LCPDelta

Switching up the smart system: How the smart system can transform energy resilience

Report 1: Analysing resilience in the UK and around the world

A project for CALISEN

25 JUNE 2026

> Resilience isn't optional - it's worth billions and protects every home.

1. Defining resilience

As Great Britain transitions toward a sustainable, futureproof energy system, resilience is the backbone of our electrified future. A second energy crisis, triggered by international conflict, has increased the pressure to reduce oil and gas dependence. The stakes are enormous: the UK is investing an estimated **£1.4 trillion** in modernising an ageing system that embraces clean sources of power, yet around 25% of homes still lack a smart meter and over 7% of smart meters are non-communicating, leaving critical blind spots in our energy system. The number of non-communicating meters has been tracking down as the industry identifies issues.

Resilience means more than keeping the lights on. It safeguards health, prevents economic shocks, and ensures fairness for vulnerable consumers. Every outage avoided saves money and stress: Ofgem's latest figures show compensation for prolonged outages can reach **£2,165 per household**, while the Value of Lost Load for businesses can exceed **£250 per kWh**.

Smart meters are the foundation of this resilience. They provide near real-time visibility, enable rapid fault detection, and unlock flexibility, turning a reactive grid into a proactive one. Without them, we risk slower recovery, higher costs, and greater vulnerability as electrification accelerates. This section provides a broad definition of grid resilience, the different ways to quantify resilience and to monetise it.

Introduction

The futureproofing of GB's energy system leans heavily on electrification. As petrol cars give way to EVs and gas boilers are replaced by heat pumps, more of the economy runs on electrons rather than molecules.

While reducing exposure to international oil and gas price shocks is essential, the shift to electrify increases the need for a strong and resilient electricity distribution grid. Ageing assets and historic under-investment in local networks heighten the risk of constraints and outages just as dependence on electricity grows. Events have shown what can happen when resilience is stretched.

A frequency event on 9 August 2019 caused automatic disconnections affecting around a million consumers. Official reports traced this to the loss of two large generators and the speed of the frequency fall.

More recently, a 2025 substation fire linked to maintenance failings triggered major disruption at Heathrow, prompting an Ofgem investigation*.

These incidents demonstrate why grid resilience matters ever more in an electrified economy. At the same time, the electricity generation mix is changing. Wind and solar are intermittent by nature and not fully dispatchable (i.e., the output depends on weather and time of day rather than operator instruction) and are unable to provide system inertia.

The transition to cleaner energy systems is recognised as a massive structural undertaking.

£1.4 trillion	Estimated investment cost of achieving the UK's net zero carbon emissions target. From a 2021 report by the Office for Budget Responsibility**

From a public-policy perspective, investing in resilience is not optional. It is integral to delivering the transition in a way that is just and sustainable. A resilient system supports the shift to low carbon technologies, by enabling them to be integrated reliably, by buffering shocks from intermittent supply, and by assuring consumers that their energy remains secure.

- This resilience supports health outcomes: a household that cannot afford heating or suffers repeated outages faces direct risks to health (cold-homes, inability to run medical devices, food spoilage) and indirect risks (stress, financial strain).

Consumer expectations

From a recent Ofgem commissioned consumer outcomes research study***:

- Resilience, largely defined as uninterrupted supply, is viewed as a bare minimum. So, **consumers expect resilience** in their energy networks.
- There is strong resistance overall to passing on the cost of investment to consumers and consumers expect energy suppliers to reinvest profits and be held accountable for reaching their goals. So, **consumers are generally unwilling to pay for this resilience**.

*Source: Ofgem opens investigation into NGET
**Source: 2021 report by the Office for Budget Responsibility
***Source: Ofgem Energy consumer outcomes: research

Why do we need resilience?

The need for resilience in the GB system is driven by its growing dependence on electricity

Why the growing system need?

