experts suggest the barrier lies more in unclear regulations and poor communication of benefits, particularly regarding TABS as a flexible, energy-efficient solution. They also note that weak financial incentives and limited clarity further hinder its implementation.

The second main reason for the public rejection of flexibility mechanisms is concern over privacy. Fears of data breaches, loss of control, and intrusiveness make users hesitant to adopt these systems [34, 75, 82, 83, 97, 107, 112, 114, 116]. Additionally, distrust in new smart technologies presents a significant behavioural barrier, closely linked to the general lack of public awareness [74, 96, 114]. Many studies note that the complexity, learning curve, and maintenance of such systems further discourage adoption [33, 48, 74, 81, 112, 115]. In Belgium, experts point to a lack of training among HVAC consultants and engineers, leading to a preference for conventional systems over TABS. Economic concerns also play a major role as high upfront and maintenance costs deter users, who often doubt whether the benefits outweigh the expenses. Austrian experts highlight that many end-users are unaware of the potential return on investment and the advantages of self-consumption [74, 75, 82, 96, 116]. Other barriers include bureaucratic hurdles [116], climate change denial among some social groups [108], and a preference for traditional heating systems [117]. In Germany, experts report fears that government policies might force the shutdown of existing heating systems, contributing to resistance. Overall, a combination of privacy concerns, economic doubts, lack of knowledge, and systemic obstacles slow the adoption of flexibility technologies across society.

In relation to the latter, some end-users fear that flexibility mechanisms and related technologies, such as HPs or TABS, may not maintain desired comfort levels or indoor climate preferences [22, 105, 106, 117, 118]. Beyond general comfort concerns, three related barriers deserve explicit analysis. First, comfort constraints directly limit the extractable flexibility: pre-heating or pre-cooling to charge thermal storage may temporarily push indoor temperatures outside preferred ranges [119]. Second, behavioural heterogeneity among users, differing in temperature sensitivity, willingness to delegate control, and occupancy patterns, affects how much flexibility can reliably be activated [120]. Third, rebound effects present a practical challenge: when users override automated control strategies to restore comfort, the intended flexibility is partially or fully negated [121]. However, TABS are increasingly valued in the scientific community for supporting both indoor comfort and energy flexibility, as highlighted in literature and expert interviews [113, 122, 123]. Danish experts stress their effectiveness when systems are well-designed and managed, recommending smart control systems, continuous monitoring, integration with energy management platforms, and user education. They also note that TABS are not inherently slow; their near-room-temperature operation ensures efficient energy transfer and stability, with delays only during sharp daily temperature shifts. In Spain, long-term use has shown TABS to outperform conventional

systems in terms of comfort. Austria shares this positive view, especially in new buildings, though some users remain sceptical due to perceived slow thermal response. In Germany, concerns persist due to limited control strategies and a conservative HVAC design culture, worsened by a lack of training and transparency. Opinions in Belgium are mixed: while some experts praise TABS for enhancing comfort, others cite regulatory inconsistencies and public mistrust. Belgian experts highlight the importance of predictive control using weather forecasts and occupancy data, along with real-time monitoring of temperature, humidity, and CO_2 to ensure rapid response. Misconceptions about TABS as slow floor heating systems further fuel scepticism. In Canada, awareness is low and field experience limited, though experts agree that user-focused design is key to wider adoption.

Most of the studies analysed do not broach possible solutions to overcome the previously identified barriers [73, 79, 80, 97, 99–104, 107, 109, 110, 122, 124–135], yet some plausible solutions can be identified. In relation to the lack of knowledge, several researchers agree that the solution lies in educating citizens through governments and academics. In this sense, energy communities are seen as a common ground to promote discussion at a local level and raise citizens' awareness of the concept of flexibility [82, 98]. Further work needs to be carried out on raising awareness and influencing consumer habits to encourage their participation [75, 101]. Regarding the financial concerns, studies agree that economic benefits could positively influence public perception. The potential savings for building owners from using thermal storage devices to add energy flexibility is seen as a main driver of acceptance in all the analysed countries [33, 74, 75, 115, 136]. Nevertheless, the study conducted by [82, 123] indicates that improving the perception of user comfort when using decentralised flexibility is more suitable to increase public acceptance rather than focusing on financial aspects. This lack of agreement on the strategy to be followed is also evident when analysing the interviews with the Danish experts. One participant considered the question of indoor comfort not relevant, while another indicated that the issue is currently addressed reactively, by handling user complaints, rather than through proactive measures. This highlights a potential gap in strategy and a need for more structured strategy to ensure the deployment of decentralised flexibility mechanisms.

Financial incentives and barriers

Overview of financial incentives and support programmes

At present, financial incentives and support programmes for the deployment of decentralised flexibility are generally considered insufficient in most countries. However, the consulted literature and survey responses provide more detailed insights, highlighting current opportunities and successful examples that could help guide future efforts.

Current financial incentives for the decentralised energy flexibility of small residential consumers mainly rely on energy market participation. This can be either (i) driven by a passive motivation through implicit (price-based) DR mechanisms in which consumers are exposed to time-varying electricity prices and/or network tariffs, or (ii) driven by an active participation through explicit (market-based) DR programmes in which consumers get revenues in return for the load variation triggered by an external request and traded on the market [74, 101, 137].

The most prevalent financial incentive is linked to implicit DR and time-dependent energy prices and/or network tariffs [39, 74, 80, 97, 105, 106, 113, 136]. D'Ettorre et al. [74] collected different successful examples of dynamic pricing including experiences in Australia, France, Estonia, the UK or the Nordic region, while mentioning different kinds of time-of-use tariffs in other EU countries. The literature also mentions some specific cases in which reductions in grid tariffs are applied [83, 106]. Table 2 summarises current variable electricity tariffs in the six targeted countries.

However, time-dependent pricing programs show structural deficiencies, which constitute a relevant financial barrier. Typically, only the energy portion of the bill is variable, while network charges and taxes remain fixed, limiting potential savings. In countries like Denmark or Germany, for example, around 30% of the bill is subject to dynamic pricing, thus providing weak price signals for behavioral change [74, 80, 113]. There are discussions on how grid and market price incentives could be combined, with the result that, for example, grid charges are reduced significantly when grid limitations are not violated [138].

The second major financial support mechanism relies on explicit (incentive-based) DR schemes, which include classical programs like direct load control (DLC) or interruptible load programs, as well as market-based programs, demand-side bidding and capacity markets, among others [101, 137]. Gjorgievski et al. [136] provided a historical review of 34 large-scale projects of power-to-heat DR with dominant presence of US initiatives. The International Energy Agency (IEA) also provides an updated overview of international initiatives in which recent Korean and Japanese pilot programmes for auto DR and residential energy storage for DR, respectively, can be noted [139]. D'Ettorre et al. [74] reported a list of emerging market products for explicit DR for small residential customers including experiences in Finland, France and the UK mostly based on DLC implementations.

Focusing on the six countries covered by the present research, Zhang et al. [73] described an incentive program by the Canadian utility Hydro-Quebec aiming at reducing peak power demand. Participants receive credits to be used for electricity bill reductions. Moreover, discounted tariffs for interruptible loads, like heat pumps, are reported in Austria, while other different dedicated peak shaving programs do also exist in Canada [73].

From a broader perspective, most countries offer general incentives for energy efficiency and renewable energy deployments (examples include EU or national innovation funding, e.g. decarbonisation subsidies -PERTE- in Spain). Among these, self-consumption incentives (which result in implicit savings), feed-in tariffs or compensation schemes for grid injection, and specific subsidies for investments in heat pumps can be highlighted. While these present opportunities for incorporating flexibility measures, there are no specific support lines for flexibility or TABS, which is itself a barrier, as these technologies are often not eligible under current schemes. This is a common theme, both in literature and the survey results from the six countries.

Finally, most responses from the expert survey agree in pointing out a lack of efficient financing mechanisms, and call for grants, subsidies, tax reductions, and specific low-interest loans as the most necessary and effective measures.

Within the expert survey the financial attractiveness of the different use cases was assessed using a Likert scale (1: very unattractive to 5: very attractive). Among the 22

quantitative responses to the corresponding question (summarised in Fig. 4), Self-consumption ranks highest in both median and overall attractiveness, followed closely by the electricity market. The electricity grid received a average ranking of about 3. The balancing market is perceived as the least attractive option, but the variation (interquartile range) is notably high, reflecting the upcoming opportunities in Denmark.

This is also confirmed by literature findings. As described above, the relevant literature reveals that most financial incentives and implementations of decentralised flexibility are linked either to end-user participation in energy markets – through explicit or implicit DR schemes – or to leveraging DR to shift energy consumption to periods with surplus onsite electricity production. This approach aims to achieve economic savings by reducing grid imports.

Financial barriers

Deploying decentralised energy flexibility solutions faces a range of significant financial and economic barriers that hinder their large-scale adoption. One of the key issues lies in the complexity of evaluating financial benefits, as current methods and models used by utilities are often inaccurate, leading to either an underestimation or overestimation of the true value of flexibility. This leads to uncertainty around expected economic outcomes and makes fair assessments difficult [73, 74, 82, 101, 108].

