

International Energy Agency

Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems (Annex 82) Summary report

**Energy in Buildings and Communities
Technology Collaboration Programme**



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May 2025

Edited by

Rongling Li

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;

- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1:	Load Energy Determination of Buildings (*)
Annex 2:	Ekistics and Advanced Community Energy Systems (*)
Annex 3:	Energy Conservation in Residential Buildings (*)
Annex 4:	Glasgow Commercial Building Monitoring (*)
Annex 5:	Air Infiltration and Ventilation Centre
Annex 6:	Energy Systems and Design of Communities (*)
Annex 7:	Local Government Energy Planning (*)
Annex 8:	Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9:	Minimum Ventilation Rates (*)
Annex 10:	Building HVAC System Simulation (*)
Annex 11:	Energy Auditing (*)
Annex 12:	Windows and Fenestration (*)
Annex 13:	Energy Management in Hospitals (*)
Annex 14:	Condensation and Energy (*)
Annex 15:	Energy Efficiency in Schools (*)
Annex 16:	BEMS 1- User Interfaces and System Integration (*)
Annex 17:	BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18:	Demand Controlled Ventilation Systems (*)
Annex 19:	Low Slope Roof Systems (*)
Annex 20:	Air Flow Patterns within Buildings (*)
Annex 21:	Thermal Modelling (*)
Annex 22:	Energy Efficient Communities (*)
Annex 23:	Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24:	Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25:	Real time HVAC Simulation (*)
Annex 26:	Energy Efficient Ventilation of Large Enclosures (*)
Annex 27:	Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28:	Low Energy Cooling Systems (*)
Annex 29:	☼ Daylight in Buildings (*)
Annex 30:	Bringing Simulation to Application (*)
Annex 31:	Energy-Related Environmental Impact of Buildings (*)
Annex 32:	Integral Building Envelope Performance Assessment (*)
Annex 33:	Advanced Local Energy Planning (*)
Annex 34:	Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35:	Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36:	Retrofitting of Educational Buildings (*)
Annex 37:	Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38:	☼ Solar Sustainable Housing (*)
Annex 39:	High Performance Insulation Systems (*)

Annex 40:	Building Commissioning to Improve Energy Performance (*)
Annex 41:	Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42:	The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43:	☀ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44:	Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45:	Energy Efficient Electric Lighting for Buildings (*)
Annex 46:	Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47:	Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48:	Heat Pumping and Reversible Air Conditioning (*)
Annex 49:	Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50:	Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51:	Energy Efficient Communities (*)
Annex 52:	☀ Towards Net Zero Energy Solar Buildings (*)
Annex 53:	Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54:	Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55:	Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56:	Cost Effective Energy and CO ₂ Emissions Optimization in Building Renovation (*)
Annex 57:	Evaluation of Embodied Energy and CO ₂ Equivalent Emissions for Building Construction (*)
Annex 58:	Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59:	High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60:	New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61:	Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62:	Ventilative Cooling (*)
Annex 63:	Implementation of Energy Strategies in Communities (*)
Annex 64:	LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65:	Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66:	Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67:	Energy Flexible Buildings (*)
Annex 68:	Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69:	Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70:	Energy Epidemiology: Analysis of Real Building Energy Use at Scale (*)
Annex 71:	Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72:	Assessing Life Cycle Related Environmental Impacts Caused by Buildings (*)
Annex 73:	Towards Net Zero Energy Resilient Public Communities (*)
Annex 74:	Competition and Living Lab Platform (*)
Annex 75:	Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
Annex 76:	☀ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO ₂ Emissions (*)
Annex 77:	☀ Integrated Solutions for Daylight and Electric Lighting (*)
Annex 78:	Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79:	Occupant-Centric Building Design and Operation
Annex 80:	Resilient Cooling
Annex 81:	Data-Driven Smart Buildings
Annex 82:	Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83:	Positive Energy Districts

Annex 84:	Demand Management of Buildings in Thermal Networks
Annex 85:	Indirect Evaporative Cooling
Annex 86:	Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87:	Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88:	Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89:	Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90:	☀ EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91:	Open BIM for Energy Efficient Buildings
Annex 92:	Smart Materials for Energy-efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93:	Energy Resilience of the Buildings in Remote Cold Regions
Annex 94:	Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95:	Human-centric Building Design and Operation for a Changing Climate
Annex 96:	Grid Integrated Control of Buildings
Annex 97:	Sustainable Cooling in Cities

Working Group - Energy Efficiency in Educational Buildings (*)

Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)

Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)

Working Group - Cities and Communities (*)

Working Group - Building Energy Codes

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Project summary

The integration of variable renewable energy sources into power grids and the growing electricity demand reinforce the need for energy flexibility. Buildings can play an essential role in providing demand-side flexibility. Buildings should adapt their energy demand and/or production to weather conditions, to their users' needs, and the requirements of the electricity grid. In-depth knowledge of the energy flexibility services that buildings, especially clusters of buildings, may provide, and the stakeholder viewpoint on using this energy flexibility, is essential for designing future smart energy systems. Understanding the potential of energy-flexible services from buildings is important for the utilities that will ultimately utilize this energy flexibility. This is also important for companies developing business cases for products and services that will support the roll-out of smart energy systems, the policy makers involved in shaping the future energy systems, the government entities setting requirements for new and existing buildings, and the building users who will acquire and live with energy flexible services.

During IEA EBC Annex 67 Energy Flexible Buildings, extensive knowledge on obtaining and controlling energy flexibility in buildings has been acquired. Annex 82 focuses on areas where further work is needed to ensure that energy flexibility from buildings becomes an asset for future energy networks. These areas are:

- scaling from single buildings to clusters of buildings (aggregation);
- energy flexibility and resilience in multi-carrier energy systems (electricity, district heating/cooling, and gas);
- acceptance/engagement of the stakeholders; and
- business models.

Several IEA EBC annexes have carried out investigations and have obtained results that are relevant to Annex 82 – e.g.:

EBC Annex 51 Energy Efficient Communities

EBC Annex 52 Towards Net Zero Energy Solar Building

EBC Annex 67 Energy Flexible Buildings

EBC Annex 70 Building Energy Performance Assessment Based on In-situ Measurements

EBC Annex 72 Assessing Life Cycle Related Environmental Impacts Caused by Buildings

EBC Annex 75 Cost-effective Strategies to Combine Energy Efficiency Measures and Renewable Energy Use in Building Renovation at District Level

EBC Annex 79 Occupant-Centric Building Design and Operation

EBC Annex 81 Data-Driven Smart Buildings

EBC Annex 84 Demand Management of Buildings in Thermal Networks

Annex 82 has advanced the state-of-the-art methods to characterize, model, and harness energy flexibility of building clusters and portfolios, enabling more demonstration projects to confirm the promising results. Based on international reviews and comparisons, Annex 82 has made several key findings related to policy and regulation, price-incentive structures, business models, and key factors influencing building users' willingness and possibilities to take part in energy demand flexibility.