Western Europe, including GB, has generally enjoyed a highly resilient grid compared with other regions. As the energy system evolves, we are increasingly tapping into abundant domestic renewable resources that offer long-term cost stability, improved energy security, and lower environmental impact. At the same time, this shift brings with it new technical considerations for a grid historically designed around centralised thermal generation, including intermittent renewable generation from wind and solar, as well as less dispatchable thermal plant and inertia:

- Traditional thermal units use large synchronous machines that naturally provide rotational inertia, the kinetic “buffer” that slows frequency changes after a disturbance.
- Most modern wind and solar plants connect through power electronics and, without specific controls, contribute little or no inherent inertia.

Why the growing consumer need?

Just as the supply side is facing challenges, so the **demand side** is becoming increasingly dependent on electrification both to serve new demands and to replace conventional energy sources in:

Mobility: The shift to EVs is accelerating, from private cars and public transport to commercial fleets. This increases overall electricity demand and creates local peak-load pressures.

Heating: Electrification of heat through technologies such as heat pumps, electric boilers, and district heating networks. This not only increases overall electricity consumption but also changes demand patterns, particularly in colder seasons.

Home working: The widespread adoption of remote working and digital technologies has made households small hubs of energy use. This has shifted electricity use from offices to homes throughout the day. Combined with household electrification this increases pressure on local distribution networks.

Natural disasters

The growing need is compounded by the increased frequency and intensity of extreme weather events caused by human-caused rise in greenhouse gases*; microgrids have historically provided a degree of resilience against these.

In addition to natural disasters, the increasing development of marginal sites (such as flood plains and beachfronts) has certainly resulted in increasing losses, the so-called “growing bullseye” effect of:

- Wildfires
- Tsunami
- Hurricanes
- Floods
- Earthquakes

In California, pre-emptive measures intended to prevent wildfires have resulted in significant economic losses from grid outages.

Driven by wildfire risks, public safety power shutoff events affected more than 1 million consumers in California in 2019, with an estimated economic loss of ~$2 billion.

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* The Intergovernmental Panel on Climate Change (IPCC)’s Sixth Assessment Report explores the causes of the increased frequency in extreme weather events.

The definition of resilience

We have taken a broader definition of resilience, to include reliability (& operational performance), societal resilience and economic resilience, as well as technical resilience.

The conventional definition for grid resilience is narrower, referring to the ability of the system to withstand shocks and stresses and quickly recover from disruptive events. Traditionally, resilience is defined in purely technical terms, for example as "*the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event*".

For this report, we have broadened the concept for grid resilience to include operational resilience, societal resilience and economic resilience. This gives a more comprehensive view of the types of resilience challenges faced by the energy system today.

As society becomes more dependent on electricity, resilience becomes more important to daily lives and the overall economy.

In parallel the energy system is becoming more complex with an increasing share of intermittent generation and consequently less conventional thermal generation, increasing the vulnerability of the system and the need for resilience.

Components of grid resilience

Technical resilience
The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event. The emphasis is on high-impact, low frequency events