This difficulty in assessment stems partly from the inherent complexity of quantifying and valuing flexibility, given unpredictable forecasts and the necessity of maintaining operational security. Indeed, cost savings associated with flexibility solutions can vary widely, depending on comfort requirements, weather conditions, and the volatility

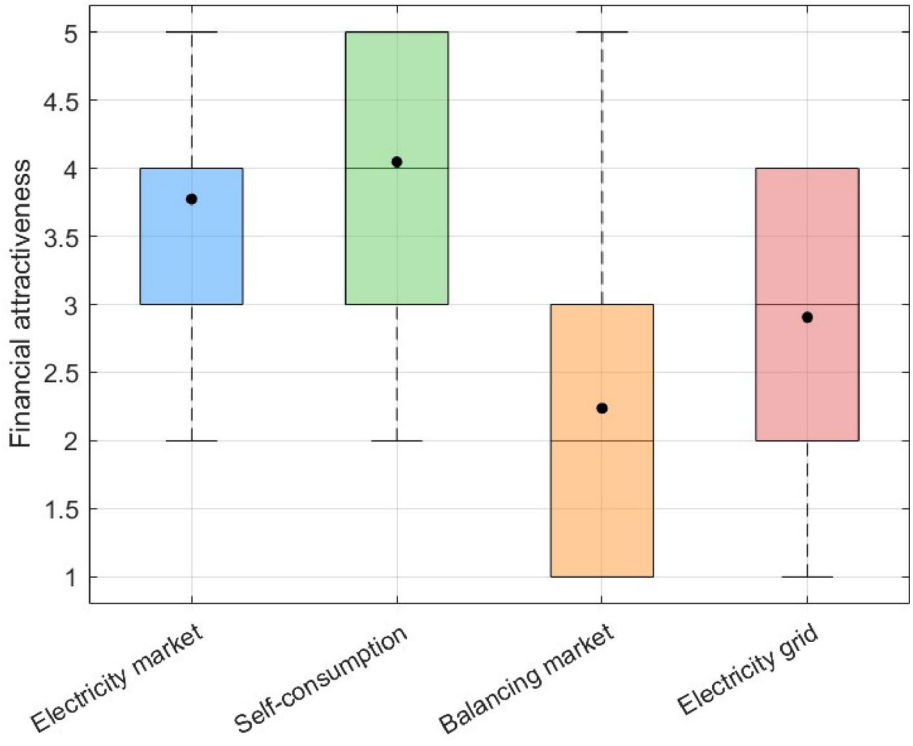

Fig. 4 Financial attractiveness of use cases (authors' own, based on responses to the expert survey)

of electricity prices, all of which reduce the reliability of long-term financial projections and complicate investment decisions [81, 97, 127, 128],.

Beyond quantification challenges, the energy price structure itself can act as an independent barrier to adoption. Low or stable electricity prices and non-reflective tariffs reduce the incentive to shift load or invest in flexibility-enabling technologies, as evidenced in industrial and district energy sectors [140, 141]. Under such conditions, the uncertain return on investment (ROI) and the absence of a clear business case further discourage uptake, even where technical solutions are available.

Adding to this uncertainty, two major aspects are noted in most of the reviewed literature works and surveys for the six targeted countries.

On the one hand, high upfront costs continue to be a major obstacle, even as interest in flexibility assets (such as electric vehicles or behind-the-meter storage) grows. Implementing these solutions often requires significant changes to operations, organisational structures, and IT infrastructure [74, 83, 100, 106–108, 123]. The costs of enabling Information and communication technology systems, direct load control infrastructure, model development, and advanced control strategies like model predictive control are perceived as high and pose a barrier, especially when the value proposition remains unclear to consumers and other relevant investors (e.g. building managers). Limited willingness to pay for smart grid technologies aggravates this barrier [74, 75, 79–82, 106, 122, 123].

Retrofitting existing buildings, as part of the requirements for many flexibility deployments, particularly for room-level thermal zoning or sub-metering, is also economically challenging and technically complex [122]. A particularly underestimated dimension of this burden is the systemic nature of flexibility-oriented retrofits. Transitioning from fossil-based heating to a heat pump in existing buildings is repeatedly described in literature as part of a whole-house retrofit [142–144]. Indeed, it typically requires far more than a simple equipment swap: thermal emitters may need resizing or replacement to accommodate lower supply temperatures, hydraulic circuits often require full redesign, and building envelope improvements may be necessary. These cascading interventions substantially increase the total investment required and are a significant driver of user reluctance.

On the other hand, there is an evident shortage of appropriate market mechanisms, economic incentives, and compensation structures for flexibility services. As a result, retailers and aggregators often face unclear remuneration policies that vary with market conditions [75, 80, 97, 99, 101, 106, 123, 128]. As previously described, there is a general lack of accessible financing mechanisms such as loans, grants, or tax incentives. This is partly due to the emerging nature of flexibility markets, which suffer from under-developed rules and inefficiencies in current market structures [82, 127] and lead to uncertainties and limitations to offer tailored financial products and support. In that sense, a lack of long-term policy objectives adds another layer of uncertainty for investors [108] and bureaucratic hurdles, such as those seen in the UK's capacity markets and Germany's complex application processes, further complicate cost-benefit analyses [99].

Hence, absolute savings from flexibility tend to be modest, especially in regions in which energy bills comprise a small share of household expenditure [81, 113]. The lack of effective flexible tariffs and the overall uncertainty in regulations make it difficult to estimate the benefits and develop viable business models [80, 100, 112, 123]. Thus,

end-users also face real costs when adjusting operations to provide flexibility, and without adequate compensation, their participation is disincentivised.

Concerning TABS as a decentralised flexibility source, the reviewed literature does not provide a direct comparison of initial investment costs of TABS as a thermal emitter itself versus other conventional systems. In that sense, the perception of the survey interviewees shows relevant differences. While some experts (mainly from Belgium and Canada) remark the high upfront costs for design, construction, control and integration, there is a recurrent claim by experts in Austria, Germany, Denmark and Spain about the misconception of TABS as a more expensive system than traditional solutions. It is stated that a lack of knowledge often leads to higher pricing (innovation tax) and impedes clients from appreciating the value of TABS (contribution to higher comfort, self-sufficiency and reduced operational costs). From an integrated perspective (i.e. energy generation + distribution + emission), literature supports that TABS can be financially competitive in the long term due to the operational cost savings and the use of their thermal storage capacity to downsize the production plant, which would reduce that component of the investment costs [102] but also reduce the ability to provide flexibility to the system (see Sect. "Identified use cases").

Other financial barriers for TABS mentioned in the survey include insufficient and non-specific incentives, uncertain ROIs, as well as the growing market share of some competing technologies (e.g. cross-laminated timber construction in Denmark).

Discussion and recommendations

Key barriers and trends

In this section, based on the literature review and expert consultation, key barriers and stakeholders are noted. A general interpretation of these findings is provided by attaching them to the four utilisation mechanisms (see Sect. "Utilisation mechanisms: Options to activate residential heat pump flexibility"), as well as to the four key indicators from the country profile (see Sect. "Country profile"). The initial intention to discuss the barriers according to climatic zones was abandoned as the identified non-technical barriers did not show clear correlations with the different climatic conditions in the countries studied. Demand for cooling is also increasing in the more northern countries. In Germany, for example, a significant price spread manifested in June 2025 between negative prices at noon, resulting from high PV production, and very high prices in the afternoon due to new cooling demand (UC Electricity Market) [145]. This shows that the climate zone does not directly influence the barriers and which UCs are relevant; rather, it influences the quantity and the emergence of heating and cooling demand [146–148].

Table 3 provides a mapping of barriers according to their relevance for specific utilisation mechanisms and the stakeholders involved. A differentiation between stakeholders who are involved rather directly (primary) and those who are influenced or influencing indirectly (secondary) and overarching stakeholders that are relevant for every utilisation mechanism, is made. Some of the barriers are linked to specific mechanisms, while others are relevant for (almost) every approach. The mechanism of *local optimisation* is separated into two categories – collectively and individually organised – as the stakeholder and barriers differ between them.

The stakeholders mentioned in Table 3 are described in Sect. "Stakeholders involved and related barriers". The table depicts that the approaches differ significantly with

Table 3 Barrier mapping across utilisation mechanism for flexibility and stakeholder involved

Utilisation mechanisms	Stakeholders			Key barriers	
	Primary	Secondary	Overarching	Overarching	Specific
Variable tariffs	• End-users • Energy retailers • DSOs and TSOs	• Market operators • RE operators • ESCOs & flexibility providers	• Policymakers • Research institutions • Technology manufacturers	1.Lack of awareness and knowledge 2. High stakeholder diversity 3. Uncertain ROI 4. Fragmented regulations and strategies	5. Lack of transparency 6. Uncertain effects
Active Market participation	• Aggregators • Energy communities & local organisations • ESCOs & flexibility providers	• Market operators • RE Operators • DSOs and TSOs • End-users			7. Market access 8. Undefined role of aggregator
Regulated direct load control	• DSOs • (TSOs)	• End-users • Market operators			9. Privacy concerns
Local optimisation (collectively)	• End-Users • Energy Communities & Local Organisations	• DSOs • Energy retailers			10. Self-consumption : system benefits not evident
Local optimisation (individually)	• End-users				

Source: Compiled by authors

regard to how many stakeholders are involved. End-users are, evidently, involved in all approaches as this analysis' focus is on residential flexibility. Policymakers, research institutions and technology manufacturers influence all approaches to a certain extent.

The first four key barriers are overarching for all utilisation mechanisms except for individual local optimisation, which is related to the UCs of device optimisation and self-consumption. In the individual optimisation approach, mainly single end-users are involved, which reduces the number of stakeholders involved and the number of systems that have to interact significantly. This is one reason why it is currently the most attractive approach (see Fig. 4). Self-consumption additionally shows a high financial attractiveness, resulting from current regulations which are not grounded in clear energy system benefits as, for example, self-consumption typically leads to lower grid fees but does not per se reduce peak load and thus grid costs (see Sect. "Regulatory barriers") This regulation poses a barrier to effectively harnessing small-scale flexibility for the energy system (**Barrier 10**).

