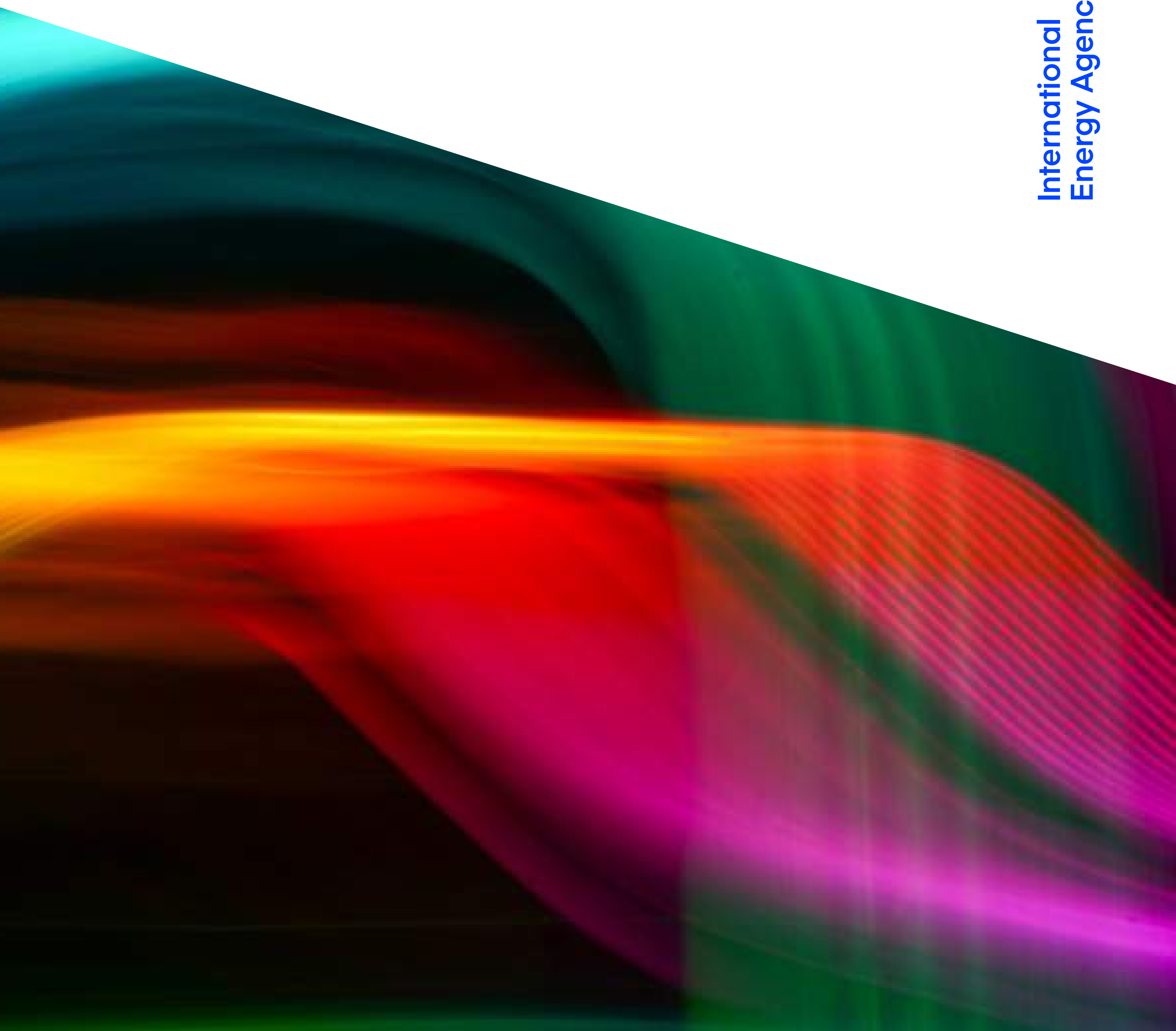
The Value of Demand Flexibility

Benefits beyond balancing



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Abstract

This policy brief, developed under the International Energy Agency's Digital Demand-Driven Electricity Networks (3DEN) Initiative, examines the value of demand flexibility as a core component of modern electricity systems, with a strong emphasis on its role in improving energy efficiency. As electricity demand grows and power systems become more electrified, decentralised and renewable-rich, managing when and how electricity is used is increasingly as important as expanding supply.

The brief sets out a clear framework for understanding demand flexibility and highlights its contribution to an efficiency-first approach to power system planning and operation. By shifting or adjusting electricity use in response to system conditions, demand flexibility improves the utilisation of existing generation and network assets, reduces peak stress, lowers losses and curtailment, and supports more efficient integration of clean energy. It also delivers wider benefits, including enhanced energy security, lower system and consumer costs, and reduced emissions, when appropriately enabled and valued.

The policy brief identifies key trends driving the need for flexibility, the main barriers limiting its uptake, and priority areas for policy action. It concludes that integrating demand flexibility alongside energy efficiency within regulatory, market and planning frameworks is essential to delivering secure, affordable and efficient power systems, while maximising the value of existing and future investments.

Acknowledgements

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Executive summary

With global electricity demand rising and set to add around 1 000 TWh each year until 2035, new ways of managing the balance between supply and demand are needed. Demand flexibility – the ability to adjust the timing or amount of electricity use in response to system needs – is central to help achieve this balance. Advances in digitalisation, including the growing use of AI tools, are further enhancing the ability to deploy flexibility effectively.

This policy brief, part of the 3DEN Initiative, presents a concise framework for understanding demand flexibility and its value across the energy system, highlighting that it can:

- **Enhance power system efficiency.** Flexibility and efficiency reinforce each other, as flexibility enables more efficient grid operation, while efficient buildings and smart equipment expand the scope for cost-effective demand shifting. By improving the use of existing generation and network assets, demand flexibility can raise system efficiency by up to 30% and deliver greater value.
- **Strengthen energy security.** Demand flexibility reinforces electricity security and system resilience by reducing peak demand and lowering reliance on fuel imports. Recent events in California, Western Australia, and France demonstrate this capability, where customers reacted quickly to support system operators, rapidly reducing consumption and helping avoid system crises such as blackouts.
- **Enhance affordability**. Shifting electricity consumption to lower-cost hours can offer financial benefits for consumers directly through smart tariffs. For instance, households can typically save 5-15% on electricity costs using dynamic tariffs. Meanwhile, it can also deliver capacity to the grid at a cost up to three times lower than building new capacity, helping keep electricity costs lower for everyone.
- **Reduce emissions.** By facilitating the integration of variable renewables and reducing reliance on fossil fuels during peak periods, demand flexibility can lower the carbon intensity of the power system by shifting consumption away from peak hours, when emissions are generally higher, sometimes by as much as 70% compared to off-peak times.

These benefits are increasingly important as energy systems evolve. Three trends are driving the need for increased demand flexibility:

- **Rising electricity consumption and changing patterns are creating new peaks and straining power systems.** Global electricity demand increased by more than 4% in 2024 and is set to continue rising as economies grow and sectors electrify. Peak demand is outpacing average demand in many regions. In Korea, for example, it has grown six times faster over the past decade, widening the gap between peak and off-peak periods. This trend increases grid stress and reduces system efficiency by driving up losses during peaks.

- **Bottlenecks in the grid are creating system pressures and wasting opportunities to fully exploit new clean energy capacity.** Grid constraints resulting from rising peak demand are increasing system costs, delaying industrial growth and limiting renewable connections. In 2024, grid congestion cost almost USD 8 billion in the United States and USD 4.5 billion in the European Union. Curtailment of surplus renewables reached over 10 TWh in the European Union in 2024, enough to power around three million homes for a year.
- **Volatility in electricity markets is increasing costs and creating investment uncertainty.** The growth in renewable capacity has lowered wholesale energy prices and improved sustainability, but operational complexity has increased certain costs. For instance, balancing costs have risen by up to eight times in some power markets in the last five years. Negative prices at times have been recorded in Australia, the United States and numerous European countries, creating revenue uncertainty for investors.

Despite demonstrated benefits, the uptake of demand flexibility remains constrained by interrelated barriers. While pilot projects have shown the value of demand flexibility, wider deployment is hindered by weak incentives and regulatory frameworks that continue to favour new infrastructure over smarter system operation. Realising its potential also often requires upfront and ongoing investment in enabling infrastructure, digital capabilities, and cybersecurity, with low digital readiness posing an additional challenge. At the same time, limited public awareness and unequal access to enabling technologies risk excluding some groups, undermining fairness and trust.

Targeted, socially inclusive policies can scale demand flexibility and unlock its full potential. When appropriately valued alongside supply, flexibility can become a cornerstone of secure and efficient power systems, supported by clear investment signals and regulatory and planning frameworks that integrate and remunerate enabling investments.

Chapter 1. What is demand flexibility?

Electricity grid management has historically emphasised supply-side solutions. When electricity demand increased, such as during a hot summer afternoon when air conditioning use peaks, the utility or grid operator often sought to increase the supply. This typically required activating additional generation units, which are often less efficient and more expensive to operate, thereby lowering overall system energy efficiency.

Demand flexibility provides an alternative strategy, as analysed under the Digital Demand-Driven Electricity Networks (3DEN) initiative, an inter-agency collaboration between the International Energy Agency (IEA), the Italian Ministry of Environment and Energy Security, and the United Nations Environment Programme. By focusing on the demand-side, it provides incentives to electricity customers, including households, businesses, and industrial facilities, to either reduce or shift their electricity consumption away from periods of high demand or grid stress.