Addressing energy flexibility at the building cluster level remains challenging, with technical and non-technical barriers to adoption. Technical barriers for early planning, design, and operation phases include the development of integrated modeling tools, control strategies addressing the building cluster or portfolio level, and the development of quantitative methodologies and indicators. Dominant factors for energy flexibility are related to occupants, building characteristics, energy systems and storage, control systems, and external factors (e.g., weather and market). Building-grid interaction signals, a generalization of "price signals" or "penalty

signals”, must be aligned with the demand response objectives to utilize available energy flexibility correctly. To characterize this flexibility, building load prediction plays a crucial role in evaluating baseline scenarios and available demand-response potential.

The work of Annex 82 highlighted the scarcity of field studies demonstrating energy flexibility at the building cluster or portfolio level. Two field implementations were conducted within Annex 82. One uses a novel control algorithm (signal matrix model predictive control) to control space heating, domestic hot water heating, and a stationary battery. The other one is the coordinated use of different assets in a fully equipped occupied building to harmonize the flexibility of all behind-the-meter assets.

There is a great variety of differences between countries regarding the extent and type of policy measures implemented. Countries with the most ambitious policies are the most advanced in deploying energy flexibility in commercial and residential buildings, which confirms that supporting policies make a difference. However, the realization of energy flexibility for smaller consumers is still limited. Relatively few aggregators exist, which points to the need for more supportive policies to create a market for flexibility. At the same time, there has been some growth of energy communities in a few countries. This points to the importance of considering alternative organizational approaches to activating the energy flexibility potential rather than only aggregators and market-based/commercial solutions. Finally, price incentives for energy flexibility vary considerably between countries. Implicit demand response is relatively widespread in countries with dynamic pricing and Time-of-Use pricing for small consumers (including households). This indicates that the potential of implicit demand response should not be ignored in policymaking. Flexible pricing schemes mainly exist within the electricity sector, are very limited within gas markets, and are non-existent within district heating.

Many actors or stakeholders are involved in the energy system, and business models often include several stakeholders. Many value propositions were identified, including energy bill savings, new equipment/technology acquisition, financial incentives, etc. Most stakeholder categories shared propositions about societal or community contributions (e.g., contributing to a better environment and mitigating climate change). This shows that not only financial benefits are in focus, but also broader societal gains. Dominating types of systems/equipment targeted by business models are heating, ventilation, and air-conditioning (HVAC) (mainly heat pumps and air conditioners), followed by photovoltaic panels and electric batteries. The reviewed business models primarily focus on load shedding and load shifting. Regarding revenue sources, 30% of the cases involved a combination of subscription fees, equipment purchases, research funds, and professional service fees. This shows that revenues often depend on a multiplicity of sources.

A review of a broader set of social, economic, and institutional factors influencing energy flexibility and the existing knowledge from experiments and trials shows – among other things – that simulation-based studies are still the main source of knowledge on the effect of energy flexibility. Thus, much of the existing knowledge is still based on more theoretical and “idealistic” studies, whereas findings from “real-world” experiments are still limited.

Previous studies have had a dominant focus on economic and price incentives, which might have the risk of ignoring the importance of other types of motivations for smaller customers to take part in energy flexibility programs (e.g., environmental concerns or the interest in contributing to local energy resilience, as in the case of energy communities). This is partly confirmed by the survey targeted at smaller customers (mainly the residential sector) carried out as part of this annex. On a more general level, the study emphasizes the importance of developing an awareness and sensitivity towards the social inclusiveness and “social fairness” of developed energy flexibility solutions and programs (including policies), as this is key to ensuring a socially just energy transition as well as the public support of such solutions and programs.

Analyses carried out in Annex 82 lead to the following conclusions and recommendations to policymakers for the implementation of energy flexibility:

- More field studies and real-world demonstrations should be promoted to test control strategies at scale to enhance robustness and scalability. Real-world demonstrations encounter situations such as communication failure, model deviation, and delay that simulations do not cover. Control strategies that mitigate possible side effects of flexibility events, such as rebound and occupant rejection, should be developed and tested at scale. Sharing field study data should be encouraged for cross-comparison, solution development, and validation.
- Implicit demand response (price-based programmes) is relatively widespread in countries with dynamic pricing and Time-of-Use pricing for small consumers (including households). This indicates that the potential of implicit demand response should not be ignored in policymaking. The rollout of energy flexibility services can start with introducing Time-of-Use tariffs or Critical Peak Pricing.
- Harvesting energy flexibility requires variable prices or other incentives. An online system to show dynamic prices and incentives should be developed. Automation equipment should be able to read online price information.
- The potential of energy communities should not be ignored, as these might represent an alternative and supplementary organization of consumers that can engage their participation in flexible energy consumption through other factors than only financial incentives, such as interests in promoting local communities, self-sufficiency or taking part in a green transition and decarbonization of the energy system.
- Assessing the role of building flexibility in long-term energy planning is key to encouraging investments. Energy and building planning have been and still are anchored in different sectors and regional scales, but more joint efforts are necessary. E.g., in the case of district heating, sector coupling will become essential to provide flexibility to the electricity grid from the district heating system,
- The policy and regulatory aspects strongly influence the long-term contribution of demand response to decarbonization targets in the building sector. The focus shall be on the regulatory framework and its impact on the rapid uptake of flexibility measures in future developments (e.g., new business models) and pricing structures related to the potential uptake of building energy storage and flexibility in new and existing buildings.
- Creating sustainable and scalable business models is essential for promoting energy flexibility in buildings. Business models should focus on not only financial benefits, but also broader societal gains (e.g., CO₂ emission reduction or sustainability branding for companies).
- An overview should be created of where and when energy flexibility is profitable, considering social welfare (including identifying risks of energy flexibility contributing to increased social and economic inequality). Based on that overview, a roadmap for deploying energy flexibility could be developed.

Project duration

June 2021 – June 2025

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Further information

<https://www.iea-ebc.org> or <https://annex82.iea-ebc.org>

Project outcomes

1. Background

Substantial and unprecedented reductions in carbon emissions are required if the worst effects of climate change are to be avoided. Reductions in carbon emissions can be achieved by reducing energy demand through energy efficiency improvements and by supplying the remaining energy demand with renewable energy sources. The foreseen large-scale deployment of intermittent renewable energy sources (RES) may seriously affect the operation and stability of energy networks. It will, therefore, be necessary to control the energy use to ensure alignment with the instantaneous and fluctuating energy production. The built-in energy flexibility in buildings is an attractive resource to control energy use due to the relatively limited infrastructure needed to operationalize this resource. Mobilizing this currently untapped resource would, therefore, allow for a large-scale roll-out of RES and make the energy networks more resilient through their ability to shift energy demand in time. This aligns with EU directive on the energy performance of buildings (EPBD) 2024 Article 11 - Zero-emission buildings: “A zero-emission building shall not cause any on-site carbon emissions from fossil fuels. A zero-emission building shall, where economically and technically feasible, offer the capacity to react to external signals and adapt its energy use, generation or storage.”