One of the most significant obstacles is the widespread lack of awareness and knowledge regarding opportunities for flexibility and their benefits (**Barrier 1**). This knowledge gap spans multiple stakeholder groups. For instance, policymakers often overlook the potential of DR when setting their agenda and (especially smaller) DSOs or energy retailers frequently lack the expertise to implement emerging regulations in this field. Project planners and HVAC professionals avoid TABS due to their slow response time, design complexity and absence of standardised sizing methods. As a result, engineers often prefer fast-reacting, familiar systems (e.g. responsive air-based HVAC) that are easier to specify, model, and commission. From the end-user's perspective, additional

barriers include distrust of new technologies, concerns over system complexity, perceptions about compromising indoor comfort, and uncertainty about ROI. These perceptions are a result of the overall knowledge gap and intersect with other barriers such as unclear financial returns, limited regulatory integration and privacy concerns.

A common identified barrier is the high diversity of stakeholders involved in certain approaches (**Barrier 2**), and a lack of effective communication among the involved stakeholders. This barrier is further intensified by the emergence of relatively new actors in the energy system, such as aggregators and the energy flexibility service providers, whose roles and responsibilities are still evolving. In relation to this barrier, it is also worth mentioning that the role of end-users becomes more complicated when it comes to rental housing. In this case, it is even less clear what role the landlord and the tenant each play, in any of the participation approaches identified above. Financial institutions may also take a role as stakeholders for supporting flexibility deployment by facilitating access to financing for HP and TABS installations, although their role remains mainly indirect and flexibility-related investment opportunities are still not widely recognized within the sector.

From this perspective, *regulated direct load control* seems to be an effective approach, primarily because it involves a limited number of stakeholders. However, it faces significant barriers, like end-user privacy concerns with a view to giving (even partial) control over household devices to grid operators (**Barrier 9**). Similarly, *variable tariffs* only involve a small group of stakeholders, but they lack transparency from the perspective of end-users, who often do not understand how tariff structures impact their electricity bills (**Barrier 5**). Furthermore, the actual effect of this approach on the targeted UC is uncertain (**Barrier 6**) as the participation rate cannot be reliably predicted.

Active market participation comprises the most complex approach, requiring the engagement and regulation of a broad range of stakeholders. In addition to this complexity, two key barriers hinder its adoption, namely market access (**Barrier 7**) which is often unfeasible due to minimum trading volumes and participation requirements; and the market role of aggregators, which is crucial for pooling small-scale residential flexibility and is not yet clearly defined in many countries (**Barrier 8**).

The literature and expert surveys highlight a series of persistent economic and financial barriers resulting in uncertainties on ROI (**Barrier 3**) and thereby inhibiting the deployment of decentralised flexibility solutions in buildings. A core issue lies in the difficulty of quantifying the financial value of flexibility, especially against the backdrop of volatile electricity prices and uncertain demand forecasts. These factors lead to inconsistent ROI projections and a lack of clear business cases. This is particularly problematic given additional upfront costs associated with installing flexibility-enabling assets and advanced control technologies like model predictive control. Additionally, there is a notable absence of suitable financial mechanisms, and the current market structure fails to offer stable and predictable revenue streams for these services. The mismatch between modest absolute savings in the energy bill and the required capital expenditures results in a weak financial incentive for end-users. In several countries stakeholders mistakenly assume that TABS is excessively expensive, without taking their long-term cost-effectiveness into account, particularly in terms of thermal storage and comfort optimisation. This is an example in which a lack of knowledge (see Barrier 1) results in perceived additional costs and in total creates an additional barrier.

Finally, regulatory fragmentation remains a major barrier across all six countries studied (**Barrier 4**). Besides the fact that only certain approaches are implemented in each country (which is not a problem per se as different mechanisms could be used to fulfill the UCs), a holistic consideration of DR is lacking in policymaking. Building load flexibility is often insufficiently integrated in national energy strategies and regulatory frameworks. Policy support for HPs, for instance, frequently overlooks whether devices meet the technical prerequisites for flexible operation, potentially leading to costly retrofits [59]. Although individual self-consumption is widely supported and the most attractive UC, often through exemptions from grid fees, this approach fails to consider its limited contribution to broader grid management in the absence of regulatory provisions. Consequently, the financial burden of grid expansion costs may shift disproportionately to the remaining electricity users. Another example of fragmentation is the fact that current Energy Performance Certificates (EPCs) rely on steady-state modelling in all the countries analysed and ignore TABS inertia in the flexibility evaluation. As a result, TABS, despite their proven ability to shift thermal loads, are not sufficiently considered in compliance incentives and performance recognition.

The future outlook of TABS adoption and the utilisation of flexibility from building integrated HPs varies significantly across the countries studied. Austria stands out as the frontrunner; TABS are frequently integrated in tender specifications for new buildings there. Yet, stakeholders continue to call for improved financial incentives and dynamic electricity pricing to fully unlock flexibility potential. Denmark also shows steady progress, aided by the development of smart controls and the gradual introduction of enabling policies. Nevertheless, experts caution that relying solely on small-scale systems without aggregation mechanisms may limit the overall system impact.

In contrast, Germany faces several structural challenges, including fragmented policy implementation, a delayed roll-out of smart metering infrastructure, and fluctuating funding schemes. Despite these barriers, recent legislative developments (e.g. introduction of dynamic tariffs from 2025) suggest future acceleration. Spain offers a cautiously optimistic scenario, driven by EU integration efforts and anticipated regulatory reforms. Meanwhile, Canada has only made minor progress in implementing TABS. At the same time, the VRES share and the resulting need for new flexibility options, as well as the development of HPs in general, are growing slowly.

Belgium shows emerging interest, with some successful public-sector projects demonstrating TABS integration, but fragmented policy frameworks, limited targeted incentives, and low market awareness continue to constrain broader adoption.

Overall, the maturity of TABS adoption for indoor climate and flexibility is most advanced in Austria and Denmark; it is evolving in Belgium, Spain and Germany, and emerging in Canada. Across all contexts, its success will ultimately depend on the interplay between supportive regulation, increasing stakeholder awareness, and interdisciplinary cooperation.

Implications and recommendations

In most of the analysed countries, the current transformation phase in the electricity sector is characterised by renewable energies emerging from their niche to become the main players. New flexibility options must therefore be developed to replace the balancing capabilities traditionally provided by conventional power plants. Without adequate

alternatives, there is an increased risk of grid frequency violations, which could lead to the curtailment of RE, load shedding and ultimately the shutdown of sub-grids (UC balancing services). In the UC electricity market, insufficient flexibility options may lead to increased RE curtailment and greater reliance on peak load power plants. Similarly, in the electricity grid UC, more grid expansion or more conventional power plants for redispatch would be required. For all of three UCs, these developments would result in higher costs and increased greenhouse gas emissions. This may even necessitate the installation of new fossil fuel power plants to replace more carbon-intensive facilities providing the needed flexibility [3, 8, 65].

To enable domestic HPs to effectively contribute to a cost-effective, resilient and low-emission electricity system, four key areas for improvement have been identified. The first three areas are primarily aimed at governments and policymakers, while the fourth addresses various stakeholders.

1. Coherent regulatory framework

Flexibility needs should be considered systematically in all energy-related policy measures, not only in the electricity sector but with a broader focus on sector integration. For example, the subsidies for heat pumps or their connection to the grid could be linked to the technical capability for flexible use (flex-ready) or the mandatory application of use cases (e.g. electricity market or grid). This is especially relevant during the current transformation phase in the heating sector. In this sector, a rapid uptake of HPs presents a unique opportunity to consider their flexibilisation from the beginning and thereby avoid costly retrofits in the future. It must also be taken into account that the regulation for new systems is more effective, whereas requirements for existing systems typically cannot be adjusted retrospectively and might lead to lock-in effects. Therefore, the subsidisation of heat pumps, for example, should be linked to the technical capability for flexible operation (flex-ready) or to actual participation in system-beneficial use cases (e.g. mandatory use of dynamic tariffs or regulated direct load control).

Another example of inter-sectoral regulation is that TABs and HP-based flexibility should be integrated in the EPC methodologies. The recognition of thermal flexibility in these assessments could offer an additional incentive for its adoption. Subsidies for electricity tariffs or measures to avoid price-peaks, e.g. regulatory caps on maximum prices on the electricity market or subsidies for hydrogen fuel cost, might be appropriate to reduce bills for end-users but diminish incentives for load shifting [149] Furthermore, regulation must be approached from a systems perspective, rather than addressing single UCs. If various UCs could be combined, it could increase both revenues and system benefits. For example, variable electricity tariffs could be combined with dynamic grid fees, reducing two negative effects of variable tariffs: the risk of overshooting, when the reaction on price signals exceeds the needs, and the risk that reacting on market signals could cause stress in distribution grids [149].

Moreover, subsidies should be based on system benefits. Self-consumption, currently the most widespread UC, receives implicit subsidies through exemptions from grid fees and other charges, despite offering limited benefits for the electricity market and grid stability [97]. To address this imbalance, regulation should ensure that self-consumption considers market and grid conditions. In Germany, the remuneration for hours with negative prices is now being suspended [150]. This seems to be an effective approach

but might cause an acceptance issue for RE installations, especially from prosumers. A more transparent alternative would be to mandate the use of dynamic electricity tariffs for self-consumption systems. Similarly, in the case of energy sharing, a reduction in grid fees should be grounded in a robust cost-benefit analysis to ensure economic and system-wide efficiency.