Demand flexibility is enabled through two principal mechanisms:

- It can be enabled explicitly, formally contracting capacity within energy and balancing markets and requiring specific agreements for load reduction or shifting. Demand flexibility agreements can be made directly between the customer and the electricity supplier, or facilitated by a third party – an aggregator – that consolidates the flexible capacity of multiple smaller consumers in a single portfolio.
- Alternatively, demand flexibility can be offered implicitly, whereby consumers adjust their energy use, either automatically or manually, in response to time-varying prices and other market signals that reflect changing grid conditions.

Demand flexibility can be a cost-effective and scalable way to manage power systems. It uses simple price signals and incentives to encourage consumers to shift electricity use, often supported by digital tools that automate timely, reliable responses. By adjusting demand up, down, or across time without disrupting normal activities, it supports strengthened system resilience. Deployed across homes, businesses, industry, and storage, it could provide a distributed resource to help balance the grid, but also to reduce reliance on expensive supply-side measures.

Where demand-shifting potential is already in place – as with industrial facilities, water heating, air conditioning, or residential heating – the main prerequisites for participation are generally digital metering and a control system. The specific ways customers can modulate their electricity use vary depending on their consumption patterns and technological capabilities. The overall goal, however, remains the same: to shift power demand away from peak grid stress or high prices.

Demand flexibility can be deployed across sectors:

- **Residential:** Households can shift the charging of electric vehicles (EVs) and the operation of heat pumps to off-peak hours when conditions allow. They can also use smart devices to precool or preheat spaces and hot water storage tanks prior to peak demand periods.
- **Commercial:** Building energy management systems can optimise energy consumption patterns in response to signals or dynamic pricing.
- **Industrial:** Facilities have the capacity to reschedule noncritical processes to times of lower electricity demand.
- **Storage:** Batteries (both standalone and paired with onsite renewables) can be integrated across varying sizes, ranging from small behind-the-meter residential units to large-scale utility-sized resources. They can be programmed to charge off-peak or store excess renewable generation, thereby helping to reduce curtailment (the practice of limiting the output of renewable energy generators when supply exceeds demand).

While demand flexibility is primarily associated with balancing supply and demand in real time to maintain system stability during stress events, it also has the potential to support the delivery of a wider set of benefits. These advantages are often less immediately apparent but are increasingly important for effective energy policy and the transition of the electricity system.

Chapter 2. Benefits of demand flexibility

Modern electricity systems are increasingly digitalised and decentralised, with growing shares of variable renewable generation. To maintain reliability and actively balance supply and demand under these conditions, demand flexibility is becoming an essential operational capability. Its benefits extend well beyond balancing as it **improves system efficiency**, **strengthens energy security**, **enhances affordability,** and **supports climate goals** by enabling greater use of clean energy.

This chapter explores each of these benefits in turn, illustrating how demand flexibility can help policy makers achieve a wide range of objectives. Anchoring demand flexibility in an efficiency-first approach means using flexible demand to complement, rather than substitute for, structural improvements in end-use efficiency and system operation. This relationship is reciprocal. Flexibility enhances system-level efficiency by reducing peaks and curtailment, and efficiency measures in homes, buildings, and industry increase the proportion of demand that can be shifted or controlled without compromising comfort or productivity.

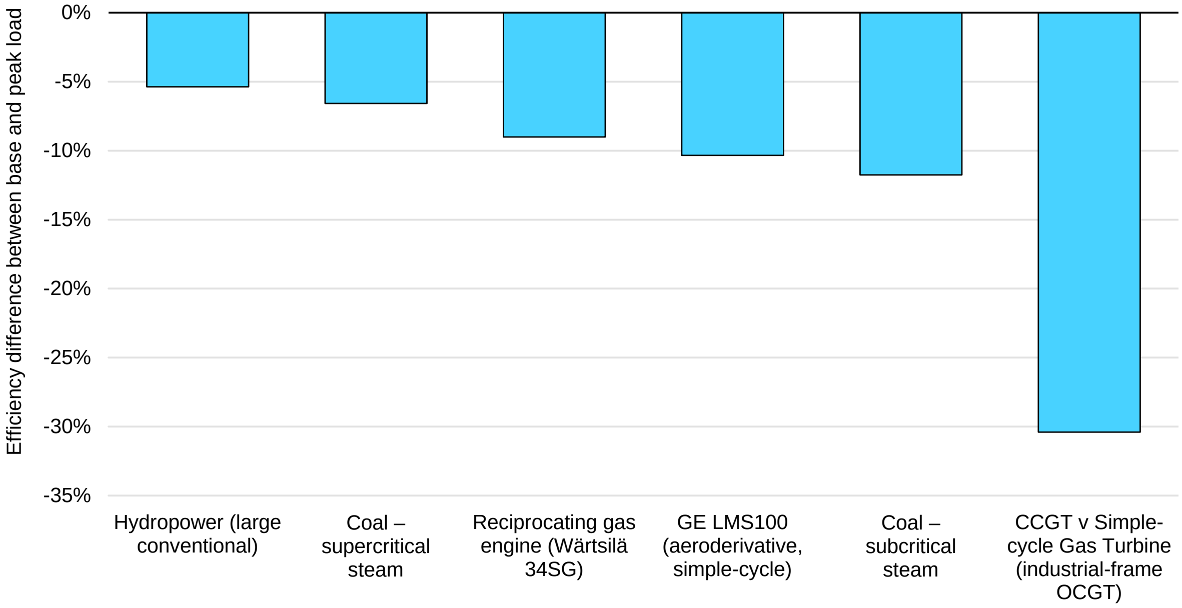
Increasing electricity system efficiency

Benefits at a glance

- **More efficient operation:** Shifting demand away from peaks reduces reliance on peaking plants, which typically operate at lower efficiency.
- **Reducing system losses:** Smoother load profiles lower strain on networks, decreasing transmission and distribution losses.
- **Greater renewable utilisation:** Flexibility increases the share of variable renewable generation that can be consumed instead of curtailed, improving overall system energy efficiency by reducing waste.

Electricity systems typically operate at their lowest efficiency during periods of peak demand, when additional generation – such as thermal plants – is dispatched often at lower operational efficiency. These inefficiencies are especially common as these power plants are asked to ramp up generation to meet variable demand during peak periods. For instance, open-cycle gas turbines, which are used as peaking plants, operate about 30% less efficiently than combined-cycle gas turbines that are primarily used for baseload generation.

Efficiency loss from peak-load operation compared to off-peak, by technology



Note: CCGT = natural gas combined cycle; OCGT = open-cycle gas turbine.
Sources: IEA analysis based on Gevernova, US Energy Information Agency, Tong et al. (2020), Wartsila and World Nuclear Association.

By shifting consumption to align with available supply, demand flexibility reduces the need to rely on inefficient peaking plants, thereby improving network energy efficiency and maximising the use of variable renewable energy generation that would otherwise be curtailed. In October 2025 in California, a new record was set with batteries providing more than 37% of evening peak demand, demonstrating how flexible resources can maintain system efficiency and significantly cut reliance on the least-efficient generation. Meanwhile, a study by the US Department of Energy estimates that unlocking 200 GW of flexibility across the United States could enable up to USD 15 billion in savings by 2030.

By flattening demand peaks, flexibility makes better use of existing capacity and supports higher system efficiency. It also strengthens renewable integration. A recent study estimates that in Ireland, around 90% of nighttime wind-power curtailment could be reduced by providing energy-poor households with free hot water by remotely activating their electric hot water systems. By cutting curtailment, this would reduce system costs by more than USD 20 million by 2030.

Improving energy security

Benefits at a glance

- **Resource adequacy**: Lowering peaks reduces the risk of supply shortfalls during critical hours.
- **Operational security**: Flexible load adjustments in real time reduce congestion on transmission and distribution networks.
- **Deferring capacity additions**: Flexibility provides a rapid and scalable alternative to new generation or grid capacity, which often takes years to build (this is known as "capital expenditure deferral").
- **Improved resilience**: Flexibility lowers dependence on volatile fossil-fuel imports in renewable-rich systems and maximises the use of local renewable resources.

Energy security according to the IEA is based on diversification, predictability, and cooperation, and relies on the ability of systems to maintain uninterrupted power flow to consumers and remain resilient in the face of emerging risks. With electrification expanding into areas such as heavy industry and building heating, the scope of electricity security now extends well beyond keeping the lights on. Consequently, system failures now carry higher social and economic costs, making resilience, flexibility, and co-ordinated planning increasingly essential.

Electricity security rests on three main pillars: adequacy, operational security, and resilience. Demand flexibility can strengthen each of these pillars. Firstly, by lowering peaks, it supports adequacy and reduces the need for additional capacity during critical hours. Secondly, by shifting demand in real time, it strengthens operational security and reduces the risk of congestion or instability. Finally, by providing rapid adjustments during shocks such as extreme weather or disruptions to fuel supply, it enhances resilience.

Demand flexibility can provide security benefits more rapidly than large infrastructure projects. It builds on existing assets; can be deployed quickly and often at low cost, thereby extending their useful life; and improves operational efficiency by reducing stress on assets, deferring an estimated USD 1.8 trillion of grid investment globally to 2050. In systems with high shares of renewables, flexibility further improves security by using more domestic clean generation and reducing exposure to volatile fossil-fuel imports. It also helps stabilise markets by absorbing electricity during surplus periods and reducing price spikes when supply tightens, improving conditions for long-term investment. Demand response programmes in the United States had more than 30 GW of flexibility available in

2024 through wholesale and retail markets to react to system conditions as needed - roughly equivalent to 6% of peak electricity demand.

Other non-market approaches exist where users mobilise demand flexibility without relying on price signals or formal market participation. For example, Flex Alerts are voluntary programmes used to prevent outages in California. In a recent alert, demand fell by over 2 100 MW in under five minutes, avoiding a rolling blackout. In 2022, on a particularly cold day in France, low temperatures driving demand for heating, together with constrained generation capacity, resulted in a notice being issued via a national alert system. Customers reacted by reducing demand by 800 MW, equivalent to around 1% of the peak demand, thereby avoiding a blackout. Demand flexibility in Western Australia was also crucial during the summer of 2023/24, with users lowering their demand when needed, thereby helping the grid operator avoid outages on six of the highest demand days in the region's history.