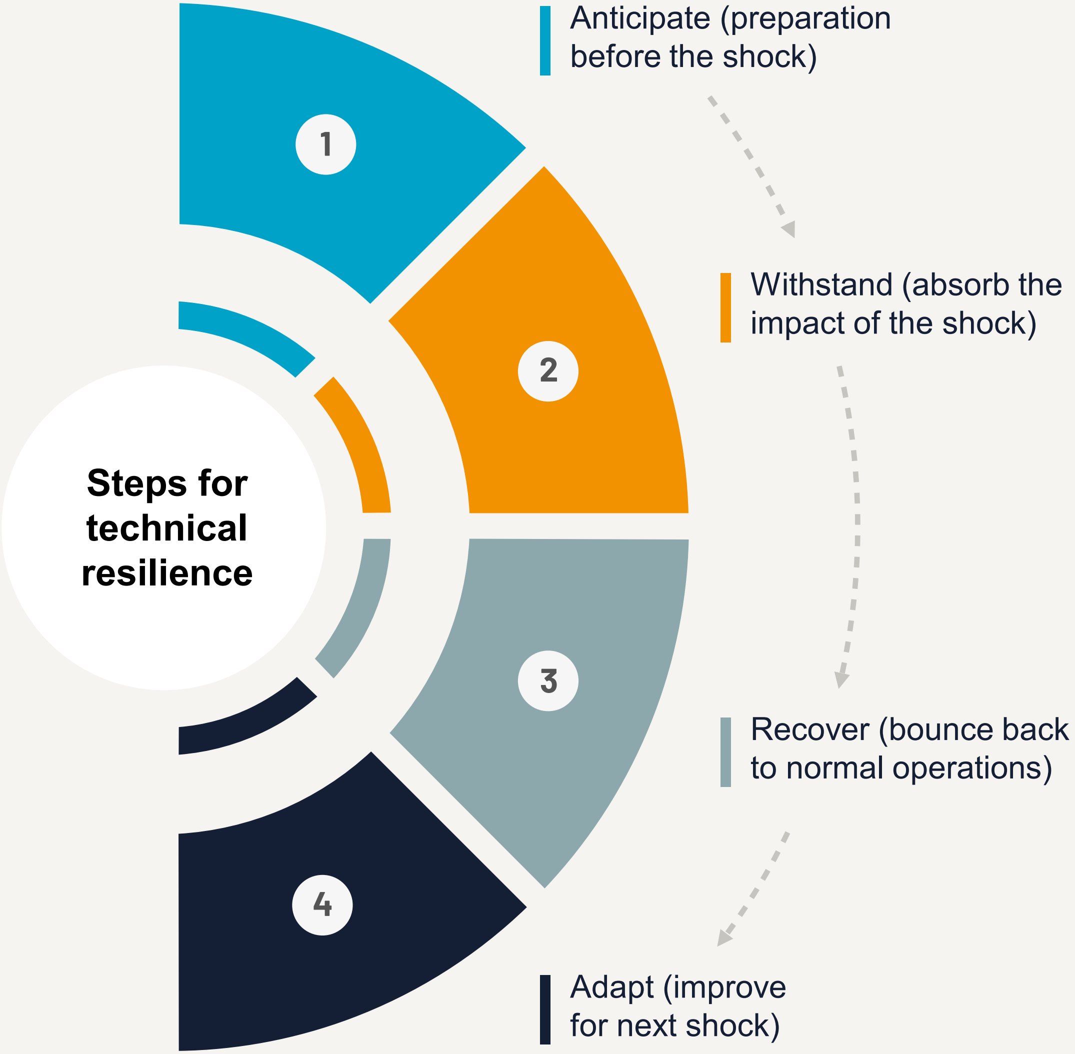
Societal resilience
The protection of consumers and communities, particularly vulnerable groups, ensuring equitable outcomes during disruptions

Operational resilience
Maintaining and avoiding failure of supply of the system under normal operating conditions. This includes reliability, operational performance such as power quality, and performance optimisation.

Economic resilience
Strategic planning of the energy system to deliver energy economically despite financial shocks (e.g., fuel price spikes, infrastructure failures).

The definition of resilience

Technical resilience



Steps for technical resilience

Anticipate (preparation before the shock)

Withstand (absorb the impact of the shock)

Recover (bounce back to normal operations)

Adapt (improve for next shock)

Technical resilience is the ability of the system to prepare for, operate through, recover as quickly as possible, and adapt from high-impact, low frequency events

Technical resilience has been defined by various organisations in closely related ways focusing on high-impact disturbances. For example, the U.S. Federal Energy Regulatory Commission proposed defining resilience as *"the ability to withstand and reduce the magnitude and/or duration of disruptive events, including the capability to anticipate, absorb, adapt to, and/or rapidly recover from such events"*.

Core to all definitions is the idea of absorbing shocks and bouncing back quickly. The emphasis is often on high-impact, low-frequency events, including extreme weather events, cyber attacks or blackouts that are infrequent but lead to major consequences.

In the GB context, the Cabinet Office defines resilience as:

> *"The ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event"*
>
> **Cabinet office definition of resilience**

The definition of resilience

Technical resilience - examples

Earthquakes

Both direct impact of earthquakes and the secondary effect of tsunami can be devastating. In the case of the Great Eastern Japan earthquake in March 2011, the most severe effects were caused by the tsunami on coastal areas.