Long-term strategies and targets for flexibility could provide security for investment in flexibility technology, otherwise private investment will continue to be risk-averse [99, 108]. Currently, policy frameworks fall short in addressing the economic constraints of decentralised flexibility. Therefore, it is imperative to design policies that recognise flexibility as a core component of energy transition strategies. From a governance and implementation standpoint, flexibility should be viewed not as an add-on, but as a core performance criterion in energy planning. Public procurement, building regulations, and utility programs will need to evolve accordingly. For example, new public building tenders could require flexibility-ready heating and cooling systems, and utilities could prioritise demand-side thermal buffers in their load-shaping strategies of DR. These institutional changes would catalyse market transformation more effectively than incentive programs alone.

2. Enable new market players

One core element identified is that the market role of aggregators needs to be more clearly defined and needs simplified market access to unfold their potential. Therefore, an unbundling of energy supply and flexibility provision is necessary as aggregator are otherwise treated like electricity retailers and therefore must also fulfill the role of a balancing responsible party.

Flexibility markets are tested in several pilot projects and yet implemented only in a very few examples, most of them without including residential HP flexibility. In general, flexibility markets suffer from underdeveloped rules and inefficiencies in the current electricity market structures [39, 127] and especially small-scale, local flexibility markets are often not providing sufficient competition, leading to uncertainties and limitations to offer financial incentives.

To promote the effective deployment of decentralised flexibility, bureaucratic hurdles like complicated application processes should be reduced. Streamlining processes is essential to facilitate efficient deployment and market access.

Smart metering infrastructure is another essential requirement. Smart meters enable real-time monitoring and market participation and are critical for leveraging residential and consequently small-scale flexibility. However, in countries with low smart meter penetration, particularly Germany, additional measures are urgently needed. These may include financial support or regulatory requirements to accelerate the roll-out.

3. Introduce measures for financial attractiveness

To improve transparency and reduce exposure to price volatility associated with dynamic tariffs, it is recommended to establish independent comparison platforms that employ standardised user profiles, such as those representing households with inflexible energy demand or those equipped with flexible HPs. Furthermore, the provision of short-term billing data should be made mandatory, along with the development of clear guidelines aimed at minimising financial risk. These may include, for instance, the introduction

of price caps or the design of well-considered hybrid tariff models that incorporate a fixed-price component, thereby offering consumers greater stability and predictability. In this context, the balance between the fixed and dynamic fractions of the electricity tariff should be carefully analysed and designed as the fixed component enhances predictability and builds trust in flexibility-oriented decision-making, but simultaneously limits the economic gains that can be achieved by aligning flexible consumption with variable pricing.

Additionally, as a targeted support measure to facilitate this transition, several experts have suggested the provision of investment grants. This type of financial assistance could serve as an effective mechanism to lower the initial cost barrier associated with acquiring and installing information and communication technology (ICT) systems. Such grants would be particularly valuable during the initial roll-out phase, helping to bridge the gap until small-scale flexibility measures that are beneficial for the energy system as a whole become more widespread and well-established. These grants could also be combined with subsidise for HP installations.

4. Increase knowledge and public awareness

To overcome informational barriers of the public and end-users, concerns related to privacy such as device control for example by DSOs, and potential impacts on indoor climate, must be addressed to build trust in emerging technologies. Additionally, a broader awareness of the role of individual end-users in the energy transition should be created, showing that residential flexibility can contribute significantly to the electricity system [80].

In parallel, the technical training of professionals, especially HVAC installation companies and consultants, must be improved [151], mainly to overcome the conservative design culture and skill gaps observed in countries such as Belgium and Germany. This could also reduce the costs for TABS installation as the so-called "innovation tax," resulting from lack of knowledge, could be diminished.

The implementation of TABS should also be supported through design tools and trainings. Adoption of TABS is hindered not only by regulation but also by a lack of industry familiarity and practical design guidance. National research funding and industry associations should invest in accessible tools, case libraries, and continuing education modules for mechanical engineers and energy consultants. Clear sizing guidelines, simplified commissioning protocols, and validated simulation templates would reduce perceived complexity and increase confidence in TABS as a mainstream design choice.

There is a need for better methodologies to evaluate the financial value of flexibility in a standardised and transparent manner. Thus, tools to simulate ROI under varying price signals, comfort constraints, and grid conditions should be developed, as well as standardised valuation metrics for flexibility are needed to support informed investment decisions. This requires interdisciplinary studies that merge economic modelling with behavioural science so that it can appropriately acknowledge human factors such as user willingness to pay, risk tolerance, and perceived value.

International collaboration is essential to harmonise definitions, key performance indicators, metrics, and protocols for building flexibility. Without alignment across jurisdictions, decentralised assets will remain constrained by fragmented compliance rules and incompatible system architectures. A common framework for evaluating building

flexibility, analogous to that which exists for energy performance, could support future benchmarking, trade, and certification efforts.

Building-level flexibility should be considered by TSOs and DSOs, with the result that it gets embedded into grid codes, e.g. with a specification of its key performance indicators or communication protocols.

To enhance the stakeholder framework for decentralised flexibility implementation, a more coordinated and structured strategy across all stakeholders is essential. This includes fostering cross-sector collaboration among governments, TSOs, DSOs, aggregators, energy communities, and service providers, supported by clear and consistent regulatory frameworks particularly important in federated systems such as Canada and Belgium. For example, regulators, TSOs, and DSOs need to coordinate effectively to ensure that buildings can be integrated into frameworks for congestion management, redispatch, and capacity planning.

Research limitations

This analysis provides insights based on expert consultations and a systematic literature review across six countries, Austria, Belgium, Canada, Denmark, Germany, and Spain. These countries were selected to reflect a range of climatic conditions and regulatory environments. However, the findings may not be fully generalisable to regions with significantly different energy systems, policy landscapes, or stakeholder constellations.

The expert consultation involved a diverse set of professionals across institutions, offering a broad perspective on non-technical barriers to building-integrated HP flexibility. Nonetheless, the sample size remains limited, and while efforts were made to ensure diversity, the consultation may not fully capture views from underrepresented sectors, such as smaller utilities, specific end-user groups, or emerging market actors in other not studied countries.

Furthermore, this research presents a current assessment of the countries situation, reflecting policy, market, and stakeholder conditions as of early 2025. Given the dynamic nature of energy policy and the rapid evolution of decentralised energy technologies, certain conclusions may require re-evaluation in the light of future developments.

Finally, the geographic scope, focused on countries from Europe and North America, constrains the global applicability of the results. Insights may not directly translate to countries with less mature policy frameworks, different grid infrastructures, or energy systems undergoing rapid transformation.

Conclusions

This analysis examines the non-technical barriers hindering the flexible operation of decentralised HP systems with a special focus on TABS across six countries: Austria, Belgium, Canada, Denmark, Germany, and Spain. Despite growing urgency due to increasing VRE shares and technical maturity, the deployment of decentralised flexibility solutions remains limited. It identified regulatory, stakeholder-related and financial barriers that hinder the realisation of thermal flexibility in residential buildings.

By analysing findings across multiple countries, use cases and utilisation mechanisms, to activate flexibility, this study demonstrates that non-technical barriers vary not only by national policy context but also by the specific use case and flexibility mechanism employed.

While regulatory frameworks remain fragmented and insufficiently aligned with the potential of building-integrated thermal flexibility, TABS, in particular, are not adequately reflected in regulatory framework, for example in energy performance certificates or incentive schemes, despite their proven load-shifting and efficiency capabilities. Moreover, access to flexibility markets is still limited, especially for residential systems, due to high entry thresholds and unclear roles for aggregators. National authorities should link subsidies for HPs or grid connection conditions to the requirement that HPs are ready to provide flexibility or even that they have to contribute to one or more UCs. Elsewise HP demand provides additional pressure to the electricity system instead of offering solutions.

Financial barriers were found to be similarly pervasive. Although some countries offer time-dependent electricity pricing or pilot demand response programs, the overall financial attractiveness of flexibility use cases remains modest. Self-consumption ranks highest in perceived economic value, but its system-level benefits are limited. Furthermore, upfront investment costs in combination with a lack of transparent return-on-investment models, and insufficient financing instruments continue to deter adoption. This applies particularly for TABS, which are often perceived as costly despite their long-term savings potential.

From a stakeholder and societal perspective, the analysis revealed a widespread lack of awareness and limited technical knowledge, and persistent scepticism toward new technologies such as TABS. End-users often question the comfort implications and privacy aspects of smart meter control, while planners and installers frequently lack training and guidance on flexibility-enabling design strategies. Aggregators and local energy communities could help bridge this gap, but their roles remain underdeveloped and insufficiently defined in most national contexts.

Four of the ten key barriers identified are overarchingly relevant for all utilisation mechanisms, with the exception of individual local optimisation. To overcome these four key barriers in order to achieve an effective deployment of building-based thermal flexibility, the following strategies are recommended: (1) integrating flexibility into core energy performance and building policy frameworks, which includes an acceleration of smart meter deployment for countries lagging behind; (2) enhancing market access and legal clarity for aggregators; (3) providing targeted financial incentives and reduce perceived investment risks; and (4) increasing public awareness and technical training to overcome knowledge barriers, especially regarding the benefits and capabilities of TABS.

By offering an integrated perspective that links non-technical barriers with specific UCs, this analysis contributes to providing insights into practical and policy-relevant solutions to facilitate the flexible operation of decentralised HP systems. Overcoming the identified non-technical barriers of decentralised flexibility would contribute to a resilient and economically-efficient low-carbon energy future.

Abbreviations

COP	Coefficient of performance
DLC	Direct load control
DR	Demand response
DSO	Distribution system operator
ESCO	Energy service company
EnWG	Energiewirtschaftsgesetz (German Energy Industry Act)
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IEA	International energy agency

RE	Renewable energy
ROI	Return of investment
TABS	Thermally activated building systems
TSO	Transmission system operator
UC	Use case
VRE	Variable renewable energy

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42162-026-00673-2.