Managing cyber threats as digitalisation expands

Despite its role in contributing towards improved energy security, demand flexibility also raises potential cybersecurity concerns. As with other sectors where digitalisation is being incorporated, the growing deployment of smart meters, connected devices, automated controls, and data-driven operational tools used to provide flexibility does widen the potential attack surface, and digital and automated operations make systems vulnerable to such attacks. By 2030, an estimated 30 billion connected devices including appliances, heating, and lighting, will be in use worldwide. Vulnerabilities in these technologies could lead to loss of control over devices and processes, interruptions to electricity supply for customers, and in the most extreme scenarios, large-scale disturbances.

While still relatively infrequent, disruptions caused by cyber incidents targeting electricity systems have been observed, such as:

- Cyberattacks on the Ukrainian power grid in 2015 and 2016 remotely switched off substations, causing outages for around 225 000 customers and blackouts in Kyiv.
- A ransomware attack on a local utility in South Africa in 2019 encrypted key IT systems, temporarily preventing over 250 000 customers from buying electricity.
- The national grid operator in Sweden also suffered a ransomware attack in 2025, leading to a data breach.

This growing number of high-profile attacks on energy systems has prompted governments to strengthen protection measures for critical infrastructure. Many regions are now strengthening regulatory frameworks to address cyber threats. The EU Network Code on Cyber Security, the updated US critical-infrastructure standards, and new codes of practice in countries such as Australia, Japan, Singapore, and the United Kingdom, all reflect a common shift toward more rigorous oversight as systems become more digitalised and decentralised.

Enhancing affordability and lowering system costs

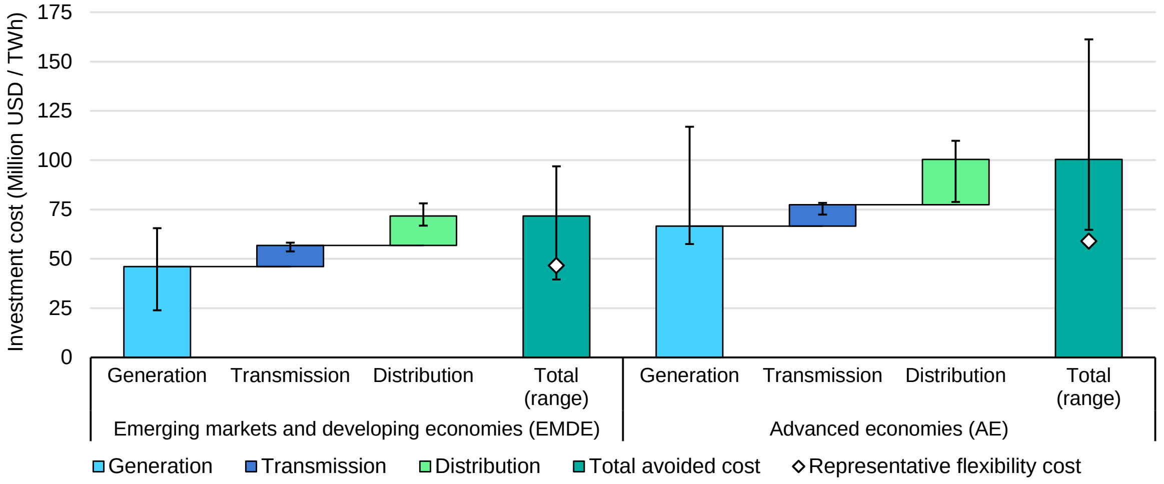
Benefits at a glance

- **Improved equity**: With targeted incentives and support to increase participation, flexibility measures can help reduce the financial burden of low-income households, who spend a higher proportion of their income on energy.
- **End-user cost savings**: Shifting consumption to lower-priced hours under time-of-use tariffs reduces bills for households and businesses.
- **Wholesale electricity price reduction**: Shifting demand away from peaks decreases expensive peak generation, reducing market-clearing prices and spreading the benefits across all consumers.
- **Decreased network costs and tariffs**: Easing local constraints and deferring grid upgrades reduces reinforcement needs.

Electricity prices increasingly reflect variations in the supply mix as renewables expand. In solar-rich systems, prices are typically the lowest during daytime periods of high solar output. In Portugal and Spain, for instance, on a typical day such as 1 November 2025, the day-ahead prices surged twelve-fold from around USD 10/MWh in the afternoon to almost USD 120/MWh during the evening peak. If retail tariffs more closely reflect wholesale prices, consumers can reduce their bills by shifting electricity use to lower-cost periods and benefit from lower generating costs. Households and businesses can take advantage of flexibility measures such as time-of-use tariffs and smart appliance controls, shifting activities, such as charging vehicles, heating water, or running appliances, to lower-cost hours.

Flexibility coupled with energy efficiency improvements can also promote greater equity, as lower-income households who spend a larger share of their income on energy stand to gain the most from well-designed tariffs and targeted support to access enabling technologies. In the United States, empirical modelling suggests that each additional utility offering a time-of-use tariff can reduce the incidences of energy poverty by roughly 4 600–6 000 households per state; widespread nationwide adoption could help hundreds of thousands of lower-income households ease their energy burden.

Range of upfront investment costs for 1 TWh of electricity by world region and representative costs for flexibility programmes, 2023-30



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Notes: Capital cost estimates are shown for 2023-2030 and will be sensitive to changes in the cost of capital. The graph shows the average of all types of generation in each World Energy Outlook model region (United States, European Union, Japan, other AE, People's Republic of China [China], India, Southeast Asia, Africa, and other EMDE). Columns denote average of all regions. Spread indicators denote the range for all regions. Flexibility cost refers to the amount of electricity that is shifted in time.

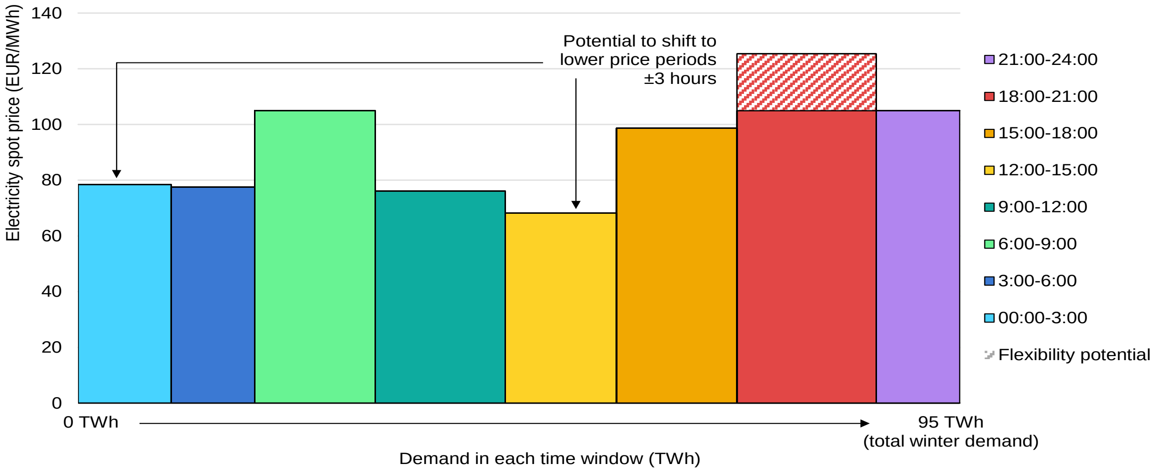
Sources: IEA analysis based on IEA (2025), Multiple Benefits of Energy Efficiency; Northwest Power and Conservation Council (2021), The 2021 Northwest Power Plan; South African National Energy Development Institute (SANEDI) (2024).

Meanwhile, demand flexibility – alongside investments in energy efficiency – can also help defer or decrease the need for investments in the electricity system, a critical benefit at a time of rapid growth. Freeing up 1 TWh of electricity through demand flexibility and end-use efficiency measures can cost up to three times less than providing the same amount of energy by expanding supply, which typically requires USD 30-150 million in new investment.

These cost savings will be especially valuable in the coming years. With electricity demand set to grow by up to 1 000 TWh each year until 2035 – equivalent to adding almost 500 million EVs each year to the global fleet of vehicles – flexibility can be a useful policy lever to help moderate the investments needed in new or replaced generation, distribution, and transmission capacity. An efficiency-first perspective encourages policy makers and system operators to assess targeted efficiency and flexibility measures as primary options before undertaking more capital-intensive network and generation investments.

In many jurisdictions, the price paid to all generators is set by the most expensive generators, meaning that lowering peak prices can reduce total electricity costs. For example, in Spain, shifting just 1.7% of winter demand from the peak period of 18:00 to 21:00 could reduce the overall system cost by 3.4%. Although other aspects make up retail tariffs, reducing the wholesale cost should ultimately benefit consumers through lower tariffs.

Peak shaving potential based on the average demand and price in each time window for winter in Spain, 2024/25



Source: IEA (2025), Real-time electricity tracker.