The aim of Annex 82 was to gain important knowledge about the energy flexibility services that buildings and clusters of buildings may deliver to different types of energy networks. It further aims to increase the understanding of stakeholders' motivation for utilizing such systems and the barriers preventing further participation. This knowledge is important when developing business cases that will utilize building energy flexibility in future energy systems. It is equally important for policymakers and government entities involved in shaping the direction of future energy systems.

To reach these goals, the objectives of Annex 82 were:

- Mapping the current barriers in deploying energy demand flexibility and energy system resilience
- Modelling of energy flexibility from clusters of buildings both physically connected and commercially connected
- Demonstration of energy flexibility in clusters of buildings through simulations and field studies
- Investigation of how to include the view of the stakeholders in the development of feasible technical solutions
- Investigation of business models for energy flexible services to the energy networks

This report and the project outcomes are based on the two deliverables of Annex 82: Deliverable 1 - Methodologies and evaluations of energy flexibility for clusters of buildings¹, and Deliverable 2 - Review and assessment of market, policy, and stakeholder participation in energy flexibility of buildings². Specifically, readers can see more details in deliverable 1 regarding chapters 2 - 4 contents, and in deliverable 2 regarding chapters 5 - 8 contents. This is further detailed in a series of journal articles. Links to these may be found in Chapter 9, Annex 82 publication.

¹ Lopes, et al., 2025. Methodologies and evaluations of energy flexibility for clusters of buildings, published by Technical University of Denmark, July 2025. Access: <https://annex82.iea-ebc.org/publications>.

² Wittchen, et al., 2025. Review and assessment of market, policy and stakeholder participation in energy flexibility of buildings, Published by Technical University of Denmark, July 2025. Access: <https://annex82.iea-ebc.org/publications>

2. Research gaps

To enable demand-side flexibility in buildings and clusters of buildings, there is a need for innovative business models, supportive legislation and regulations, and technological development, while operational evaluation of real performance is hampered by the lack of demonstration projects.

Policy: The main barriers are related to the legal and regulatory framework, the limited access to the wholesale electricity market, and the privacy and cybersecurity concerns. The legislative and regulatory framework has developed rapidly in recent years, and the landscape will continue to evolve. However, the rapid pace of change has sometimes resulted in a lack of customer awareness. The development of energy flexibility is also often linked to the development of energy communities and Distributed Energy Resources (DERs). Two types of Energy Communities (i.e., Renewable Energy Communities and Citizen Energy Communities) have been explicitly legislated for by the EU. However, member state's implementation at local level differs and the design of effective support for energy flexibility remains unclear. Increasing participation in energy markets of energy flexible resources is more advanced in the US through measures, such as Federal Energy Regulatory Commission, permitting DERs to participate in wholesale electricity markets. This, coupled with dynamic or real-time pricing at retail level, thereby reflecting actual renewable generation output, is a key enabler for flexibility in both the US (at state level) and the EU (through Directive 2019/944). In Australia, an overall review of the electricity market is underway and further initiatives to increase energy flexibility are expected. Resource planning is starting to incorporate the energy flexibility capabilities of DERs, such as through Australia's Demand Management Incentive Scheme, and it would be beneficial if such initiatives were replicated in other jurisdictions.

Social: limited end-user knowledge of flexibility, and even energy in general, is one of the main limitations. Energy Communities can be used as a common ground to promote discussion at the local level and to raise citizens' awareness to the concept of flexibility. The environmental and societal benefits of energy flexibility should be emphasized, and the design of demand response (DR)-programmes should account for the diversity of end-users. More studies are needed to evaluate the relevance of price-based DR-programmes to decrease Greenhouse Gas emissions. Moreover, some privacy and security concerns remain for customers, such as cyber-physical devices and systems, need to be integrated to enable smart management of homes and communities. Perceived consequences include potential leakage of personal information, losing control of devices, and risk of financial losses.

Economy: the financing of DR primarily comes from flexibility activation payments and tariff optimization, but additional approaches that are being developed include virtual net metering, flexibility tenders and leveraging the collective power of energy communities. However, significant economic barriers still exist, particularly the lack of clarity around the value capture from multiple, small sources of flexibility and specific financing mechanisms for flexibility within energy communities. The lack of a standardized building-to-grid assessment framework limits the ability of stakeholders and industry to quantify the value of flexibility. A standardized building-to-grid assessment framework could include (but not be limited to) a list of flexible systems with some quantitative indicators (installed power, availability, constraints) and information on the building's connectivity to the grid and the degree of interoperability. Business models such as cooperatives, Energy Service Companies (ESCOs), or public-private partnerships have been most viable in a microgrid configuration. Further work is needed on the value proposition, motivating households and small participants in flexibility services.

Technology barriers exist at the technology and energy management levels. Cost-effective and reliable technologies should be developed to activate flexible loads. Communicating these flexible loads with the grid is also a cornerstone in developing DR in buildings. A suite of technologies needs to work in harmony to control flexible loads, local generation or energy storage and create value for building owners, Transmission System Operators (TSOs), and Distribution System Operators (DSOs). A reliable and secure two-way communication with a relatively high sampling rate is usually required, and any failure in the chain of control or actuation may result in loss of transmission signal. Such issues may arise from databases, hardware, and technologies beyond building levels. Communication failure in operational projects can occur more frequently than planned in a design stage. Interoperability and standardization should help improve reliability, but the robustness of solutions to communication failure should be tested. At the energy management level, the low diffusion of Building Automation System (BAS) and the lack of standards and seamless cross-domain data exchange solutions represent some of the main barriers for the implementation of energy flexibility services. During the design phase, the data exchange between the cross-domain applications required to perform these processes also suffers from interoperability and standardization challenges. Studies on semantic web technologies have made progress on this topic. However, there is a lack of application of studies dedicated to energy flexibility with standardized and replicable workflows.

Professionals also face barriers at the design stage, which were also identified. The development of quantitative and qualitative methodologies (such as EU's Smart Readiness Indicator and the Grid Optimal Buildings LEED pilot credit) should be pursued in the early planning stages to assess the flexibility potential of projects, even with low levels of information. At the design stage, building energy simulations (BES) are often limited in their ability to incorporate flexibility and load management strategies. For a district, several single-building models must be connected and coordinated, a feature which is not currently part of commercially available BES modelling software. Therefore, modelling flexibility in single buildings and districts with BES often requires the development of external algorithms, co-simulation, and pre- and post-processing. All together, the co-simulation environment, complex energy system modelling, and prediction horizon might cause a time-consuming model set-up, numerical problems, and long simulation times due to its complexity. There is therefore a need for further development of district level modelling tools capable of testing control strategies for building clusters at early design stages. In terms of stakeholders, there is very limited cooperation between the building and the energy sector, with the two working in silos. The energy infrastructure and building development are considered separately due to differing industry practices, stakeholders, project timelines, and regulatory frameworks within each sector. Overcoming these barriers will require improved collaboration between sectors to better consider their interrelated impacts and optimize solutions at the interface between buildings and the grid. This will require the energy sector to be more present at the local level to enable collaborative decision making.