However, the indirect effect of the failure of the Fukushima nuclear power station had catastrophic effects on the environment. The precautionary shut down of Japan's entire nuclear fleet subsequently had a severe and long-lasting impact on the entire country.

Ukraine cyber attack

In December 2015, three electricity distribution companies in Ukraine were the target of a coordinated cyber-attack that led to power cuts for around 225,000 consumers. It is widely considered the first confirmed case where a cyber-attack directly caused a power outage.

The series of events for the attack were:

- Attackers entered through simple phishing emails sent to staff.
- They spent months inside the IT network without being detected, eventually reaching the systems that remotely control substations.
- On the day of the attack, they used stolen credentials to open circuit breakers and switch off power.
- They also wiped computers, disabled communications equipment, and disrupted call centres to slow the response.
- Engineers restored supply manually within hours, but digital systems took longer to rebuild.

Hurricanes

Superstorm Sandy made landfall near Atlantic City, New Jersey as a post-tropical cyclone on October 29, 2012 .

A storm surge of 12.65 feet hit New York City causing flooding across the state. In all, the storm damaged 650,000 homes and knocked out power for 8.5 million consumers.

The storm caused an estimated $65 billion in damages and 159 deaths, where 50 of those were attributed to power outages alone.

The definition of resilience

Operational resilience

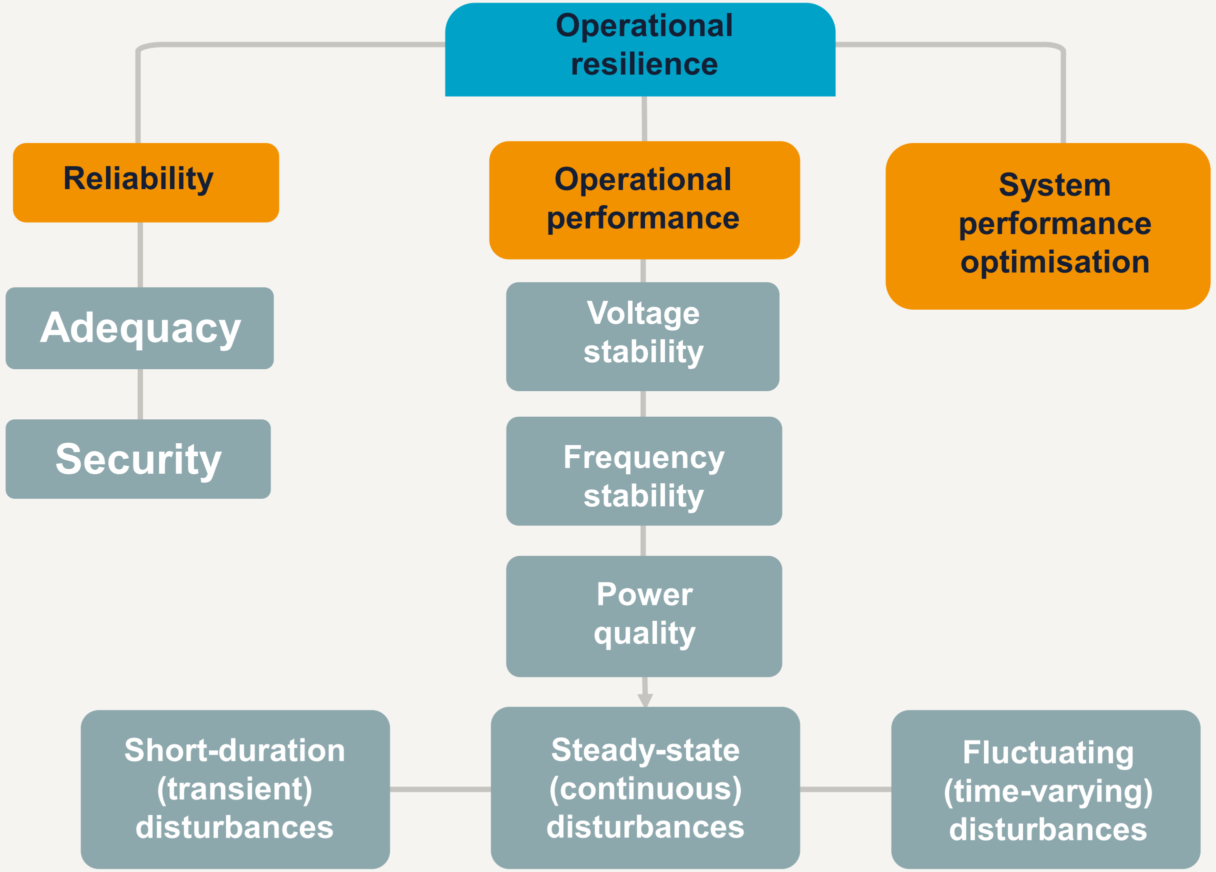
Operational resilience is defined as the ability to maintain supply of the system under normal operating conditions