Reducing emissions

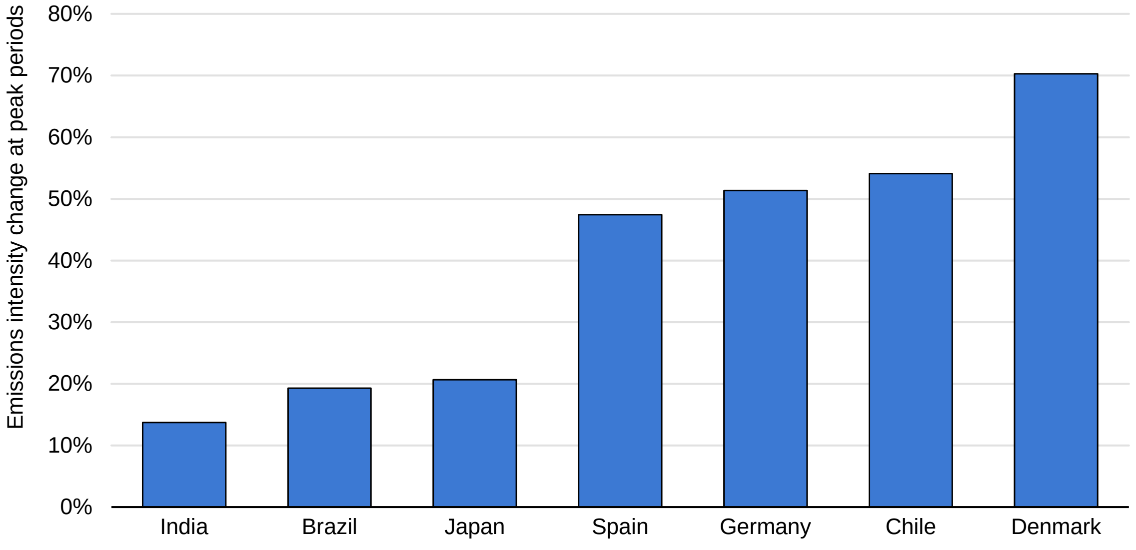
Benefits at a glance

- **Reduced fossil-fuel consumption**: Shifting demand away from morning and evening peaks typically supplied by fossil fuel power plants lowers average carbon intensity.
- **Greater renewable integration**: With demand shifted to off-peak and renewable-rich hours, excess renewable generation can be consumed rather than curtailed.
- **Improved thermal plant operation**: Even in a system with fewer renewables, moving demand to off-peak periods allows units to run more efficiently and with lower emissions.
- **Progress in electrification**: Flexibility helps align electricity demand from new end uses with available low-carbon supply.

Demand flexibility reduces emissions by shifting electricity use to periods when low-carbon and efficient generation is available, lowering the carbon intensity of electricity consumption and helping to reduce peak demand. Carbon intensity – which measures the amount of carbon per unit of electricity generated – varies by region and throughout the day, depending on the generation mix, demand patterns, and the availability of low-carbon sources.

Shifting demand to periods of high renewable output, such as the middle of the day in solar-rich systems, or when wind is at its highest, can significantly reduce carbon intensity. For instance, Denmark has incorporated high shares of renewables – predominantly wind at around 58% of its generation mix, with growing shares of solar – reaching potential reductions in carbon intensity of over 70%. The ability to flexibly shift demand can limit curtailment of wind and solar power and reduce reliance on fossil generation. In 2024, a district-heating utility in the Danish city of Aarhus used large electric boilers and heat pumps to consume around 256 GWh of electricity during low-price, renewable-rich periods, helping to absorb surplus wind and solar generation that would otherwise have been curtailed.

Increased emissions intensity (g CO_2/kWh) of electricity at peak hours compared to off-peak for selected countries, 2025



Note: Peak demand is based on the top three hours with the highest demand on any given day in the period; off-peak is all other hours of the day.

Source: IEA (2025), Real-time electricity tracker.

In regions that are operating predominantly traditional thermal power systems, gains are more marginal. Improved carbon intensity using flexibility is still possible. In these systems, flexibility eases the pressure on peaking plants and reduces the need for ramping, enabling more efficient operation of thermal units. In India, even with lower shares of variable renewables relative to other regions, shifting flexible demand to off-peak periods lowers carbon intensity by around 14%. This occurs because it increases the efficiency of thermal plant operation. By reducing ramping requirements, which refers to the controlled adjustment of a power plant's output to match changes in electricity demand, the system operates more smoothly and with fewer associated emissions.

As electricity systems decarbonise and new sources of demand grow, policy makers are increasingly examining how demand-side flexibility can support long-term planning, system adequacy, and efficient integration of low-carbon technologies. Across many regions, flexibility is now being considered not only as an operational tool but as a strategic component of decarbonisation pathways. Recent policy work illustrates this shift. The United Kingdom Government's 2024-25 Clean Flexibility Roadmap and the European Parliament's 2025 study on Increasing Flexibility in the EU Energy System highlight that consumer-led flexibility is essential to ensure that rising electricity demand from new end uses can be reliably met by available low-carbon resources through measures such as smart EV charging, intelligent heat pumps, and home energy storage.

Chapter 3. Key trends driving the need to unlock demand flexibility

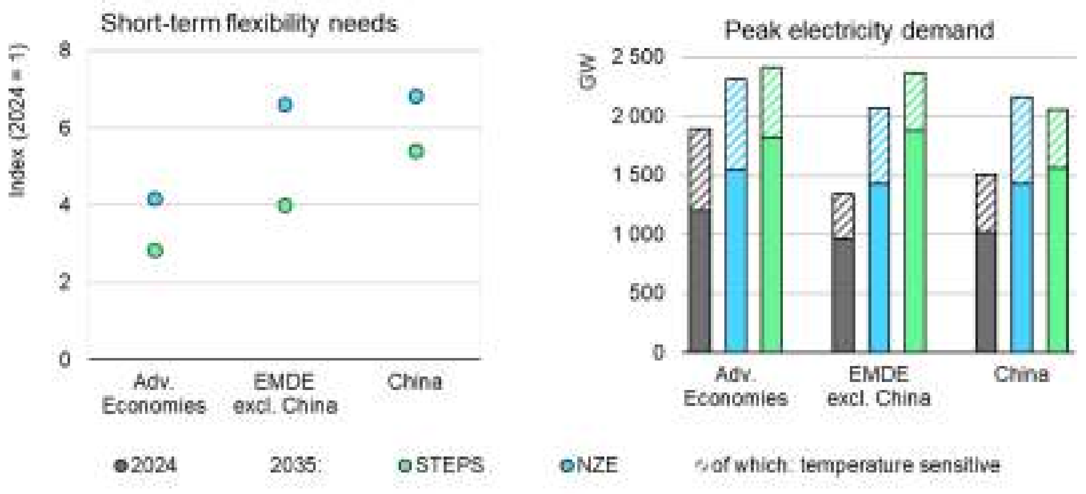
Power systems face significant structural pressures driven by several overlapping and interrelated trends: rising electricity consumption, the emergence of new use patterns such as electric vehicle charging, and rapid changes in the generation mix, with higher shares of variable renewables. These developments are revealing the limits of existing electricity infrastructure and the need to examine current market design.

These interacting trends are already generating operational and economic challenges that were not previously evident over such gradual changes, with electricity demand rising slowly over extended time spans. Understanding how these pressures manifest across regions and timeframes is critical for assessing where and when flexibility will be most needed in the coming decades.

Rising electricity consumption is creating new demand peaks

Global electricity demand increased by 4.4% in 2024, equivalent to almost 1 160 TWh. The main drivers of electricity demand are rising industrial electricity use, increasing appliance loads, and rapidly growing space-cooling needs – with air conditioner uptake a particularly strong and fast-growing driver in emerging markets and developing economies – alongside the electrification of transport, rapid expansion of data centres and AI, growing electrified building services, and rising incomes and economic activity in emerging markets. This growth is expected to continue, with forecasts of 3.3% for 2025 and 3.7% for 2026. These rates are among the highest observed in the past decade, and well above the 2015-23 average of 2.6%. Irrespective of the scenario, the IEA anticipates a rise in peak electricity demand by 2035 and associated growth in the need for short-term flexibility, which could reach levels two to seven times higher than today.

Short-term flexibility needs and peak electricity demand by scenario, 2024-2035



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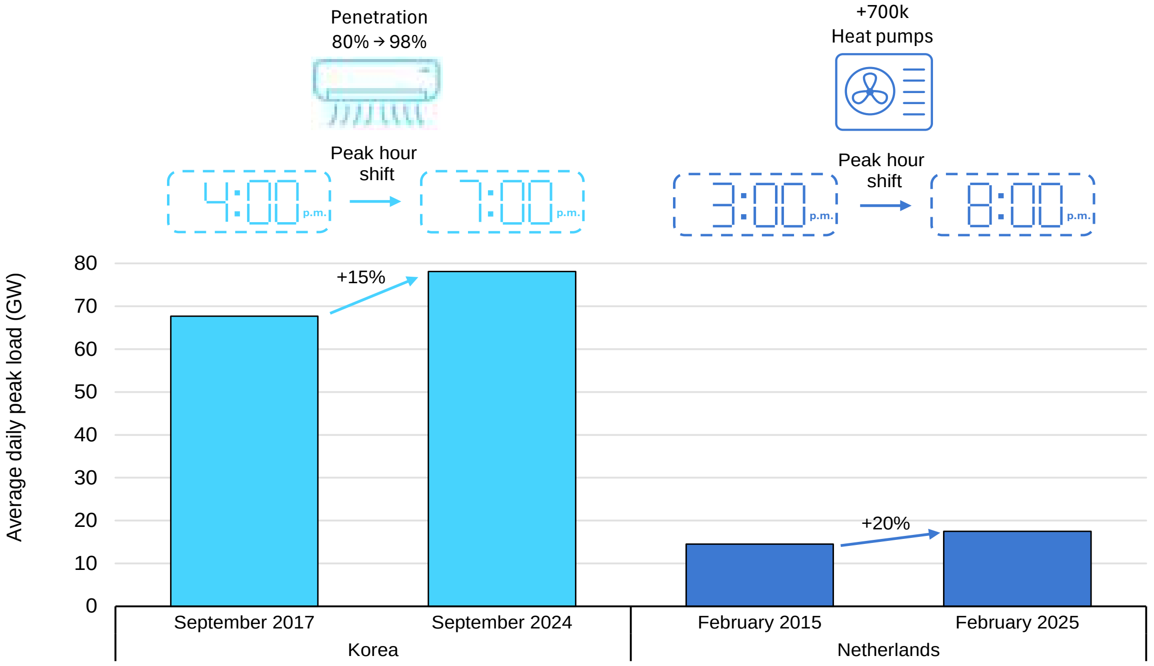
Note: GW = gigawatt. STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; Adv.Economies = advanced economies; EMDE excl. China = emerging market and developing economies excluding China. Peak demand does not include the activation of demand response.
Source: IEA (2025), World Energy Outlook.