Supplementary Material 1

Acknowledgements

We thank the IEA Task Members Matthias Kersken, Daniel Muschick and Rosie Christodoulaki who participated in supportive discussions and reviewed a paper draft. Special thank also goes to the multiple experts from the countries of Austria, Belgium, Canada, Germany, Denmark and Spain, who contributed to the expert consultation. Further, we thank Vanessa Cook for proofreading and Hans Löbermann for designing the presented figures.

Author contributions

Conceptualisation: David Ritter, Christoph Rohringer, Alireza Afshari, Kaya Duenzen.- Data curation: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Shady Attia.- Formal analysis: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Shady Attia.- Funding acquisition: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz.- Investigation: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Shady Attia.- Methodology: David Ritter, Christoph Rohringer, Alireza Afshari, Kaya Duenzen.- Project administration: Christoph Rohringer.- Supervision: David Ritter.- Validation: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Dierk Bauknecht, Shady Attia.- Visualisation: David Ritter, Manuel Andrés Chicote, Pablo Hernandez-Cruz, Kaya Duenzen- Writing – original draft: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Dierk Bauknecht, Shady Attia.- Writing – review and editing: David Ritter, Christoph Rohringer, Alireza Afshari, Pablo Hernandez-Cruz, Manuel Andrés-Chicote, Kaya Duenzen, Dierk Bauknecht, Shady Attia.

Funding

Open Access funding enabled and organized by Projekt DEAL. David Ritter and Kaya Dünzen received funding for their work on this article from the German Federal Ministry for Education and Research (BMBF) [Grant number 03SFK5FO-2]. Christoph Rohringer is Task Manager of the International Energy Agency Energy Storage Technology Collaboration Programme Task 43 and received funding from the Austrian Federal Ministry of Innovation, Mobility and Infrastructure in the programme 'IEA-Forschungskooperation 2022'. Pablo Hernandez-Cruz received funding from the R+D+i project PID2024-156054OB-C22, financed by MICIU/AEI/10.13039/501100011033 and FEDER, UE. A way of making Europe'. Alireza Afshari is Leader of Subtask C of the International Energy Agency Energy Storage Technology Collaboration Programme Task 43 and received funding from the Danish Energy Agency in the 'Energy Technology Development and Demonstration Programme'. Shady Attia reports financial support was provided by University of Liege.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

Author details

[1]Faculty of Environment and Natural Resources, Albert Ludwigs University Freiburg, Freiburg, Germany
[2]Oeko-Institut, Freiburg, Germany
[3]AEE - Institute for sustainable Technologies, Gleisdorf, Austria
[4]Department of the Built Environment, Aalborg University, Copenhagen, Denmark
[5]Departamento de Ingeniería Energética y Fluidomecánica Grupo de Investigación de Termotecnia, ITAP Escuela de Ingenierías Industriales Universidad de Valladolid, Valladolid, Spain
[6]ENEDI Research Group, Energy Engineering Department, University of the Basque Country UPV/EHU, Bilbao, Spain
[7]Sustainable Building Design Lab, Department UEE, Faculty of Applied Sciences, Université de Liège, Liège, Belgium

Received: 1 April 2026 / Accepted: 31 May 2026
Published online: 23 June 2026

References

1. Martinot E (2016) Grid integration of renewable energy: flexibility, innovation, and experience. Annu Rev Environ Resour 41:223–251. https://doi.org/10.1146/annurev-environ-110615-085725
2. Wind, Europe (2025) Iberian Peninsula blackout proves the need for grid resilience. https://windeurope.org/newsroom/news/iberian-peninsula-blackout-proves-the-need-for-grid-resilience/ (accessed 4 June 2025)

3. IPCC (2012) Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
4. United Nations Climate Change, Registry NDC 26.26.2025. https://unfccc.int/NDCREG (accessed 2 July 2025).
5. UNFCCC, Long-term strategies portal | UNFCCC (2025) https://unfccc.int/process/the-paris-agreement/long-term-strategies (accessed 2 July 2025).
6. Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R (2019) The role of renewable energy in the global energy transformation. Energy Strategy Reviews 24:38–50. https://doi.org/10.1016/j.esr.2019.01.006
7. Sinsel SR, Riemke RL, Hoffmann VH (2020) Challenges and solution technologies for the integration of variable renewable energy sources—a review. Renewable Energy 145:2271–2285. https://doi.org/10.1016/j.renene.2019.06.147
8. Jacobson MZ, Delucchi MA, Cameron MA, Frew BA (2015) Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. Proceedings of the National Academy of Sciences 112:15060–15065. https://doi.org/10.1073/pnas.1510028112
9. Bareiß K, de La Rua C, Möckl M, Hamacher T (2019) Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Applied Energy. https://doi.org/10.1016/j.apenergy.2019.01.001
10. de Carne G, Marousi SM, Beiranvand H, de Angelis V, Gevorgian V, Waczowicz S, Mather B, Liserre M, Hagenmeyer V (2024) The role of energy storage systems for a secure energy supply: a comprehensive review of system needs and technology solutions. Electric Power Systems Research 236:110963, 110963. https://doi.org/10.1016/j.epsr.2024.110963
11. Ruhnau O, Qvist S (2022) Storage requirements in a 100% renewable electricity system: extreme events and inter-annual variability. Environ Res Lett. https://doi.org/10.1088/1748-9326/ac4dc8
12. Bogdanov D, Ram M, Aghahosseini A, Gulagi A, Oyewo AS, Child M, Caldera U, Sadovskaia K, Farfan J, de Souza Noel Simas Barbosa L, Fasihi M, Khalili S, Traber T, Breyer C (2021) Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy 227:120467, 120467. https://doi.org/10.1016/j.energy.2021.120467
13. Franco A (2025) Green Hydrogen and the Energy Transition: Hopes, Challenges, and Realistic Opportunities. Hydrogen 6:28. https://doi.org/10.3390/hydrogen6020028
14. Cruz MR, Fitiwi DZ, Santos SF, Catalão JP (2018) A comprehensive survey of flexibility options for supporting the low-carbon energy future. Renew Sustain Energy Rev 97:338–353. https://doi.org/10.1016/j.rser.2018.08.028
15. Bareiß K, Schönleber K, Hamacher T (2018) The role of hydrogen, battery-electric vehicles and heat as flexibility option in future energy systems, in: 20th European Conference on Power Electronics and Applications, Riga, pp. 1–10
16. Arteconi A, Polonara F (2018) Assessing the Demand Side Management Potential and the Energy Flexibility of Heat Pumps in Buildings. Energies 11:1–19. https://doi.org/10.3390/en11071846
17. Hong J, Kelly NJ, Richardson I, Thomson M (2013) Assessing heat pumps as flexible load. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 227:30–42. https://doi.org/10.1177/0957650912454830
18. Bloess A, Schill W-P, Zerrahn A (2017) Power-to-Heat for Renewable Energy Integration: Technologies, Modeling Approaches, and Flexibility Potentials: Discussion Papers 1677
19. Heidenthaler D, Leeb M, Schnabel T, Huber H (2021) Comparative analysis of thermally activated building systems in wooden and concrete structures regarding functionality and energy storage on a simulation-based approach. Energy 233:121138. https://doi.org/10.1016/j.energy.2021.121138
20. Xu X, Wang S, Wang J, Xiao F (2010) Active pipe-embedded structures in buildings for utilizing low-grade energy sources: A review. Energy Build 42:1567–1581. https://doi.org/10.1016/j.enbuild.2010.05.002
21. Weiß T, Fulterer AM, A. and, Knotzer (2019) Energy flexibility of domestic thermal loads – a building typology approach of the residential building stock in Austria. Adv Building Energy Res 13:122–137. https://doi.org/10.1080/17512549.2017.1420606
22. Heidenthaler D, Leeb M, Moltinger M, Bednar T (2023) Characterizing the energy flexibility of districts using urban building energy modelling. Building Simul 2023 18:2507–2514. https://doi.org/10.26868/25222708.2023.1285
23. Do HQ, Luther MB, Amirkhani M, Wang Z, Martek I (2022) Radiant Conditioning Retrofitting for Residential Buildings. Energies 15:449. https://doi.org/10.3390/en15020449
24. European Commission (2020) A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives. COM(2020) 662 final.: EUR-Lex – 52020DC0662 - EN, 2026. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0662 (accessed 21 May 2026)
25. Rinaldi A, Yilmaz S, Patel MK, Parra D (2022) What adds more flexibility? An energy system analysis of storage, demand-side response, heating electrification, and distribution reinforcement. Renew Sustain Energy Rev 167:112696. https://doi.org/10.1016/j.rser.2022.112696
26. Schöniger F, Mascherbauer P, Resch G, Kranzl L, Haas R (2024) The potential of decentral heat pumps as flexibility option for decarbonised energy systems. Energ Effi 17:1–27. https://doi.org/10.1007/s12053-024-10206-z
27. International Energy Agency (2022) The Future of Heat Pumps
28. Weigert A (2022) Identification and classification of heat pump problems in the field and their implication for a user-centric problem recognition. Energy Inf 5:1–37. https://doi.org/10.1186/s42162-022-00250-3
29. Sitzmann A (2025) Unlocking Thermal Flexibility for the Electricity System by Combining Heat Pumps and Thermal Storage
30. Reynders G, Nuytten T, Saelens D (2013) Potential of structural thermal mass for demand-side management in dwellings. Build Environ 64:187–199. https://doi.org/10.1016/j.buildenv.2013.03.010
31. Grilli G, Zambotti S, Pezzuto S (2017) European Heat Pump Market Analysis: Assessment of Barriers and Drivers. Int J Contemp ENERGY 3. https://doi.org/10.14621/ce.20170207
32. Chitchyan R (2025) Overcoming barriers to heat pump adoption among able-to-pay households. Energy Policy 206:114660. https://doi.org/10.1016/j.enpol.2025.114660
33. Gaur AS, Fitiwi DZ, Curtis J (2021) Heat pumps and our low-carbon future: A comprehensive review. Energy Res Social Sci 71:101764. https://doi.org/10.1016/j.erss.2020.101764
34. Pezzutto S, Bottino-Leone D, Wilczynski E, Fraboni R (2024) Drivers and Barriers in the Adoption of Green Heating and Cooling Technologies: Policy and Market Implications for Europe. Sustainability 16:6921. https://doi.org/10.3390/su16166921
35. Corbett M, Rhodes E, Pardy A, Long Z (2023) Pumping up adoption: The role of policy awareness in explaining willingness to adopt heat pumps in Canada. Energy Res Social Sci 96:102926. https://doi.org/10.1016/j.erss.2022.102926