Based on the barriers identified, several research directions can be formulated for the different development phases (**Figure 1**). Assessing the role of building flexibility in long-term energy planning is seen as a key factor in encouraging investments. Energy planning and building planning have been and still are anchored in very different sectors and regional scales. The policy and regulatory aspects have a strong influence on the long-term contribution of DR to decarbonization targets in the building sector. Key research questions in this context relate to the regulatory framework and its impact on the rapid uptake of flexibility measures in future developments, as well as pricing structures related to the potential uptake of building energy storage and flexibility in existing and new buildings.

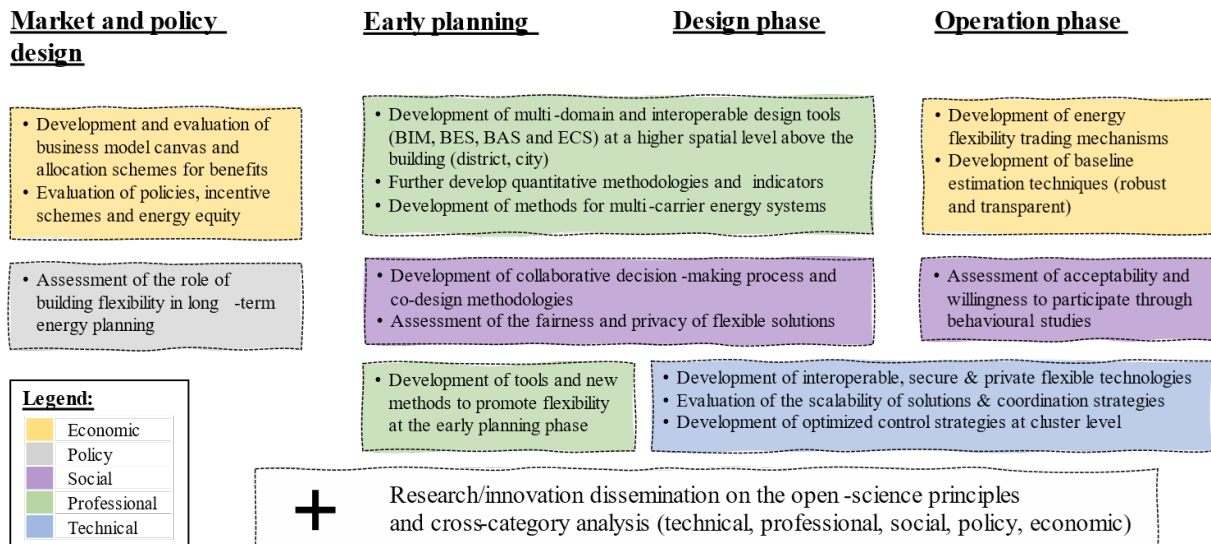


Figure 1: Summary of links between research gaps and phases³.

3. Modelling energy flexibility of building clusters

Dominant factors and uncertainties

Dominant factors affecting energy flexibility from the built environment can be categorized into 5 segments:

- Occupant and customer behavior, which introduces both aleatory and epistemic uncertainties due to unpredictable human actions (such as appliance use) and the lack of comprehensive data on energy usage patterns. Addressing these requires better data collection and modeling approaches. Effective strategies must account for individual behaviors, engagement with energy flexibility services, and external factors like dynamic pricing and weather conditions.
- Building characteristics, which refers to the thermal mass of a building, its heat loss rate and its materials when focusing on buildings' thermal properties. Uncertainties in thermal properties and retrofitting measures (i.e. the building performance gap) lead to challenges in predicting a building's energy flexibility potential. Addressing this requires improved empirical data, real-time monitoring, and advanced models for evaluating the energy performance of different building archetypes and retrofit outcomes.
- Technology and HVAC, which includes energy storage (thermal and electrical). We discuss the critical nature of fast/active storage for energy flexibility, alongside self-generation and use of controls to deliver energy flexibility. Uncertainties arise, at this level, from incomplete knowledge about their configuration and interaction with other systems, as well as from external variability like weather conditions. To reduce the barriers and limit the uncertainty improved empirical data and real-time monitoring are key, as well as complete information on the systems and their capabilities.

³ Le Dréau et al., 2023. Developing energy flexibility in clusters of buildings: A critical analysis of barriers from planning to operation. Energy and Buildings. <https://doi.org/10.1016/j.enbuild.2023.113608>

- Control systems and optimization that utilize building energy management systems (BEMS) and advanced control algorithms. They play a significant role in managing energy flexibility due to their role of interpreting fuzzy or complex data on the grid/network side and turning this information into system actuation to deliver flexibility. However, uncertainties arise from the lack of accurate real-time data and the complexity of predicting energy demand and renewable generation. Improving data quality and system coordination is critical to enable and improve accurate energy flexibility quantification.
- External factors and interactions, such as weather conditions, energy market fluctuations, and interactions with other buildings or energy networks can significantly influence the overall levels of exploitable energy flexibility. Challenges and barriers in managing energy flexibility are mostly due to aleatory sources such as unpredictability in weather data/predictions, fluctuating energy prices, and limited coordination between buildings and building clusters. Communication delays and insufficient data further complicate building-grid interactions and introduce epistemic uncertainty. Effective strategies to reduce these impacts include real-time data integration, improving forecasting accuracy, and regulatory adjustments to incentivize flexible energy behaviour.

A summary of mitigation strategies for key stakeholders can be summarized as follows:

- Occupants/customers can contribute towards uncertainty mitigation through increasing awareness and engagement of energy flexibility programs. Strategies include using smart appliances, real-time energy monitoring, and providing financial incentives such as cost savings or rewards. Empowering occupants with better information on energy use through user-friendly interfaces can improve participation. Additionally, wider use of automation tools can be used to help manage energy use in response to dynamic pricing signals at the single and multi-building scales – the seamless integration of this information from households to the aggregate level can help reduce unpredictability from human behaviour in energy demand.
- Aggregators face challenges in managing diverse building energy demands and predicting their flexibility potential. Mitigation strategies include using real-time data for more accurate forecasting and clustering techniques to group similar energy profiles, improving the reliability of predictions, and diversity and redundancy of flexible resources. Aggregators can employ advanced optimization algorithms, such as stochastic modelling to handle uncertainties and reduce risks.
- Electricity utility companies need to have a reliable estimate of their power need for the coming days/months/years. Reliable forecast, accounting for both technological and behavioural changes are thus necessary to optimize their investments. Encouraging wider participation of end-users through flexible pricing models and incentives might help balancing supply and demand and improve overall financial performance.
- Network operators need to manage aleatory uncertainties related to grid stability and capacity given by the external factors like weather and market fluctuations (mostly in the case of the transmission system). Mitigation strategies include improving communication infrastructure for real-time data sharing between demand and supply players. Regulatory reforms to incentivize energy flexibility and clearer market frameworks for demand response programs can reduce risks and enhance grid reliability and flexibility.