With rising global temperatures, increased demand for cooling in particular is intensifying electricity demand in many regions during peak periods and challenging grid security. In June 2025, heatwave-driven power shortages in the Southeast of the United States led utilities to require plants to operate at maximum output. At the same time in the Northeast, wholesale electricity prices for peak demand reached more than USD 1 300 per MWh – 25 times higher than the peak price of the previous week – due to surging demand as a result of a heatwave. Load profiles are also changing in both scale and timing, with major implications for system planning.

In Korea, peak demand in September 2024 was 15% higher than in 2017, while daily average demand rose by only 9%. The peak hour also shifted from 16:00 in 2017 to 19:00 in 2024, reflecting the growing impact of frequent heatwaves and near-universal residential air conditioning coverage. In the Netherlands, peak load in February 2025 was 20% higher than in 2015, driven in part by the deployment of over 700 000 heat pumps that had replaced gas heating with electric systems. The peak hour shifted from 15:00 to 20:00, from commercial to residential demand, underscoring the growing importance of the role of households and the need for flexibility in all sectors.

Rising peak demand and shifting peak hours, Korea and the Netherlands, 2015-2025



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Note: The peak represents the highest daily electricity load, averaged over the month. The hour indicates the time of day at which these peaks most frequently occur in that month. The peak time refers to the hour beginning at the stated time. The drivers shown have a significant influence, but they represent only part of the overall effect.

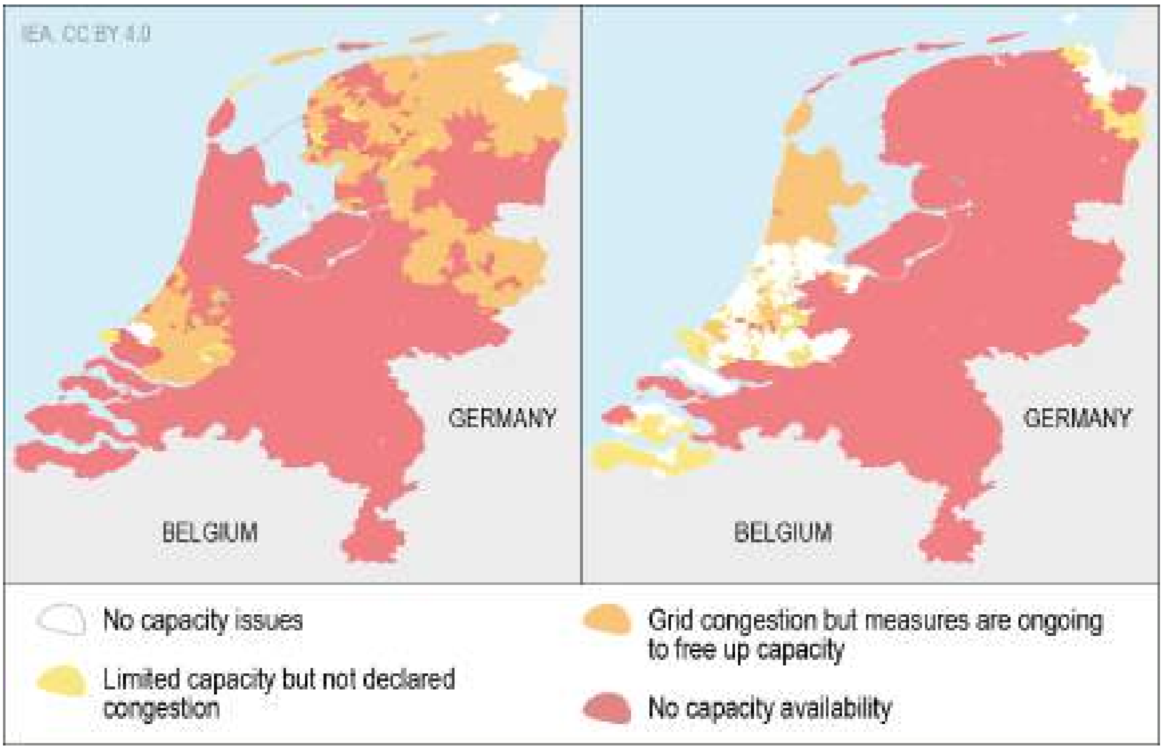
Source: IEA analysis based on Real-Time Electricity Tracker.

Bottlenecks in the grid are creating system pressures and wasting clean energy

Delays in expanding generation and grid capacity to manage rising demand are creating both operational and policy challenges, as rising energy costs from system blockages risk undermining economic and industrial competitiveness. This further underscores the important role of energy efficiency in reducing demand pressure.

In 2024, grid congestion is estimated to cost almost USD 8 billion in the United States and over USD 4.5 billion in the European Union. Across the European Union in the same period, curtailment of renewables exceeded 10 TWh, enough to power almost three million homes for a year. In Japan's Kyushu region, the national system operator association reported some level of renewable curtailment for 120 days in 2024. More recently, in Ireland and the United Kingdom, over 5.5 TWh of renewables were curtailed during just the first half of 2025, owing to grid capacity limits during times of high wind generation.

Map showing areas with limited grid capacity, restricting new connections for consumption (left) and feed-in (right), the Netherlands, October 2024



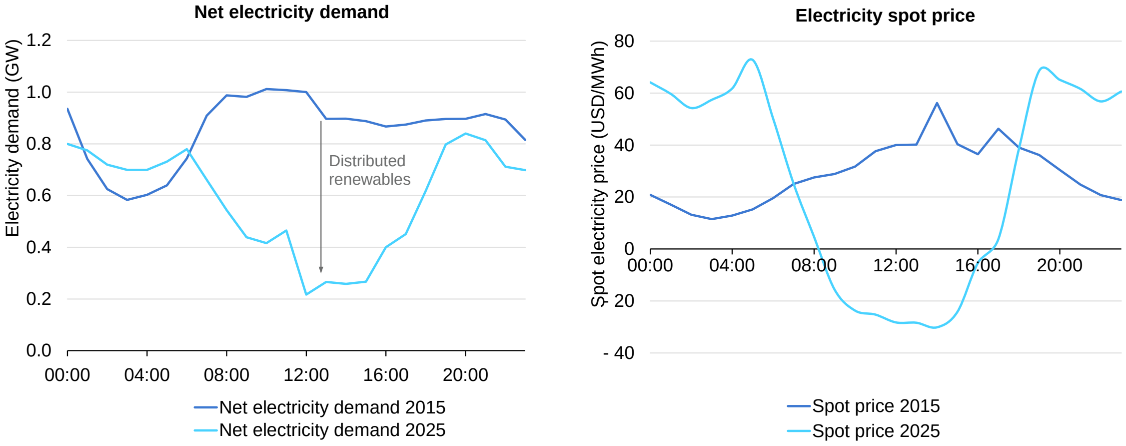
Source: Netbeheer Nederlands, Electricity grid capacity map.

In addition to system constraints restricting access to generators, households and businesses may face delays in obtaining new connections, and housing projects can be postponed or altered. In the Netherlands, a distribution system operator announced in May 2025 that regional grid constraints prevented it from providing connections to housing developments totalling over 500 planned homes. That same year, more than 9 000 businesses across five Dutch provinces faced delays in receiving upgraded power connections. Similar issues have been reported in Ireland and the United Kingdom. Some regions are changing regulations to account for local constraints. Flexibility can also help network operators connect new industrial loads, such as data centres, in constrained areas by shifting operations to off-peak periods, which can facilitate connections for new loads in constrained areas.

Increasing volatility in electricity markets is seeing costs rise and creating investment uncertainty

Renewables are projected to provide over one-third of the world's electricity in 2025, surpassing coal. Balancing costs (the system-wide expenses incurred to keep electricity supply and demand in equilibrium in real time) are rising as solar and wind output fluctuate, while increased investment in grid infrastructure and higher network tariffs add further pressure despite falling renewable generation costs. Electricity prices in the Nordic region, for instance, were the lowest in Europe, dropping by over 20% year-on-year in the first half of 2025 to around USD 40/MWh, driven mainly by greater wind generation and increased hydropower output. In the United States, long-term trends since 2003 show that electricity generation costs have fallen by around 24%, while capital spending on grid infrastructure has risen sharply, including a 160% increase in investment in distribution networks.

Comparison of weekday average net electricity demand and spot prices, hourly, South Australia, January 2015 and January 2025



IEA. CC BY 4.0.