Traditional **reliability** typically covers two aspects: adequacy (having sufficient resources to meet demand) and security (the ability to handle contingencies without uncontrolled outages).

For the purposes of this report, the definition of operational resilience also includes operational performance and system performance optimisation in addition to traditional reliability.

- **System adequacy** ensures there are sufficient resources to meet demand. Without sufficient generation and network capacity, even a mild stress can lead to outages.
- **Operational performance** is about how clean and stable the supply is even under load changes or disturbances. This includes frequency stability, voltage stability and the handling of power quality issues such as harmonic distortion or transient surges.
  - Power quality issues can be split into three types: steady state (including voltage deviations, unbalance and harmonics), short duration (transients, interruptions) and fluctuating (flicker).
- **Performance optimisation** means that resilience (avoidance of outages) is not achieved solely by brute-force redundancy, but also by smart operation and efficient use of resources. Modern grids use advanced monitoring, automation, and analytics to optimise their performance.

Components of operational resilience



Reliability vs resilience

Reliability is how well the network performs during *normal* conditions.
Resilience is how well the network copes with *unexpected or extreme* events.
In this report, reliability is treated as part of operational resilience, and reliability metrics are often used to benchmark overall resilience

The definition of resilience

Operational resilience - examples

Reliability

Two metrics are frequently used to measure reliability, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). Based on these, **Singapore's** power system is the most reliable in the world.

SAIDI	0.13 – 0.26 minutes per year over 2021 to 2025
SAIFI	0.006 – 0.008 per year over 2021 to 2025

By contrast, many African countries do not consistently enforce SAIDI / SAIFI limits. In **Kenya**, the reliability is much lower with SAIDI reported in hours rather than minutes. Both SAIDI and SAIFI do not meet the target set by the Energy & Petroleum Regulatory Authority.

SAIDI	9.42 hours for year ended June 2025
SAIFI	3.67 for year ended June 2025

Operational performance

The recent blackout in the Iberian Peninsula (**Spain** and **Portugal**) demonstrates an operational performance failure.

The blackout was *triggered* by a short circuit on a 400 kV transmission line in the Basque region.

The main issue was an **overvoltage** event (a deviation from normal voltage levels, a power quality issue) that created a positive feedback loop, worsened by weak grid stability and limited fast-response flexibility.

At the time of the event, wind generation had already been curtailed, and gas plants were running near full capacity, limiting the system's ability to react quickly.

System performance optimisation

In **Great Britain**, the Demand Flexibility Service (DFS) is a notable example of system performance optimisation aiming to keep demand peaks lower in winter 2022/23 and 2023/24. National Grid ESO paid homes and businesses to shift or reduce demand during peak consumption periods.

- In winter 2022/23, 1.6 million homes and businesses actively participated. By winter 2023/24, this grew to 2.6 million subscribed meters.
- Total demand reduction increased from 3.3 GWh across all events in winter 2022/23 to 3.7 GWh in winter 2023/24.
- Payments for delivery rose from approximately £11.1 million in winter 2022/23 to about £11.9 million in winter 2023/24.

The definition of resilience

Societal resilience

Societal resilience addresses fairness so that the most at-risk consumers are not disproportionately harmed by disruptions

Societal resilience is aimed at protecting people and communities, especially those who are most vulnerable, during energy system shocks.