Energy resilience

Energy flexibility and energy resilience are two different concepts, but both relate to the adaptation of the built environment to external factors. The work undertaken highlighted the similarities and differences between the two. Resilience and flexibility are deeply interconnected, particularly in the context of adapting to

both anticipated and unforeseen extreme events, such as flooding, heat waves, winter storms, etc. While these two concepts are distinct, they often work side-by side to improve building performance, occupants' well-being and sustainability. For example, a building with PV and battery could be both resilient during a heat wave and flexible during a non-heat wave period through load shifting. Resilience enhancement strategies are identified and categorized into five main groups:

1. Design: Early stage building design strategies, such as optimizing building orientation, selecting materials with high thermal mass, and incorporating passive design features.
2. Retrofit: Strategies to improve existing buildings, including optimized building envelope retrofitting, combining mitigation and adaptation strategies, and employing passive cooling techniques.
3. Predictive control: Advanced heating, ventilation, and air-conditioning (HVAC) control systems and natural ventilation to enhance building resilience.
4. Micro-grid: Implementation of micro-grids with renewable energy sources and energy storage systems to maintain functionality during power outages.
5. Other approaches: Urban planning measures, policy and standard establishment, and training for building operators and end-users.

Activating buildings – Building-Grid Interaction signals

To activate a building's energy flexibility potential (whether thermal, electrical or other), an activation signal is required to allow a decision to be made regarding when and how much flexibility is required. At the single building scale, decentralized control can be made by an occupant or facility manager through a building management system to optimize the building's/household's objectives. Whereas at the multi-building scale, a centralized controller may be used by the network operator or aggregator as this is more likely to provide a more significant flexibility response to the signal and reduce the risk of spikes in the electricity grid.

The use of single or multiple Building Grid Interaction signals can be one way of achieving such a variety of objectives. In addition to the service objectives, there are several types of signals which can be used to achieve different strategic objectives at the multi-building scale:

- Price signals are one of the most common forms of signals in energy flexibility services provision. They use dynamic pricing models such as time-of-use or real-time pricing to encourage consumers to reduce or shift their energy use during peak periods. By aligning energy use with lower-priced periods, consumers can save money while helping balance grid demand.
- Emissions-based signals aim to reduce greenhouse gas emissions by encouraging energy use when grid emissions are lower, or when renewable energy is more available. Signals of this type can serve consumers by reducing their carbon footprint if they use grid-derived energy. However, it can also be a self-sufficiency objective, where the on-site generation can be maximized and therefore reducing reliance on more carbon intensive grid electricity.
- Grid-based signals can be used to maintain or achieve grid stability and resilience. The use of these signals is not widespread, mainly due to the lack of smart-grid infrastructure at various levels of the energy system and the lack of regulatory basis for incentivizing action. Further, grid/network-based signals can only be applied to building clusters of a certain size, due to the required response rate being met from many tens, hundreds or thousands of buildings (depending on the grid scale). Under this context, the following should be taken into consideration:
 - a. *Frequency regulation or voltage control signals* can help maintain grid stability by responding to real-time frequency deviations. When supply and demand become unbalanced, frequency regulation signals can prompt adjustments, ensuring that the grid operates within safe frequency limits. Voltage control signals ensure a consistent power supply across the grid by

monitoring and adjusting voltage levels, to help prevent fluctuations that could damage equipment or disrupt service.

- b. *Load-based flexibility* focuses on shifting or modulating (through increase or decrease of) electrical loads to enhance grid stability, especially during peak demand periods. Load shifting signals in energy flexibility programs can be used to reduce strain on the grid when either excess or lack of power has been forecasted. This happens over a longer timeframe than frequency or voltage control signals and therefore can form part of a grid-focused load-shaping exercise.

Energy forecast tool

Energy forecasting plays a central role in the operation and planning of electricity grids. On short time scales, generation and demand are forecasted to ensure stable system operation and mitigate adequacy risks. Likewise, these demand forecasts also often form the basis for establishing flexibility baselines and counterfactuals. At longer time scales, energy forecasts are also critical to inform investment decisions. Within Annex 82, [Energy Forecast Benchmark Toolkit](#), an open-source benchmarking framework was developed to address these challenges by creating a community-driven tool for forecast creation and evaluation. This allows researchers and practitioners alike to quickly determine which forecast strategies work well for which kind of end-use case (e.g., forecasting hourly energy demand in commercial buildings).

Analysis revealed that models such as recursive [LightGBM](#) and direct linear regression exhibit strong overall performance. However, their prediction consistency varies significantly across different buildings. By leveraging daily metrics, we gain additional critical insights into model reliability and variability, highlighting the importance of considering accuracy and stability in model selection. This comprehensive approach enhances our understanding of model capabilities and informs better decision-making for deploying forecasting models in diverse energy use cases. Future work will continue benchmarking other state-of-the-art models from previous competitions and diving deeper into identifying which forecast models perform well for which building energy demand time series. This should lead to more general insights for the broader research community. We also aimed to couple the forecast models more closely with flexibility-related use cases (i.e., how forecast-derived baselines can be used for measurement and verification of use cases, for instance). Likewise, there is significant potential to extend the benchmark further and consider more sophisticated forecasting use cases (e.g., hierarchical stochastic forecasts for energy demand in buildings and districts).

Common Exercise

In IEA Annex 82, ten research teams from across the globe joined to address the topic of energy flexibility offered by building portfolios by responding to a joint challenge, called the Common Exercise. The spirit of this Common Exercise was to enable the various research groups to come together in a joint challenge while still being allowed to use their respective toolchains, simulation environments, and datasets. While the spectrum of flexibility services that a building portfolio can provide is broad, we designed a simple scenario in which the building portfolio is expected to respond to a high price signal during “event periods”, i.e., a small number of event hours every day of the month, with a base price prevailing for all other hours. Some teams were more concerned about electric system peaks associated with heating, others with cooling, and yet others with both. The Common Exercise was designed such that teams could choose which scenario or scenarios were of greatest interest to them.

Regarding the three main points analysed through the Common Exercise, i.e., sensitivity of demand flexibility to pricing signals, negative rebound effects and increase of overall demand, the ten teams involved reached similar conclusions:

- The electric energy demand from heating and cooling systems is sensitive to control strategies based on pricing signals and its modification increases with the amplitude of price variation compared to the base scenario.
- The demand reduction during peak pricing is always accompanied by a rebound effect, before or after a peak clipping event with a severity dependent on the type of control implemented (Rule based control, proactive or reactive, Model Predictive Control) if there are no mitigation strategies in place.
- The overall demand tends to increase in the presence of energy flexibility strategies.