36. Sperber E, Frey U, Bertsch V (2020) Reduced-order models for assessing demand response with heat pumps - Insights from the German energy system. Energy Build 223 https://doi.org/10.1016/j.enbuild.2020.110144
37. Ruhnau O, Hirth L, Praktiknjo A (2020) Heating with wind: Economics of heat pumps and variable renewables. Energy Econ 92 https://doi.org/10.1016/j.eneco.2020.104967
38. Bloess A, Schill W-P, Zerrahn A (2018) Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. Appl Energy 212:1611–1626. https://doi.org/10.1016/j.apenergy.2017.12.073
39. Dréau JL, Heiselberg P (2016) Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 111:991–1002. https://doi.org/10.1016/j.energy.2016.05.076
40. Chen X, Lu X, McElroy MB, Nielsen CP, Kang C (2014) Synergies of wind power and electrified space heating: case study for Beijing. Environ Sci Technol 48. https://doi.org/10.1021/es405653x
41. Villar J, Bessa R, Matos M (2018) Flexibility products and markets: Literature review. Electr Power Res 154:329–340. https://doi.org/10.1016/j.epsr.2017.09.005
42. Pedro A, Krutnik M, van Yadack M, Pereira L, Morais H (2023) Opportunities and challenges for small-scale flexibility in European electricity markets. Utilities Policy 80:101477. https://doi.org/10.1016/j.jup.2022.101477
43. Morstyn T, Teytelboym A, McCulloch MD (2019) Designing Decentralized Markets for Distribution System Flexibility. IEEE Trans Power Syst 34:2128–2139. https://doi.org/10.1109/TPWRS.2018.2886244
44. Dörre E, Pfaffel S, Dreher A, Girón P, Heising S, Wiedemann K (2021) Flexibility Reserve of Self-Consumption Optimized Energy Systems in the Household Sector. Energies 14:3017. https://doi.org/10.3390/en14113017
45. Battaglia M, Haberl R, Bamberger E, Haller M (2017) Increased self-consumption and grid flexibility of PV and heat pump systems with thermal and electrical storage. Energy Procedia 135:358–366. https://doi.org/10.1016/j.egypro.2017.09.527
46. Smale R, van Vliet B, Spaargaren G (2017) When social practices meet smart grids: Flexibility, grid management, and domestic consumption in The Netherlands. Energy Res Social Sci 34:132–140. https://doi.org/10.1016/j.erss.2017.06.037
47. Bogdanov D, Satymov R, Breyer C (2024) Impact of temperature dependent coefficient of performance of heat pumps on heating systems in national and regional energy systems modelling. Appl Energy 371:123647. https://doi.org/10.1016/j.apenergy.2024.123647
48. Preßmair W, Amann G, Stipsits A, Schoisengeier S, Wenig F (2024) Thermally Activated Building Structures as Flexibility Option for the Electricity Market. Int Sustain Ener Conf Proc 1. https://doi.org/10.52825/isec.v1i.1132
49. Spiliotis K, Ramos Gutierrez AI, Belmans R (2016) Demand flexibility versus physical network expansions in distribution grids. Appl Energy 182:613–624. https://doi.org/10.1016/j.apenergy.2016.08.145
50. Bauknecht D, Flachsbarth F, Koch M, Vogel M (2024) The role of decentralised flexibility options for managing transmission grid congestions in Germany. Electricity J 37:107363. https://doi.org/10.1016/j.tej.2023.107363
51. Olivella-Rosell P, Lloret-Gallego P, Munné-Collado Í, Villafafila-Robles R, Sumper A, Ottessen S, Rajasekharan J, Bremdal B (2018) Local Flexibility Market Design for Aggregators Providing Multiple Flexibility Services at Distribution Network Level, Energies 11 822. https://doi.org/10.3390/en11040822
52. Poplavskaya K, Lago J, Strömer S, de Vries L (2021) Making the most of short-term flexibility in the balancing market: Opportunities and challenges of voluntary bids in the new balancing market design. Energy Policy 158:112522. https://doi.org/10.1016/j.enpol.2021.112522
53. Lazović Đ, Đurišić Ž (2023) Advanced Flexibility Support through DSO-Coordinated Participation of DER Aggregators in the Balancing Market. Energies 16:3440. https://doi.org/10.3390/en16083440
54. Davis J, Mengersen K, Bennett S, Mazerolle L (2014) Viewing systematic reviews and meta-analysis in social research through different lenses. SpringerPlus 3:1–9. https://doi.org/10.1186/2193-1801-3-511
55. Tranfield D, Denyer D, Smart P (2003) Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. Br J Manage 14:207–222. https://doi.org/10.1111/1467-8551.00375
56. International Energy Agency, Renewable Energy Progress Tracker: Renewable electricity (2024) https://www.iea.org/data-and-statistics/data-tools/renewable-energy-progress-tracker (accessed 20 May 2025)
57. European Heat Pumps association (2024) European Heat Pump Market Statistics Report
58. Statistics, Canada (2023) The heat is on: How Canadians heat their home during the winter. https://www.statcan.gc.ca/o1/en/plus/2717-heat-how-canadians-heat-their-home-during-winter (accessed 20 May 2025)
59. Roth A, Gaete-Morales C, Kirchem D, Schill W-P (2024) Power sector benefits of flexible heat pumps in 2030 scenarios. Commun Earth Environ 5:1–12. https://doi.org/10.1038/s43247-024-01861-2
60. Statista (2023) Share of household consumers equipped with a smart meter in Europe in 2023, by select country: Smart meter penetration Europe 2023. https://www.statista.com/statistics/916317/share-of-households-equipped-with-a-smart-meter-in-europe/ (accessed 20 May 2025)
61. Energie-Control (2024) Austria für die Regulierung der Elektrizitäts- und Erdgaswirtschaft, Bericht zur Einführung von intelligenten Messgeräten in Österreich 2024: Berichtsjahr 2023
62. economie (2024) Monitoring Report Belgian electricity market: Implementation plan
63. Jones JS (2024) Smart meter penetration surpasses 80% in North America. https://www.renewableenergyworld.com/news/smart-meter-penetration-surpasses-80-in-north-america/#:~:text=In%20a%20new%20study%2C%20Berg,and%2015.4%20million%20in%20Canada (accessed 26 June 2025)
64. FfE (2023) Der Smart Meter Rollout in Deutschland und Europa. https://www.ffe.de/veroeffentlichungen/smart-meter-rollout-in-deutschland-und-europa/ (accessed 20 May 2025)
65. Bundesministerium der Justiz und für Verbraucherschutz, Gesetz über den Messstellenbetrieb und die Datenkommunikation in intelligenten Energienetzen,MsbG, (2025) https://www.gesetze-im-internet.de/messbg/
66. ASHRAE (2021) Climatic Data for Building Design Standars: ANSI/ASHRAE Addendum a to ANSI/ASHRAE Standard 169–2020
67. Ministerio de Vivienda y Agenda Urbana, CTE DB-HE: Documento Básico: Ahorro de energía., (2022)
68. Amann W, Preßmair G, Stipsits A, Schoisengeier S, Amann C, Preisler A, Mayr M (2023) Bewertung der Bauteilaktivierung als Option für Flexibilität im Strommarkt
69. Kuehnbach M (2025) Interview Questions for IEA ES Task 43, Subtask C. Interview with Kempten University of Applied Sciences about Flexibility, Germany
70. Akrami A, Doostizadeh M, Aminifar F (2019) Power system flexibility: an overview of emergence to evolution. J Mod Power Syst Clean Energy 7:987–1007. https://doi.org/10.1007/s40565-019-0527-4