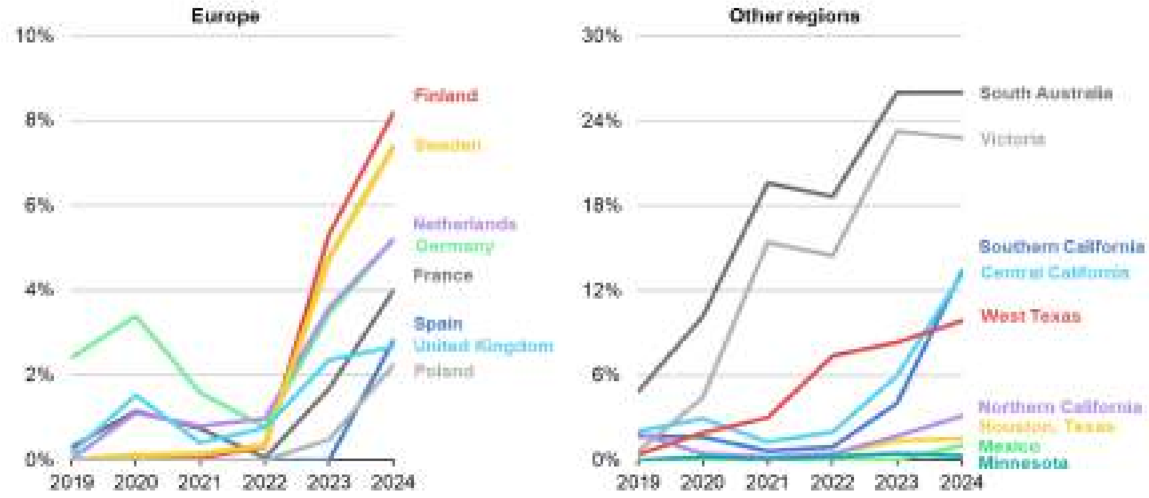
Note: Net electricity demand refers to electricity demand less generation from utility-scale wind and solar PV. The effect of distributed generation (mainly rooftop solar PV) occurs behind the meter and is captured as reduced electricity demand.

Source: IEA (2025), Real-time electricity tracker.

South Australia illustrates the challenge clearly. In January 2025, growing rooftop solar output reduced mid-day net electricity demand – total electricity output from the power system after subtracting the output from renewables – to around half of its 2015 level, creating steep evening ramps as other generation sources are brought online. The electricity spot prices reflect the same operational swings, shifting from a high of more than USD 72/MWh to a low of USD/MWh -30 when solar PV is abundant. Over 27 days during the month of January, wholesale prices were negative at least once.

With renewable capacity set to grow by a further 50% by 2030, this trend is likely to continue. Similar patterns emerged in parts of the United States and many European countries. These swings reflect limited demand-side responsiveness, which reduces the ability to absorb renewable generation and increases investor uncertainty.

Fraction of negative wholesale prices in selected regions, 2019-24



Notes: Southern California corresponds to area SP-15 in the state's zonal regions, Central California to area ZP-26, and Northern California to area NP-15. In Spain, negative electricity prices on the day-ahead market were permitted in December 2023 following updated rules on the operation of electricity markets. In Italy, negative prices were previously not allowed, but this changed in January 2025 with the implementation of the Testo Integrato del Dispacciamento Elettrico reform. For South Australia and Victoria, five-minute interval prices were converted to hourly averages to enable comparison.

Source: IEA (2025), Real-time electricity tracker.

Heightened electricity price volatility has increased system costs by raising financial risk for consumers and producers, weakening investment certainty, and amplifying the need for flexibility resources to manage more frequent extreme price events. These effects collectively place upward pressure on the cost of operating and financing electricity systems, particularly where flexibility and interconnection remain limited. In the European context, while renewables have reduced average wholesale prices, short-term volatility has increased by 30-50% since 2015, with extreme price swings becoming more frequent after 2021. These swings contribute to higher balancing, system operation, and risk-management costs, which are then passed through to end users.

Enhancing flexibility across markets and demand resources is therefore becoming essential for managing peak loads and integrating variable renewables efficiently and cost-effectively, yet many hurdles remain.

Chapter 4. Challenges to scaling demand flexibility

The practical deployment of demand flexibility remains limited, despite it being increasingly recognised as a potentially important resource for modern power systems. Realising its potential requires understanding the range of barriers that shape how consumers participate, how systems operate, and how markets and institutions reward flexibility. This chapter examines these barriers and explains why, despite growing interest and clear system needs, demand flexibility has yet to scale in line with its value.

Participation levels by users are currently low

For many consumers, the case for engaging in demand flexibility remains weak. Incentives are limited, potential revenues are uncertain, and the costs of enabling participation are often felt before benefits are realised. This combination reduces participation by households, small businesses, and aggregators – and it slows uptake. In many cases, the administrative and behavioural transaction costs associated with enrolling in programmes, managing participation, and understanding tariff structures further erode the already-limited economic case for households and small businesses.

Weak consumer incentives under current pricing structures

Dynamic or time-varying retail tariffs provide a direct price signal for end users to adjust consumption and offer flexibility. Under fixed-price contracts, however, consumers have little incentive to shift demand unless additional rewards are offered. European energy regulators note that such contracts dominate the market, accounting for 73% of household contracts in 2023, which significantly limits customer responsiveness and system flexibility. Business customers face similar constraints under expanding block tariffs, where electricity is priced in blocks and the rate changes only once consumption passes a specified threshold. Because only customers close to this threshold see a meaningful financial impact from adjusting consumption, most have little motivation to shift demand. Even where price signals are available, many consumers are discouraged by non-financial transaction costs, including the time and effort required to compare offers, understand tariff structures, or reconfigure devices.

Limited and uncertain consumer revenues

Flexibility events are intermittent, and for households and small- to medium-sized enterprises, the flexibility available based on their own electricity use is typically modest. Consequently, earnings at the individual level tend to be small and variable. For example, a winter-peak programme in Québec collectively engaged over 400 000 households, enabling up to a 530 MW reduction in capacity per peak demand event in the 2024/25 season when mobilised by the system operator. Per household, however, average compensation ranged from just USD 37 to USD 150 for the entire season. For many households, these modest earnings may be outweighed by perceived transaction costs, including the effort required to monitor events, adjust usage, or interact with third-party platforms.

Significant upfront costs to enable participation

Without the digital infrastructure already in place, there can be a barrier to entry for deploying demand flexibility schemes for both the customer and business. The installation of smart meters and control devices may not be supported by government institutions, and adoption sometimes requires households or businesses to make upfront payments. Equally, aggregators need to invest in control and automation systems, data analytics platforms, customer engagement mechanisms, and market participation capabilities. These costs are largely front-loaded, while revenues accrue over time as flexibility is dispatched. The resulting time mismatch could slow wider rollout.

System readiness remains limited

Scaling up flexibility does not just depend on consumer participation; it also depends on whether the power system itself is equipped to handle it. Limited visibility of local networks, weak co-ordination between platforms, growing cybersecurity risks, and sometimes the lack of available flexibility where it is most needed all constrain its effectiveness.

Gaps in system visibility and co-ordination

Visibility enables both effective demand flexibility and improved operational energy efficiency. However, flexibility only works if both system operators and consumers can see clearly what is happening on the grid and respond in a co-ordinated manner. Today, visibility at the local level is often limited, and information is fragmented across different platforms. Even when data exist, they are not always easy to share or act upon, as devices and operators often lack common standards or consistent signals. Inadequate co-ordination increases costs and reduces confidence in flexibility markets. Internationally, flexibility markets increasingly seek common, interoperable registration and management systems to avoid duplicating and fragmenting processes across platforms and operators. This fragmentation raises transaction costs for market participants, who must navigate multiple interfaces, standards, and verification processes to deliver a single flexibility service.

Risks to trust and security

Greater digitalisation increases the importance of robust cybersecurity measures. For example, cyberattacks on US utilities surged by nearly 70% in 2024 compared to 2023. Globally, the average number of attacks per energy organisation tripled between 2020 and 2024, from around 500 to more than 1 500 every week. These vulnerabilities extend to demand flexibility, which relies on distributed energy resources, digital control and automation, and often third-party providers. If clear rules on data access, system monitoring, and incident reporting are not in place, consumers and businesses may be hesitant to participate, and it may be difficult for operators to exchange information reliably. Governance becomes increasingly important as unclear roles and legal responsibilities can also create uncertainty about who is accountable for data handling and for responding to cybersecurity incidents.

Flexibility is not always available where it is most needed

The availability of flexible resources does not in itself guarantee system value, because flexibility is most valuable in areas facing network capacity constraints. When local distribution networks are already operating near safe thermal or voltage limits, only resources located close to the constraint can provide meaningful value and relieve local stress. Evidence from congestion management shows that a locational mismatch can render flexibility procurement impractical. In the Dutch province of Gelderland, for example, investigations by the distribution network operator found that no local flexible capacity from large consumers had been contracted in the first half of 2025, limiting the applicability of this approach. The volume of demand flexibility that can be activated also depends on weather and system conditions, which leads to seasonal and locational variations in activation frequency and earnings. Although the industrial sector can typically shift larger volumes of electricity use than households and small businesses, these shifts are constrained by operational requirements and by perceived risks of disrupting core processes or missing production targets.

Markets are not generally designed for demand flexibility

Current market arrangements make it difficult for demand flexibility to compete on equal terms. Rules are often incomplete or inconsistent, participation requirements favour larger providers, and incentives are not aligned with the real value offered by flexibility. These design gaps limit uptake and keep markets biased towards supply-side solutions.

Incomplete market rules and frameworks

A complete framework sets out clear service definitions, along with eligibility, verification, remuneration, and stacking rules. Where these design elements are only partially specified or missing entirely, market participation and procurement are constrained. Common definitions and practices are also needed. Without them, participant predictability is weakened, valuation becomes inconsistent, and local flexibility arrangements do not align with national markets and system planning.

Participation barriers for smaller players

High minimum thresholds and overly complex technical requirements limit eligibility for small providers and tilt procurement towards large, dispatchable supply-side assets. Demand flexibility remains underused, even in cases where it could meet the same system need. In the United States for example, the minimum participation threshold for electricity markets is about five times higher than average household annual consumption, effectively excluding most households and smaller businesses unless they join through intermediary aggregators. In addition, the administrative transaction costs of qualification, metering, verification, and settlement can be disproportionately high for smaller resources, reducing their ability to compete on equal terms.