Furthermore, thanks to the specific features of the different case studies, additional considerations can be retrieved from the analysis of the results:

- In the presence of Photovoltaic (PV) and battery energy storage used as energy flexibility provider, the recharging phase of electric batteries can be critical for the grid, especially if the battery energy storage recharging is also allowed from the grid. To control the rebound, typically in the evening when the PV production is not available, such recharging needs to be properly scheduled across different buildings.
- Increasing the pricing signal during the peak period leads to a higher reduction of the peak demand. However, such reduction is not proportional to the price increase. Therefore, the pricing signal needs to be properly set. However, it is reasonable to consider a maximum limit.
- Demand flexibility is closely linked to the heating and cooling demand during the peak shaving event. In the presence of more severe outdoor conditions, e.g., very cold or hot climate outside, the possibility of reducing the electric heating or cooling demand by using the storage capacity of the building is limited if the indoor comfort needs to be maintained.
- To limit the rebound effect caused by energy flexibility strategies, an effective strategy is to diversify the involvement of end users in the event, by for example clustering the demand and applying different pricing signals/control setpoints variations. In the latter case, the possibility for occupants to override the control action can have a considerable unexpected impact on the load shape. Another approach to reduce the rebound effect, when the energy flexibility comes from thermostatically controlled loads, is to modulate the ramping variation of indoor temperature setpoints, however this approach is case dependent and requires an active involvement of the local control.
- When a large number of buildings are involved in the DR strategy, the rebound effect on the feeder, in terms of ramping of the demand variation, before or after a peak clipping event, can be so severe that it leads to a reduction in grid stability, introducing a drawback effect that calls for mitigation actions.

4. Field implementations

Two field implementations were conducted based on the NEST building at Empa in Switzerland⁴. In Test 1, a novel signal matrix model predictive control algorithm was used, which provides stochastic predictions with

⁴ <https://www.empa.ch/web/nest/>

high-probability constraint satisfaction. In Test 2, we explored how a fully equipped occupied building can function as an emission-aware prosumer with flexible energy use responding to the needs of the system, to harmonize the flexibility of all behind-the-meter assets effectively.

Test 1 Data-driven control: This first field study concerns a novel signal matrix model predictive control algorithm designed to address the lack of scalable modelling and control procedures in practical implementations. Compared to existing data-driven methods, the algorithm explicitly provides stochastic predictions considering disturbance and measurement errors with few tuning parameters, ensuring reliability through high probability constraint satisfaction. This type of modelling lies in between the model-based and the model-free approaches. Several standalone tests have been carried out to ensure the robustness of the conclusion from the field implementation, covering multiple aspects encountered in real implementation. The study considers transferability across heterogeneous controlled systems, transferability from simulation to experiment, and the impacts of specific control tasks. Three controlled systems were investigated: a space heating system, a Domestic Hot Water (DHW) heating system, and a stationary Lithium-ion electric battery, representing typical demand-side resources. We considered typical control tasks, including constrained resource planning and trajectory tracking. In the building sector, constrained resource planning is prevalent and aims to minimize total energy use while ensuring constraint satisfaction. Reference tracking tasks can also be formulated for stationary electric batteries, as they are promising candidates for ancillary service provision, as they track reference signals set by system operators.

Test 2 Energy flexibility provision of an energy prosumer: This study examined how a real occupied building, with all its energy assets, could function as an emission-aware prosumer with flexible energy use. In the experiment, a building self-reports its flexibility envelope to the DSO, who in turn remains idle until flexibility needs are foreseen according to the weather forecast. The DSO examines the reported flexibility envelope and notifies the flexibility provision to the building. The proposed flexibility envelope captures the thermal inertia of a building, the storage of a domestic hot water tank, the bidirectional charging of a stationary electric battery and/or an EV, and the curtailable PV power. When this envelope is communicated in advance, a DSO obtains a comprehensive overview of the available flexibility at a given building. Upon receiving the flexibility envelope, the DSO sends a flexibility provision request to the building, including the starting time and the ending time of flexibility provision, and the power level that needs to be tracked. At the building level, this is achieved by modifying the cost function of the optimal control problem upon receiving the request from the system operator. Moreover, the overall two-stage framework can enable the DSO to address local network issues using local flexibility resources.

Within the two field implementations, energy flexibility has been exploited thanks to the system's inertia, such as thermal inertia, and the operating regions of each system, such as the water tank temperature limits. Such flexibility provides the basis for modifying energy use patterns necessary for energy efficiency and the secure operation of large-scale energy infrastructure. While these implementations have shown promising signs in technical development, large-scale demonstrations covering heterogeneous types of systems will further validate the robustness of the conclusions above. There is still a scarcity of large-scale demonstrations, and it remains to be seen how technological advancement can synergize practical business development and social acceptance to achieve massive rollout in practice necessary for sufficient impacts on the energy infrastructure. Crucially, the implementation depends on the availability of sensing, actuation, and impacts from energy end users. Performance gaps exist, and the authors suggest the implementation results are cautiously interpreted, bearing in mind the dependency of performance on regional system regulation, climate conditions, occupant behaviors, energy consumption patterns, and availability of supporting digitalization. Regarding integrating advanced control schemes into critical infrastructure, reliability assessment should not be neglected.

5. Stakeholder engagement

With the systematic literature review of studies on factors influencing customer enrolment and participation in building demand management programs, which was carried out in Annex 82, we aimed to contribute to a better understanding of the key drivers behind Demand Side Management (DSM) in buildings. Based on literature review, we identify the following common themes of relevance to utilities, grid planners, and other decision-makers seeking to increase DSM program deployment and efficacy.

First, we found the focus on economic incentives and DSM participation to be dominating and often explored through simulation methods rather than through experimental trials or full-scale rollouts. While there might be methodological reasons why participation studies prevail (changes in enrolment might be more difficult to measure/model compared to changes in loads related to participation), it seems recommendable to reduce the dependence on simulations and to a higher extent prioritizing studies based on measured data within DSM research and development. The dominance of economic incentives studies likely reflects the emphasis in much policy-making and smart energy R&D on financial and market-based DSM strategies. This ties in with the predominant belief in stakeholders (e.g., households) being rational agents reacting primarily to economic incentives. However, this emphasis on the rational character of stakeholders' decision-making has also been criticized by social science researchers for underestimating the importance of other factors such as structural conditions or how DSM solutions fit in with existing household and business practices.

Second, we found a muted hierarchy in DSM impacts across influencing factors and other relevant dimensions. The analysis of the papers indicates that interventions within third party services, customer engagement and removal of structural barriers have the highest overall scores regarding their impact on DSM participation. However, the review showed generally high variation around the scored impacts of DSM factors, and it is, therefore, difficult to make certain conclusions about their internal hierarchy when it comes to their effectiveness. In addition to many papers being based on simulated results, a reason for this variation can be related to the vast diversity in contexts across studies. There seems to be a need for more research that compares the relative impacts of interventions under similar conditions and with similar evaluation metrics.