71. Strbac G, Pudjianto D, Aunedi M, Djapic P, Teng F, Zhang X, Ameli H, Moreira R, Brandon N (2020) Role and value of flexibility in facilitating cost-effective energy system decarbonisation. Prog Energy 2:42001. https://doi.org/10.1088/2516-1083/abb216
72. Sperber E, Schimeczek C, Frey U, Cao K-K, Bertsch V (2025) Aligning heat pump operation with market signals: A win-win scenario for the electricity market and its actors? Energy Rep 13:491–513. https://doi.org/10.1016/j.egyr.2024.12.028
73. Zhang K, Saloux E, Candanedo JA (2024) Enhancing energy flexibility of building clusters via supervisory room temperature control: Quantification and evaluation of benefits. Energy Build 302:113750. https://doi.org/10.1016/j.enbuild.2023.113750
74. D'Ettorre F, Banaei M, Ebrahimy R, Pourmousavi SA, Blomgren E, Kowalski J, Bohdanowicz Z, Łopaciuk-Gonczaryk B, Biele C, Madsen H (2022) Exploiting demand-side flexibility: State-of-the-art, open issues and social perspective. Renew Sustain Energy Rev 165:112605. https://doi.org/10.1016/j.rser.2022.112605
75. Freire-Barceló T, Martín-Martínez F, Sánchez-Miralles Á (2022) A literature review of Explicit Demand Flexibility providing energy services. Electr Power Syst Res 209:107953. https://doi.org/10.1016/j.epsr.2022.107953
76. Schittekatte T, Meeus L (2020) Flexibility markets: Q&A with project pioneers. Utilities Policy 63:101017. https://doi.org/10.1016/j.jup.2020.101017
77. Kostková K, Omelina Ľ, Kyčina P, Jamrich P (2013) An introduction to load management. Electr Power Syst Res 95:184–191. https://doi.org/10.1016/j.epsr.2012.09.006
78. Gesetz über die (2024) Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz): EnWG
79. Langner F, Kovačević J, Zwickel P, Dengiz T, Frahm M, Waczowicz S, Çakmak HK, Matthes J, Hagenmeyer V (2024) Coordinated price-based control of modulating heat pumps for practical demand response and peak shaving in building clusters. Energy Build 324:114940. https://doi.org/10.1016/j.enbuild.2024.114940
80. Agora, Energiewende (2023) Forschungsstelle für Energiewirtschaft e.V., Haushaltsnahe Flexibilitäten nutzen. Wie Elektrofahrzeuge, Wärmepumpen und Co. die Stromkosten für alle senken können
81. Thorsteinsson S, Kalaee AAS, Vogler-Finck P, Stærmose HL, Katic I, Bendtsen JD (2023) Long-term experimental study of price responsive predictive control in a real occupied single-family house with heat pump. Appl Energy 347:121398. https://doi.org/10.1016/j.apenergy.2023.121398
82. Le Dréau J, Lopes RA, O'Connell S, Finn D, Hu M, Queiroz H, Alexander D, Satchwell A, Österreicher D, Polly B, Arteconi A, de Andrade Pereira F, Hall M, Kırant-Mitić T, Cai H, Johra H, Kazmi H, Li R, Liu A, Nespoli L, Saeed MH (2023) Developing energy flexibility in clusters of buildings: A critical analysis of barriers from planning to operation. Energy Build 300:113608. https://doi.org/10.1016/j.enbuild.2023.113608
83. Regina H, Sarah F, Mihai C, Anjali W, Steven W (2023) Challenges and opportunities of flexibility markets related to operational planning, in: 2023 19th International Conference on the European Energy Market (EEM), Lappeenranta, Finland, Ieee, pp. 1–5
84. Europäische, Union (2018) Directive (EU) 2018/844 of the European Parliament and of The Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. EBPD
85. European Parliament E, Council (2023) Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. RED III
86. Energinet, Timeline for market changes (2025), https://en.energinet.dk/electricity/balancing-and-ancillary-services/upcoming-market-changes/timeline-for-market-changes/ (accessed 5 June 2025)
87. BMWE, Smart meters: the key to a smarter energy future (2025) https://www.bmwk.de/Redaktion/EN/Textsammlungen/Energy/smart-meters.html (accessed 5 June 2025)
88. MA 20, Technische Richtlinien für Bürogebäude in Wien: Magistratsabteilung - Energieplanung (MA 20) (2021) https://www.wien.gv.at/stadtentwicklung/energie/tr-richtlinien.html (accessed 1 March 2025)
89. REHVA, REHVA COVID-19 guidance (2021) and EPBD-related technical reports. https://www.rehva.eu/activities/covid-19-guidance (accessed 1 March 2025)
90. ELIA, Elia Group's study (2023), 'The Power of Flex', explores how widespread consumer-side flexibility can deliver benefits for both consumers and the electricity system. https://www.eliagroup.eu/en/press/2023/11/20231121_thepowerofflex (accessed 5 June 2025)
91. esios (2025) Active energy invoicing price. https://www.esios.ree.es/en/pvpc# (accessed 5 June 2025)
92. OMIE, Local Markets: Local flexibility negotiated in the new markets, (2025) https://www.omie.es/en/division-innovacion/mercados-locales (accessed 5 June 2025)
93. esios, INFORMACIÓN SOBRE SERVICIO RESPUESTA ACTIVA DE LA DEMANDA EN EL SISTEMA PENINSULAR (2025) https://www.esios.ree.es/es/gestion-de-la-demanda?date=13-05-2025# (accessed 5 June 2025)
94. MITECO, PROYECTO DE REAL DECRETO POR EL QUE SE APRUEBA EL REGLAMENTO GENERAL DE SUMINISTRO, Y CONTRATACIÓN Y SE ESTABLECEN LAS CONDICIONES PARA LA COMERCIALIZACIÓN (2025), AGREGACIÓN Y LA PROTECCIÓN DEL CONSUMIDOR DE ENERGÍA ELÉCTRICA
95. Regulator CE (2025) Market Snapshot: Electricity Trade — who regulates what in Canada? https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2025/market-snapshot-electricity-trade-who-regulates-what-in-canada.html (accessed 5 June 2025)
96. Ma Z, Knotzer A, Billanes JD, Jørgensen BN (2020) A literature review of energy flexibility in district heating with a survey of the stakeholders' participation. Renew Sustain Energy Rev 123:109750. https://doi.org/10.1016/j.rser.2020.109750
97. Eicke A, Hirth L, Mühlenpfordt J (2024) Mehrwert dezentraler Flexibilität: Oder: Was kostet die verschleppte Flexibilisierung von Wärmepumpen, Elektroautos und Heimspeichern? Berlin
98. Sassenou L-N, Olivieri L, Olivieri F (2024) Challenges for positive energy districts deployment: A systematic review. Renew Sustain Energy Rev 191:114152. https://doi.org/10.1016/j.rser.2023.114152
99. Rodríguez-Vilches R, Martín-Martínez F, Sánchez-Miralles Á, Gutiérrez de la Cámara, Rodrigo J (2024) S. Muñoz Delgado, Methodology to assess prosumer participation in European electricity markets, Renewable and Sustainable Energy Reviews 191 114179. https://doi.org/10.1016/j.rser.2023.114179
100. Schmidt D, Hoffmann S (2021) Simulation-based analysis of the load-shifting potential of Heat Pumps in Multi-Family Houses using co-simulation. Building Simul 2021 17:151–158. https://doi.org/10.26868/25222708.2021.30351