Weak incentives and misaligned cost recovery

Incentives and compensation mechanisms frequently remain limited. Traditional regulatory frameworks that reward capital expenditure over operating costs compound this imbalance. Under cost-of-service models, utilities can earn a return on new physical infrastructure, but not on operational measures such as demand response. This encourages investment in capital-intensive assets over distributed or virtual power plants, constraining the availability of cost-effective alternatives and slowing the deployment of demand flexibility measures.

Public awareness and trust remain low

Without stronger public engagement, demand flexibility may not gain traction. Low awareness means that many people see little reason to participate, while doubts over fairness, reliability, and data use undermine trust. Renters and residents of multi-unit buildings may face additional barriers, as they often have limited control over installing enabling technologies or accessing building-level flexibility schemes. If access remains uneven, the benefits could be captured mainly by wealthier households and larger businesses, reinforcing inequalities. Some aspects of consumer perception, such as concerns over privacy, automation, or loss of control, may be difficult to shift and in some cases may never change entirely, underscoring the need for approaches that accommodate differing levels of trust and willingness to participate.

Limited public understanding slows uptake

Many consumers are still unfamiliar with power systems in general (and demand flexibility in particular) and how they work. Without public information campaigns, flexibility programmes can seem complex: terms such as “time-of-use tariffs” and “aggregation” are poorly understood. Many consumers know their tariff but not how their pricing structure works, and often lack a full understanding of what they are paying for. Without a clear communication of benefits, consumers may not see why participation is worthwhile. This lack of awareness slows uptake and reduces the pool of flexible resources available to system operators.

Trust and social licence are essential for engagement

Awareness may help obtain a certain level of participation in demand flexibility programmes, but it may not be sufficient to achieve wide acceptance. Even if consumers are aware of flexibility options, they may not trust the fairness and reliability of such schemes. Concerns include whether savings will be significant, whether automation will compromise comfort or productivity, and whether personal data will be handled securely. Building trust requires transparent programme design, straightforward offers, and strong data protection. In particular, when demand flexibility is enabled via digital tools, securing a social licence for automation will be essential for reliable, long-term engagement. If participation processes are perceived as complex or risky, the implicit transaction costs of engaging with flexibility schemes can reinforce scepticism and limit uptake.

Equity gaps risk leaving vulnerable groups behind

Access to enabling technologies (such as smart appliances, EVs, and digital tools) is often concentrated among higher-income households, homeowners, and larger businesses. By contrast, individuals who are financially vulnerable, younger, on prepayment meters, or behind on bills tend to have lower confidence in and understanding of energy use. Time-poor households, including those with multiple jobs or care responsibilities, may find the behavioural and administrative effort required to participate particularly challenging. Yet these are often the people who could benefit the most from clearer billing, targeted support, and the ability to shift or reduce demand.

Without deliberate policy measures, flexibility programmes risk excluding these groups, reinforcing inequalities and allowing system cost savings to be captured mainly by wealthier participants. Ensuring fair access, addressing the barriers facing vulnerable consumers, and supporting equitable participation are therefore critical to demand flexibility becoming a genuinely inclusive system resource.

Chapter 5. Insights from international experience

Around the world, demand flexibility is already being demonstrated and integrated into power systems to improve the efficiency, reliability, and security of supply. While specific approaches vary depending on system conditions and market design, common features are emerging. These include the digital visibility of distributed resources, controllability of loads, and signal-driven responses integrated into system operations. International examples show that demand flexibility can be a core component of system operation, supporting renewable integration, reducing costs, and enhancing adequacy.

Managing high shares of solar in South Australia

South Australia has some of the highest levels of rooftop solar penetration in the world, providing over 18% of electricity generation in 2023 – nearly twice the contribution of large-scale solar (around 10%). While this ensures significant renewable generation, it also creates operational challenges, including distribution bottlenecks and system-balancing needs. Traditional fixed-export limits risk leading to higher levels of solar curtailment and increasing network stress. Demand flexibility in South Australia has been developed through programmes led by energy retailers, as well as the aggregation of behind-the-meter resources supported by government initiatives, technology providers, and aggregators. Demonstration programmes in 2021 tested the operational capability of these aggregated resources and showed their ability to deliver reliable system services. In parallel, newly introduced connection standards required solar and battery systems to adopt dynamic export limits, allowing export levels to vary according to local grid conditions.

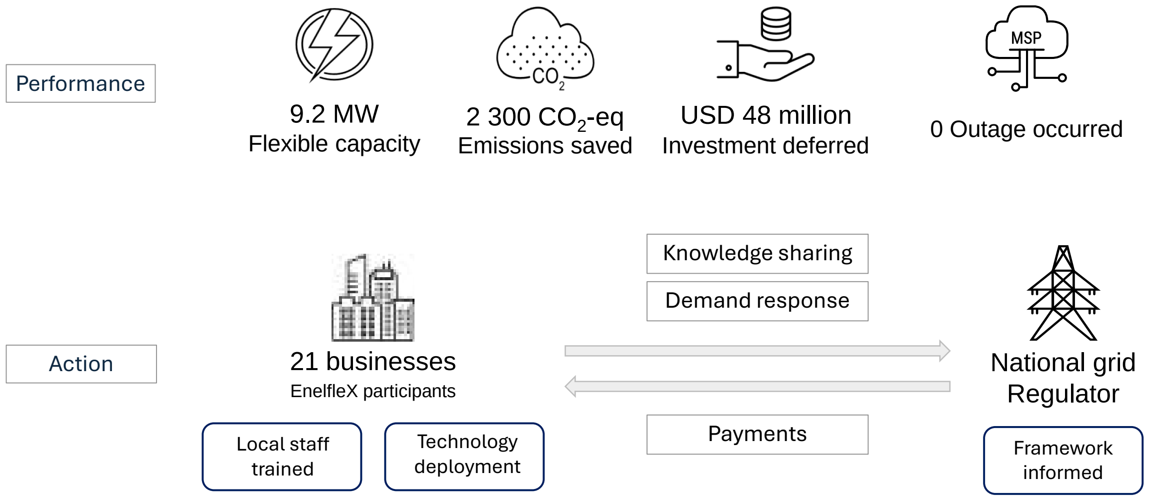
Integrating flexibility into markets and operations

These initiatives have integrated distributed resources into system operations and market participation, ensuring that growing solar capacity supports rather than challenges the grid. Aggregation has successfully enabled small-scale assets to provide system services, and dynamic export controls have reduced congestion and improved utilisation, enhancing both operational efficiency and renewable integration. Between 2019 and 2021, demonstration projects by flexibility providers successfully delivered balancing services, and as a result, rules were formalised to include the participation of distributed energy resources. Since July 2023, almost 90% of eligible households with new or upgraded solar and battery systems have opted for dynamic export limits. Some utilities are offering free electricity to incentivise demand shifting during solar peak, and the government is also considering introducing a regulated tariff to make this offer available to all customers.

Improving grid reliability in Colombia

Electricity demand in Colombia is growing rapidly, with the network in Bogotá experiencing particular strain. Risks from increasingly frequent extreme weather events, as during the 2023/24 El Niño, further expose system vulnerabilities, with major outages affecting hundreds of thousands of customers. The EnelfleX project was launched under the Digital Demand-Driven Electricity Networks (3DEN) initiative, with support from the Italian Ministry of Environment and Energy Security and the United Nations Environment Programme. Undertaken from 2023 to 2025, the pilot project was designed to test demand response as a cost-effective alternative to grid reinforcement in Bogotá's Sabana Norte region.

Colombia's 3DEN initiative pilot and national impacts since 2023



Source: IEA illustration based on data from Enel Colombia as part of the 3DEN phase I pilot projects

Avoiding outages and lowering emissions

Businesses across multiple sectors were engaged in EnelfleX, with twenty-one participants under contracts for both offering their availability to provide flexibility and their willingness to provide activation payments when demand flexibility was requested. Findings from the pilot project are being shared with regulators to inform a national demand-response framework. Altogether, 9.2 MW of flexible capacity were enabled by digital technologies, achieving deferred investment of over USD 48 million in transmission reinforcement.

The project contributed to reliability gains, with simulations showing outage times reduced from 26 hours per year to zero, and with estimated emissions reductions of more than 2 300 t CO_2-eq annually. Moreover, customers valued advance alerts and improved reliability as much as financial incentives. Long-term and wider uptake however requires permanent regulation, new tariff structures, and broader customer engagement. Colombia's system operator and international partners are planning full-scale tests before the end of 2025 to support the design of a permanent regulatory framework for demand flexibility.

Reducing costs and supporting economic development in Kenya

In Kenya, a mismatch between the times when renewable generation is abundant and when electricity is needed has necessitated a new approach. The country faces the associated costs of growing curtailment of renewable generation, which makes up to almost 88% of all electricity generated – particularly at night, when wind and geothermal output can exceed demand. Reducing electricity costs for commercial and industrial users has become a strategic priority for Kenya, both to strengthen competitiveness and advance national development objectives.

To address these issues, the Energy and Petroleum Regulatory Authority introduced time of use (ToU) tariffs in December 2017. The scheme offers a 50% discount during off-peak hours for users who meet a minimum consumption threshold, encouraging demand at times of low system use while helping to reduce renewable curtailment.