Third, we found that automated technologies play a clear role across studies. The application of controls seems important to removing structural barriers to DSM participation and is also an enabling condition for other factors (in particular, remote third-party load aggregation and time-varying price signals for demand response). In addition, the automation of such controls seems to result in larger, positive impacts on participation outcomes compared to active or manual control schemes. However, and interestingly, highest impacts are found if automation and manual control are combined, e.g., by providing customers the possibility for overriding automated and/or remote control.

Fourth, we identified some important gaps in the existing literature. One of these relates to the lack of studies on regulatory interventions, which seems to be problematic as regulatory factors are expected to play an important role in promoting DSM solutions for buildings. Another gap in the literature relates to studies on the intersection of building load electrification (seen as pivotal for the energy system decarbonisation) and DSM enrolment or participation. It seems recommendable to focus more on these gaps in the existing knowledge in future studies.

In many countries, studies have been carried out on users' involvement in DR events. In connection with Annex 82, three national survey studies were carried out, exploring the potential of diverse households, as well as partly offices and educational buildings, in demand response initiatives. The Annex 82 surveys, conducted in the U.S., Belgium and Austria, show that the willingness to adjust the timing of household activities

varies across countries and between weekdays and weekends. Additionally, various incentives, rate structures, preferred times of day for shifting, and perceptions of DSM influence participants' willingness to change the timing of their activities. Overall, the U.S. participants demonstrated more flexibility in adjusting the timing of their activities. Belgium and Austria showed a stronger preference for maintaining fixed schedules. This may be due to U.S. participants being more familiar with DSM/DR programs and related tariff systems. Across the countries, more flexibility is provided during less occupied and sleeping periods. Monetary and environmental incentives were generally effective across all countries. Additionally, price-based incentives and self-initiated participation were preferred in the U.S. and Austria, while Belgium showed a slight preference for automated participation.

6. Dynamic price signals

Some countries have implemented variable price structures that support the utilization of energy flexibility by the end-users. This is especially the case for electricity prices. However, also gas and district heating price structures have been investigated. To be able to apply energy demand flexibility there is a need for general roll-out of smart meters and setting up a billing system that operates at the same frequency as the varying prices in the supply grid. In the European Union, roll-out of smart meters are mandatory in all member states concerning the electricity and gas markets. In other countries it is often up to the end-user to implement smart meters to be able to participate in an energy flexibility programme. To analyse this potential, example cases have been collected and are reported in the following. Annex 82 collected information on pricing structures in different countries for collective energy supply (electricity, gas, and district heating). The questionnaire used for this survey covers not only the raw energy price, but also the different net tariffs and taxes, i.e., the breakdown of the energy prices. The questionnaire focussed on residential customers. We received answers to the questionnaire from Australia (Queensland and Victoria), France, USA (California), Canada (Quebec), Czech Republic, Switzerland, Austria, Ireland, and Denmark. The individual country answers can be found in the Annex 82 report - Review and assessment of market, policy and stakeholder participation in energy flexibility of buildings.

In all evaluated countries, some sort of fluctuating electricity price (often as time of use) is available to all customers. Most countries offer the option of real-time pricing, which is hourly pricing (Australia, USA (California), Czech Republic (not for households), Austria, Denmark, and soon Ireland). When it comes to network tariffs, some countries, i.e., Czech Republic, Ireland, Canada (Quebec) and with exceptions Austria, still apply fixed tariffs (especially on the household level). A higher network tariff for higher consumption is available in France, USA (California), and Czech Republic. A higher network tariff for higher consumption means that once a certain consumption threshold is reached or exceeded, the network tariff increases and becomes more expensive. Additionally, peak power consumption is rarely priced for households (only in Switzerland and Canada (Quebec)). The number of available electricity suppliers and (distribution) network operators vary significantly by country. Furthermore, the change of the electricity supplier is easy in all evaluated EU countries and Australia. However, retail competition is not possible in all US states and Canadian provinces and a change of electricity supplier is not possible in Switzerland.

Example: In Denmark, 70% of consumers are on hourly prices. Many Danes have shifted electricity use away from the “cooking peak” as can be seen in [Figure 2](#). People have postponed the use of dishwashers, washing machines, and tumble dryers and programmed postponed charging of EVs. The figure shows a reduction of the peak values of approximately 10% at 18:00 between 2020 and 2023, and additionally, the figure shows an increase in demand in the night between 1:00 and 3:00 of approx. 25%. So, dynamic prices

have influenced the use pattern of electricity over the day – shifting consumption from the “cooking peak” to the night.

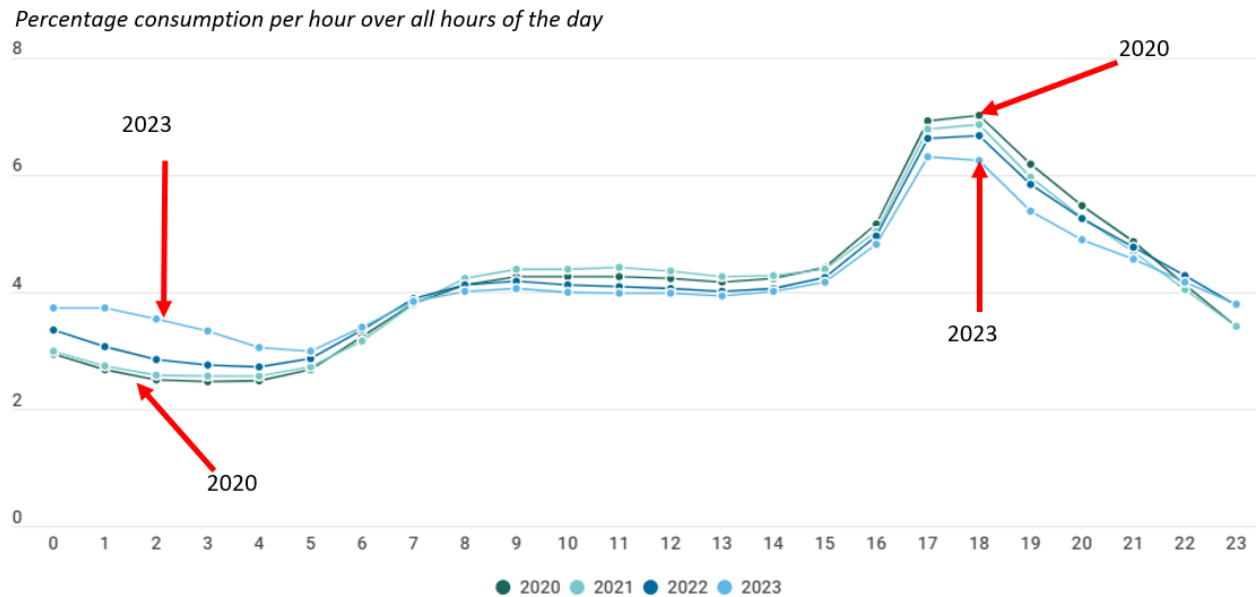


Figure 2: Distribution of domestic electricity consumption (percentage consumption per hour over all hours of the day) for the years 2020-2023 Hour 0 is the timeslot 0:00-1:00, and so on⁵.