101. Fitzpatrick P, D'Ettorre F, de Rosa M, Yadack M, Eicker U, Finn DP (2020) Influence of electricity prices on energy flexibility of integrated hybrid heat pump and thermal storage systems in a residential building. Energy Build 223:110142. https://doi.org/10.1016/j.enbuild.2020.110142
102. Carnieletto L, Kazanci OB, Olesen BW, Zarrella A, Pasut W (2024) Combining energy generation and radiant systems: challenges and possibilities for plus energy buildings. Energy and Buildings 325:114965, 114965. https://doi.org/10.1016/j.enbuild.2024.114965
103. Mostafa M, Heise J, Baboli PT, Becker C Exploiting Flexibility in Multi-Energy Systems through Distributionally Robust Chance-Constrained Optimization, in: 2024 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Napoli, Italy, Ieee, 6/19/2024–6/21/2024, pp. 295–300
104. Leerbeck K, Bacher P, Junker RG, Tveit A, Corradi O, Madsen H, Ebrahimy R (2020) Control of heat pumps with CO2 emission intensity forecasts. Energies 13:2851, 2851. https://doi.org/10.3390/en13112851
105. Stute J, Kühnbach M (2023) Dynamic pricing and the flexible consumer – investigating grid and financial implications: a case study for Germany. Energy Strategy Reviews 45:1–14
106. Globisch J, Kühnbach M, Dütschke E, Bekk A (2020) The stranger in the German energy system? How energy system requirements misalign with household preferences for flexible heat pumps. Energy Res Social Sci 67:101604. https://doi.org/10.1016/j.erss.2020.101604
107. Uspenskaia D, Specht K, Kondziella H, Bruckner T, Buildings (2021) 11 78. https://doi.org/10.3390/buildings11020078
108. Heffron RJ, Körner M-F, Schöpf M, Wagner J, Weibelzahl M (2021) The role of flexibility in the light of the COVID-19 pandemic and beyond: contributing to a sustainable and resilient energy future in Europe. Renew Sustain Energy Rev 140:110743, 110743. https://doi.org/10.1016/j.rser.2021.110743
109. Wanapinit N, Thomsen J, Kost C, Weidlich A (2021) An MILP model for evaluating the optimal operation and flexibility potential of end-users. Applied Energy 282:116183, 116183. https://doi.org/10.1016/j.apenergy.2020.116183
110. Alvarez MAZ, Agbossou K, Cardenas A, Kelouwani S, Boulon L, Clustering K-M (2020) IEEE Trans Sustain Energy 11:524–533. https://doi.org/10.1109/TSTE.2019.2897288
111. Schwabeneder D, Corinaldesi C, Lettner G, Auer H (2021) Business cases of aggregated flexibilities in multiple electricity markets in a European market design. Energy Conv Manag 230:113783. https://doi.org/10.1016/j.enconman.2020.113783
112. Mlecnik E, Parker J, Ma Z, Corchero C, Knotzer A, Pernetti R (2020) Policy challenges for the development of energy flexibility services. Energy Policy 137:111147. https://doi.org/10.1016/j.enpol.2019.111147
113. Johansen K, Johra H (2022) A niche technique overlooked in the Danish district heating sector? Exploring socio-technical perspectives of short-term thermal energy storage for building energy flexibility. Energy 256:124075. https://doi.org/10.1016/j.energy.2022.124075
114. Energy Transitions Commission (2025) Achieving Zero-Carbon Buildings: Electric, Efficiend and Flexible, Version first.0
115. Maturo A, Buonomano A, Athienitis A (2022) Design for energy flexibility in smart buildings through solar based and thermal storage systems: Modelling, simulation and control for the system optimization. Energy 260:125024. https://doi.org/10.1016/j.energy.2022.125024
116. Antretter M, Klobasa M, Kühnbach M, Singh M, Knorr K, Schütt J, de Boer J, Hernandez Diaz D, Fritschen F, Garcerán A, Reina R, Rolser O, Stemmer S, Steinbach J, Popovski E (2022) Digitalisation of Energy Flexibility
117. Lind J, Ottermo F (2025) Energy flexibility in multi-family houses heated by thermally activated building systems. Energy Build 330:115345. https://doi.org/10.1016/j.enbuild.2025.115345
118. Liu D, Yang X, Guan W, Tian Z, Zong Y, Tang R (2023) Model predictive control for heat flexibility activation of the Thermally Activated Building System. Building Simul 2023 18:3284–3288. https://doi.org/10.26868/25222708.2023.1343
119. Wilczynski EJ, Chambers J, Patel MK, Worrell E, Pezzutto S (2023) Assessment of the thermal energy flexibility of residential buildings with heat pumps under various electric tariff designs. Energy Build 294:113257. https://doi.org/10.1016/j.enbuild.2023.113257
120. Kaspar K, Nweye K, Buscemi G, Capozzoli A, Nagy Z, Pinto G, Eicker U, Ouf MM (2024) Effects of occupant thermostat preferences and override behavior on residential demand response in CityLearn. Energy Build 324:114830. https://doi.org/10.1016/j.enbuild.2024.114830
121. Sarran L, Gunay HB, O'Brien W, Hviid CA, Rode C (2021) A data-driven study of thermostat overrides during demand response events. Energy Policy 153:112290. https://doi.org/10.1016/j.enpol.2021.112290
122. Amato V, Knudsen MD, Petersen S (2023) Dual-zone economic model predictive control of residential space heating for demand response using a single heat meter. Energy Build 281:112759. https://doi.org/10.1016/j.enbuild.2022.112759
123. Marszal-Pomianowska A, Widén J, Dréau JL, Heiselberg P, Bak-Jensen B, de Cerio ID, Mendaza (2020) Operation of power distribution networks with new and flexible loads: A case of existing residential low voltage network. Energy 202:117715. https://doi.org/10.1016/j.energy.2020.117715
124. Camporeale PE, Mercader-Moyano P (2021) A GIS-based methodology to increase energy flexibility in building cluster through deep renovation: A neighborhood in Seville. Energy Build 231:110573. https://doi.org/10.1016/j.enbuild.2020.110573
125. Aparisi-Cerdá I, Ribó-Pérez D, Gómez-Navarro T, García-Melón M, Peris-Blanes J (2024) Prioritising Positive Energy Districts to achieve carbon neutral cities: Delphi-DANP approach. Renew Sustain Energy Rev 203:114764. https://doi.org/10.1016/j.rser.2024.114764
126. Knudsen MD, Fiorentini M, Petersen S (2024) A heat-measurement-free strategy for Economic Model Predictive Control of hydronic radiators. J Building Eng 97:110694. https://doi.org/10.1016/j.jobe.2024.110694
127. Kröger D, Peper J, Rehtanz C (2023) Electricity market modeling considering a high penetration of flexible heating systems and electric vehicles. Appl Energy 331:120406. https://doi.org/10.1016/j.apenergy.2022.120406
128. Huynh T, Schmidt F, Thiem S, Kautz M, Steinke F, Niessen S (2022) Local energy markets for thermal-electric energy systems considering energy carrier dependency and energy storage systems. Smart Energy 6:100065. https://doi.org/10.1016/j.segy.2022.100065
129. Hastings-Simon S, Kanduth A (2021) Barriers to innovation in the Canadian electricity sector and avaialbel policy responses
130. Kanduth A, Anna, Dion J (2022) Electric Federalism: Policy for aligning Canadian electricity systems with net zero
131. FutuRed (2021) Flexibilitdad en redes des distribución eléctrica

132. Ministerio para la Transición Ecológica y el Reto Demográfico, El MITECO da luz verde a cinco proyectos piloto para acelerar la innovación y flexibilización del sistema eléctrico español (2025) https://www.miteco.gob.es/es/prensa/ultimas-noticias/2025/marzo/el-miteco-da-luz-verde-a-cinco-proyectos-piloto-para-acelerar-la.html (accessed 15 April 2025)
133. Lee ZE, Sun Q, Ma Z, Wang J, MacDonald JS, Max K, Zhang (2020) Providing Grid Services With Heat Pumps: A Review. J Eng Sustain Bldgs Cities 1:011007. https://doi.org/10.1115/1.4045819
134. Maturo A, Vallianos C, Buonomano A, Athienitis A (2023) A novel multi-level predictive management strategy to optimize phase-change energy storage and building-integrated renewable technologies operation under dynamic tariffs. Energy Conv Manag 291:117220. https://doi.org/10.1016/j.enconman.2023.117220
135. Yang X, Liu D, Tian Z, Deng N, Wang R, Jiang Y, Tang R, Zong Y (2024) Comparison of different control methods on the thermally activated building system (TABS) with large energy flexibility. Appl Therm Eng 254:123863. https://doi.org/10.1016/j.applthermaleng.2024.123863
136. Gjorgievski VZ, Markovska N, Abazi A, Duić N (2021) The potential of power-to-heat demand response to improve the flexibility of the energy system: An empirical review. Renew Sustain Energy Rev 138:110489. https://doi.org/10.1016/j.rser.2020.110489
137. Albadi MH, El-Saadany EF (2008) A summary of demand response in electricity markets. Electr Power Syst Res 78:1989–1996. https://doi.org/10.1016/j.epsr.2008.04.002
138. Weidlich A, Bublitz A, Fichtner W, Grimm G, Hagenmeyer V, Helfer M, Herrmann M, Hofmann R, Jahn A, Löbbe S, Möst D, Neuhoff K, Staudt P, Tretter R, Weißbach T, Zapf M (2025) Dynamische Netzentgelte und ihre mögliche Ausgestaltung für Deutschland. Professur für Technologien der Energieverteilung; Institut für Nachhaltige Technische Systeme, Albert-Ludwigs-Universität Freiburg
139. International Energy Agency, Demand response (2025) https://www.iea.org/energy-system/energy-efficiency-and-demand/demand-response (accessed 5 June 2025)
140. Leinauer C, Schott P, Fridgen G, Keller R, Ollig P, Weibelzahl M (2022) Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation: Energy Policy. Energy Policy 165:112876. https://doi.org/10.1016/j.enpol.2022.112876
141. Møller D, Sneum (2021) Barriers to flexibility in the district energy-electricity system interface – A taxonomy. Renew Sustain Energy Rev 145:111007. https://doi.org/10.1016/j.rser.2021.111007
142. Lingard J (2020) Residential retrofit in the UK: The optimum retrofit measures necessary for effective heat pump use. Build Serv Eng Res Tech. https://doi.org/10.1177/0143624420975707
143. Lämmle M, Metz J, Michael K, Wapler J, Oltersdorf T, Günther D, Herkel S, Bongs C (2023) Heat Pump Systems in Existing Multifamily Buildings: A Meta-Analysis of Field Measurement Data Focusing on the Relationship of Temperature and Performance of Heat Pump Systems: Energy Technology. Energy Technol 11:2300379. https://doi.org/10.1002/ente.202300379
144. Zhuang C, Choudhary R, Mavrogianni A (2023) Uncertainty-based optimal energy retrofit methodology for building heat electrification with enhanced energy flexibility and climate adaptability: Applied Energy. Appl Energy 341:121111. https://doi.org/10.1016/j.apenergy.2023.121111
145. Enkhardt S (2025) Day-ahead-Strompreise in 389 Stunden negativ im ersten Halbjahr. https://www.pv-magazine.de/2025/06/30/day-ahead-strompreise-in-389-stunden-negativ-im-ersten-halbjahr/ (accessed 9 July 2025)
146. Larsen M, Petrović S, Radoszynski AM, McKenna R, Balyk O (2020) Climate change impacts on trends and extremes in future heating and cooling demands over Europe. Energy Build 226:110397. https://doi.org/10.1016/j.enbuild.2020.110397
147. Scoccimarro E, Cattaneo O, Gualdi S, Mattion F, Bizeul A, Risquez AM, Quadrelli R (2023) Country-level energy demand for cooling has increased over the past two decades. Commun Earth Environ 4:1–17. https://doi.org/10.1038/s43247-023-00878-3
148. International Energy Agency (2025) 2025
149. Ritter D, Grafmüller D, Bauknecht D, Wingenbach M, Dünzen K (2025) Electricity market design for 100% renewable energy in Germany – Challenges and solutions. Energy Rep 14:634–647. https://doi.org/10.1016/j.egyr.2025.06.006
150. Erneuerbare-Energien-Gesetz vom 21 (2014) Juli 2014 (BGBl. I S. 1066), das zuletzt durch Artikel 1 des Gesetzes vom 29. Juni 2015 (BGBl. I S. 1010) geändert worden ist. EEG
151. Decuypere R, Robaeyst B, Hudders L, Baccarne B, van de Sompel D (2022) Transitioning to energy efficient housing: Drivers and barriers of intermediaries in heat pump technology. Energy Policy 161:112709. https://doi.org/10.1016/j.enpol.2021.112709

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.