Scaling up flexibility for wider participation

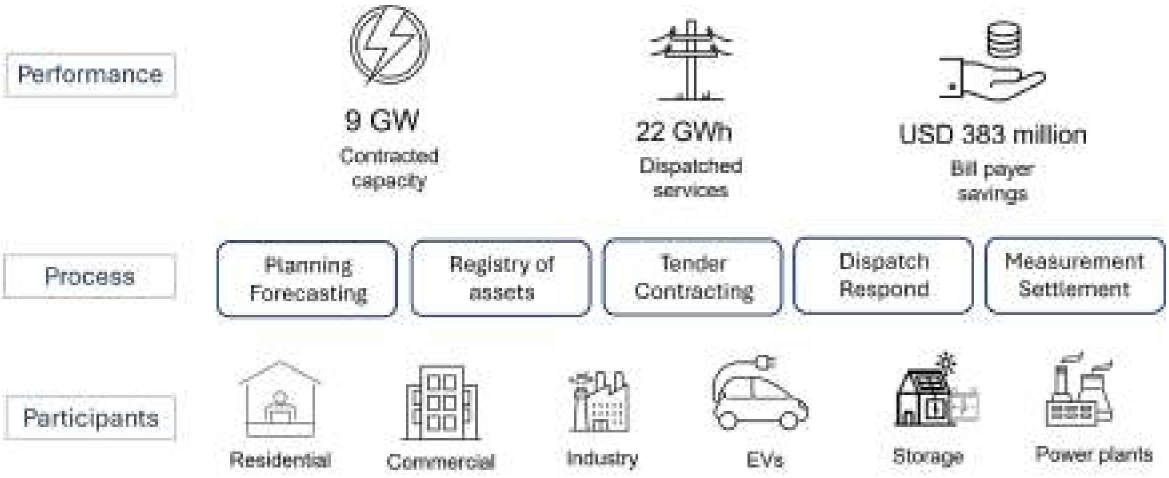
Kenya Power supported the rollout of ToU tariffs through its Rapid Results Initiative, launched in 2023 to accelerate the deployment of smart meters. In 2024, more than 105 000 meters were installed for industrial and commercial consumers, improving their ability to monitor and shift demand in line with the ToU tariff.

Originally targeted at commercial and industrial consumers in 2017, the ToU tariffs were expanded in 2023 to include offers for small commercial and e-mobility users. As a result, the number of ToU subscribers nearly doubled in 2024 compared to 2023. The programme saved almost USD 14 million collectively in 2024, highlighting the programme's effectiveness in delivering cost savings for power utilities, businesses, and other users while also improving system flexibility.

Addressing grid congestion in the United Kingdom

In the United Kingdom, the Open Networks Programme was in place between 2017-2025, supported by the UK government, the Energy Networks Association, the energy regulator, and the six Distribution System Operators. Its guiding principle, “Flexibility First”, required operators to consider market-based flexibility services before investing in grid upgrades, in order to reduce peak demand and thereby mitigate the need for additional grid capacity. Flexibility was procured through digital platforms where households, businesses, battery operators, generators, and aggregators submitted bids to provide services such as demand adjustment, load shifting, and local generation. Contracts were awarded competitively, with payments made upon verified delivery.

UK flexibility services and impacts, 2024



Source: IEA illustration based on Energy Networks Association data.

Improving system operation and delivering results

In 2024, a record 9 GW of flexibility capacity was contracted and 22 GWh of services dispatched – enough to power almost 7 000 UK homes for a year. These services delivered more than USD 380 million in savings for consumers and are projected to generate almost USD 4 billion in savings over the next 3 years.

Looking ahead, the UK energy regulator has decided that the following price control period will adopt a “build and flex” approach starting in 2028. This means that distribution network operators will be expected to plan and build reinforcement in time to meet net zero goals while still utilising distributed flexibility to improve operational efficiency. The role of distributed flexibility is evolving in UK networks, with demand-flexibility resources projected to increase fivefold, from around 2.5 GW today to as much as 12 GW by 2030.

Digital demonstrations enabling real-world flexibility outcomes: Insights from 3DEN Phase I (2019-2024)

During Phase I of the 3DEN Initiative, pilot projects were implemented in Brazil, Colombia, India, and Morocco. Scalable digital tools were tested in diverse contexts as practical demonstrations of how digitalisation can strengthen efficiency, flexibility, and reliability in emerging power systems.

Focus areas of Phase I demonstrations:

- urban grid optimisation: India’s digital twin for low-voltage networks
- demand-side flexibility for congestion management: Colombia’s industrial and commercial demand response
- industrial digitalisation: Morocco’s real-time energy and performance monitoring
- social housing and community energy solutions: Brazil’s solar-plus-storage smart neighbourhood.

The pilots delivered substantive, empirical evidence on the necessary enabling conditions, the primary barriers, and the people-centred impacts of digitalisation in the power sector. Rather than isolated demonstrations of new tools, the pilots produced tangible system benefits, including improved reliability, reduced emissions, lower costs, and strengthened local capability.

Across the four pilots, the results included:

- Improved electricity reliability for over 320 000 people.
- Nearly 3 800 t CO_2 avoided annually.
- Almost USD 60 million in deferred infrastructure investment.
- Digitalisation of over 60 GWh of industrial energy use.
- Engagement of more than 650 people through training and local participation.

Building on these foundational demonstrations, Phase II of the 3DEN Initiative will expand the focus to new geographies and sectors such as agro-food. At COP30 in Brazil, fourteen new pilot projects were confirmed, expanding implementation across **Brazil, Ethiopia, Kenya, Nigeria, Sout Africa, Tanzania, and Tunisia.**

Chapter 6. Policy priorities for demand flexibility

Demand flexibility can deliver clear benefits for electricity systems, consumers, and the wider economy. Its potential, however, remains underused in many regions, and scaling it requires deliberate action across financial, technical, regulatory, and social domains. The priorities below outline how policy makers can create the conditions that allow flexibility to play a central role in power systems.

Valuing flexibility to unlock investment

Flexibility can be treated as a system resource within market and regulatory frameworks. Time-varying prices encourage demand to shift into lower-stress periods, while locational incentives reward flexibility in constrained areas where it is most valuable. These measures create predictable revenue streams that drive investment and participation.

Building digital infrastructure to support reliable system operation

Smart control, communications, and digital platforms underpin flexibility at scale, enabling monitoring, automation, and grid visibility. Open, interoperable standards can contribute to better customer experiences, enabling appliances, EVs, and storage to integrate more seamlessly. Strong cybersecurity, clear responsibilities, and skilled operators are essential to maintaining secure data flows and consumer trust. Without these foundations, participation will remain limited.

Adapting regulation to embed flexibility in planning and markets

Transparent market rules can place demand flexibility resources on an appropriate footing compared with supply-side solutions. Regular reviews could support the removal of outdated provisions that hinder aggregation and participation. System and network planning could evaluate flexibility alongside reinforcement to ensure least-cost investment decisions. Accordingly, developing standardised processes for registration, contracting, dispatch, and settlement would contribute to improved certainty for providers and operators. Locational services ensure flexibility is deployed where it is most needed.

Ensuring inclusive access and public trust

Wider participation is more likely when access barriers are low and consumer confidence is high. Policy makers developing demand flexibility programmes could endeavour to remove financial, technical, and administrative barriers and provide simple, transparent offers through both digital and low-tech channels. Performing outreach to under-represented groups would also broaden engagement. Safeguards such as targeted support for vulnerable users and fair cost sharing could reduce the risk of a divide. Finally, social licence for automation can only be secured through clear consumer choice, robust data protection, and transparent financial redress.

Integrating demand flexibility and efficiency into broader power-sector transformation

Demand flexibility has proven its value in pilot projects and local initiatives, but scaling it across entire systems remains a key challenge in many regions. Participation and investment lag without coherent policy support, despite its demonstrated technical feasibility. Embedding the principles of efficiency and flexibility within policy packages ensures they are systematically considered as core system resources alongside new generation and grid expansion to reduce and optimise demand. Integrating the two also strengthens overall system performance, as flexibility maximises the value of efficiency by optimising when energy is used, while higher efficiency levels expand the scope for flexible loads by lowering baseline demand and reducing operational constraints.

In conclusion, integrating demand flexibility within efficiency, electrification, and renewable policies can contribute towards making power systems cleaner, more secure, and more affordable. Clear direction and consistent frameworks could give consumers, operators, and investors confidence to act. This requires integrated policy packages that align information, incentives, and regulation by building public understanding, rewarding responsive demand, and ensuring flexibility is systematically considered in system operation and planning.

Annex

Examples of demand flexibility resources and market enablers

Category	User group	Technologies	Flexibility actions	Considerations
Sources of flexibility	**Residential**	EV chargers Smart appliances	Schedule use during off-peak periods (e.g. charge EVs and run appliances as suitable).	Digital controls automate responses to changing prices and system operator signals.
		Heat pumps Smart thermostats Water heaters	Pre-heat or pre-cool within comfort limits (e.g. prepare rooms and water tanks before high-demand periods).	
	Commercial	Heating, ventilation, and air conditioning (HVAC)	Adjust heating, cooling, and ventilation in line with occupancy patterns and peak periods.	Smart building-management systems enable predictive scheduling, real-time monitoring, and reaction to external signals.
		Lighting	Schedule and dim lighting; align with occupancy and daylight.	
		Refrigeration Cold rooms	Reschedule defrost cycles, pre-chill stock, and make small temperature adjustments within safety limits.	
	Industrial	Process controls	Utilise industrial controls to automatically adjust equipment use.	Careful scheduling ensures operations remain efficient.
	All segments	Batteries	Operate batteries to charge during high-renewable periods and discharge during peaks.	Provides both demand-side and supply-side services.
Enablers of flexibility	**Aggregators**	Resource pooling and operation	Combine many small resources so they can operate as one larger, controllable portfolio.	Reliable delivery requires grid access and clear market rules.
	Market rules	Market design rules	Define the rules for how flexibility participates in the market, from registration to operation and payment.	Stakeholder engagement and valuation are crucial for uptake.
	Dynamic retail tariffs	Participation driver	Increase prices during peak periods; apply real-time prices to provide clear price incentives.	Requires advanced metering and communication systems.

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