Concerning feed-in tariffs for renewables (for households), most countries apply a fixed tariff or market premium. However, Australia (Victoria and Queensland), the Czech Republic, Switzerland (rarely), and Denmark offer time-varying feed-in tariffs. A reduced energy tariff for energy communities can be found in France, USA (California), Switzerland and Austria.

7. Energy regulations

Annex 82 surveyed ongoing legislative works in different countries that aim to facilitate the aggregation of energy flexibility from distributed energy resources. Drawing upon insights from regulatory experiences worldwide, this illustrates key components of an effective legislative framework and highlights the role of policy innovation in driving the transition towards a more flexible and resilient energy system. Information on policies and regulation regarding energy flexibility with a focus on flexibility in buildings were collected from Australia, Canada, China, European Union and selected EU member states (Austria, Denmark, Ireland, Italy and Czech Republic), Switzerland, UK and USA.

The review of existing policies demonstrates a high variety between countries in terms of both the extent and type of policy measures being implemented at national level. Some countries have gone relatively far with implementing the policies and legal framework necessary for promoting flexible energy use, such as dynamic electricity retail prices, while other countries have only implemented limited measures. The review indicates that the development of commercial and residential energy flexibility (demand response) has gotten farthest in countries with the most ambitious policies, which shows the importance of policymaking and regulation for the realization of the energy flexibility potential connected with DERs.

⁵ Faruqui, A. 2023. Flexible Demand in Denmark: A conversation with Claus Krog Ekman. <https://energycentral.com/c/em/flexible-demand-denmark-conversation-claus-krog-ekman>

Aggregators are often highlighted as key for making it feasible for small consumers, like households, to become active participants in the flexible energy markets. However, the actual realization of aggregators for small consumers still appears minimal across countries, which indicates that existing policies have been far from sufficient to create a fertile framework for aggregators to establish as commercial activities. This points to the need for more proactive and ambitious policies on this. One example of a policy change, which could support the penetration of aggregator services targeted at smaller consumers, is the trend of lowering the threshold of marketable volume for EU market operators. A trend is also seen in other countries. In EU, the threshold was typically 1 MW, but in many countries (e.g., countries under Nord Pool), bids as low as 250 kW are now allowed. This reduces the barrier to utilizing building flexibility for day-ahead and intraday arbitrage.

Energy communities appear to have gained some foothold in several countries, which is worth noticing as these can, to some extent, be seen as aggregators of multiple DERs and their related flexibility capacity. Many of these energy communities are citizen driven, which points to the effectiveness of strategies targeted at citizens and local communities, and that such strategies might in some cases be more viable than strategies aimed at more classical commercial and market-driven aggregator concepts. In this way, the review might contest the dominant market-based approaches to the energy transition. This said it is important to observe that in countries with many energy communities (like Austria and Italy), there has also been implemented significant economic benefits for these communities (e.g., substantial governmental subsidies for capital investments of smaller energy communities in Italy or reduced grid tariffs in Austria among other incentives).

Another insight from the review is that implicit demand response appears to be most prevalent in countries with a high share of small consumers having Time-of-Use and dynamic pricing already. This shows that the participation of individual (non-aggregated) consumers in energy flexibility actions, and implicit demand response, should not be ignored in policymaking and as a measure to create more flexible electricity consumption.

In countries with high fixed fees and taxes on electricity, the effect of dynamic electricity pricing is often overshadowed by these (e.g., distribution and other fees). This can be a barrier to customers' participation in energy flexibility, thus policymakers could consider implementing dynamic tax and fee structures instead of today's fixed structures.

8. Business models

The Annex 82 survey study on business models supporting energy flexibility in buildings resulted in 79 diverse case studies from 21 countries across Europe, North America, Asia, and Oceania.

Energy flexibility business models are generally structured around three fundamental components: value proposition, value creation and delivery, and value capture.

Value Proposition: Financial incentives, such as those for enrolling and participating in energy markets, energy bill savings and improved reliability, are major drivers throughout the energy flexibility value chain. There is a strong focus on societal contributions, CO₂ reduction, and sustainability branding, indicating that many stakeholders prioritise sustainability and community impact alongside cost savings. Each stakeholder group has its own focus, i.e., building owners prioritise energy savings and comfort, grid operators emphasise

service reliability, grid efficiency, and operating cost reduction, while data providers, Virtual Power Plant providers and platform enablers concentrate on empowering people and companies to drive decarbonisation, solution scalability, lower overheads, and sustainability branding. This shared interest in both financial and environmental benefits shows the potential of energy flexibility solutions to drive cross-sector impact. As the industry matures, it is also possible to see that the focus is shifting from purely financial benefits to a more balanced emphasis on community impact, environmental responsibility, and long-term stewardship.

Value Creation and Delivery: The most common types of equipment found across different use cases include HVAC systems, which are often paired with smart thermostat controls, batteries (both electric vehicle batteries and stationary batteries, such as those used in homes and commercial buildings), solar PV panels, and thermal storage systems enabled in heat pump water heaters systems.

Value Capture: The most prevalent revenue sources are subscription fees, equipment and technology purchases, and energy market incentives, including upfront enrolment payments and performance-based participation payments. Meanwhile, the most common cost types are labour, software, and capital costs for equipment. In both cases, stakeholders typically have multiple revenue sources and cost types.

9. Annex 82 publications

Methodologies and Evaluations of Energy Flexibility for Clusters of Buildings

Lopes R., Le Dréau, J., Henze G., and Kummert M. (editors), Annex 82 report, July 2025
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Review and assessment of market, policy and stakeholder participation in energy flexibility of buildings

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An international common exercise to evaluate the energy flexibility potential of building portfolios

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Canada	Polytechnique Montréal Hydro Québec Concordia University
China	Hong Kong EMSD
Czechia	Czech Technical University in Prague
Denmark	Technical University of Denmark Aalborg University
France	La Rochelle University
Germany	University Wuppertal
Ireland	University College Dublin University College Cork
Italy	Università Politecnica delle Marche
Norway	Norwegian University of Science and Technology
Portugal	Nova University of Lisbon
Switzerland	Swiss Federal Laboratories for Material Science and Technology (EMPA) University of Applied Sciences and Arts Northwestern Switzerland University of Applied Sciences and Arts of Southern Switzerland
United Kingdom	Loughborough University Leeds Beckett University
USA	University of Colorado Texas A&M University Syracuse University Michigan State University Lawrence Berkeley National Laboratory (LBNL) National Renewable Energy Laboratory (NREL)