- It goes beyond conventional resilience to consider the impact on people ensuring that critical services and vulnerable consumers are protected during outages.
- It also ensures that all consumer groups can participate in and benefit from resilience measures.

Vulnerable consumers can include definitions with both socio-economic and energy-specific criteria. This can include, but is not limited to groups such as:

- Consumers who are medically dependent on electricity.
- Elderly consumers.
- Consumers living with a disability.
- Low-income households and those in fuel poverty.

Societal resilience is just as important: if disruptions disproportionately impact vulnerable consumers, resilience goes beyond a technical issue and becomes a social issue.

Expanding on vulnerable groups

- Vulnerable consumers often have fewer buffers (economic, social, technological). For example, if a consumer is already struggling with heating costs, a prolonged outage may push them into serious difficulties. Safeguarding against this reduces systematic risks like health impacts and community disruption
- Households relying on electricity for medical equipment, life support or those who face higher risk during outages are recognised, and resilience would ensure networks prioritise support for these consumers.
- If the energy system disproportionately affects the vulnerable, public confidence will erode, making further engagement in the energy transition more challenging.

Societal resilience in Great Britain

In Great Britain, societal resilience is seen as a critical issue and network companies regulated by Ofgem have obligations for vulnerable consumers. This includes keeping a Priority Services Register (PSR) of those who are classed as vulnerable.

The ENA Energy Networks Innovation Strategy explicitly lists supporting consumers in vulnerable situations as one of six key themes.

- This led to coordinated efforts including data-sharing improvements. For example, when a vulnerable consumer moves home or their situation changes, all relevant utilities will be notified.
- The ENA and DNOs collaborate with health services to identify consumers who are reliant on medical equipment.

The definition of resilience

Societal resilience - example

Prepayment meters

Between 2022 and 2023, energy suppliers in **Great Britain** failed to meet regulations when they installed prepayment meters to recover debt without receiving household permission. This was especially harmful for vulnerable consumers.

Prepayment meters can expose vulnerable households to self-disconnection if they cannot afford top ups meaning they may lose heating and power.

This was a **fairness breach** as vulnerable consumers were disproportionately impacted.

Actions taken by Ofgem

+£5.6M	Paid by energy suppliers in compensation to 40,000 affected consumers
+£13M	Debt written off by energy suppliers for affected consumers in this period
+£55M	Financial support provided directly to affected consumers by energy suppliers prior to Ofgem's review

Fuel vouchers

In **Great Britain,** since 2018, the Energy Redress Scheme is operated and managed by the Energy Saving Trust on behalf of Ofgem.

The scheme was set up to collect voluntary redress payments from energy companies who have breached their licence conditions or other regulatory obligations.

- These payments are redistributed to benefit consumers, especially vulnerable consumers.

The Energy Redress Scheme includes a Fuel Voucher Fund, distributing vouchers to vulnerable consumers on pre-payment meters and at risk of self-disconnection across Great Britain.

+£7.8M	Distributed in fuel vouchers up to September 2024.
+134K	Distinct households received fuel -vouchers up to September 2024.

This scheme recognises some households are disproportionately at risk and provides societal resilience.

Breached obligations

In **Australia**, one of the largest energy suppliers breached obligations designed to protect vulnerable consumers on multiple occasions.

In 2024, the Federal Court ordered penalties of AUD $12 million for breaches to its life-support obligations on more than 5,000 occasions.

In 2025, the company was ordered to pay AUD $17.6 million after breaches to energy rules. This included failing to provide adequate support to 6,806 consumers experiencing payment difficulty.

When consumers who rely on life-support equipment are disconnected or not properly registered, the risk of serious harm increases.

The definition of resilience

Economic resilience

Economic resilience refers to the strategic planning of the energy system to withstand financial shocks or stresses

Economic resilience includes maintaining affordability for consumers in the face of volatile fuel prices or unforeseen costs, ensuring network companies remain financially healthy (so they can invest in infrastructure), and having robust supply chains and workforce arrangements to deliver projects on time and on budget.

- It also covers how the market and regulatory mechanisms handle extreme events. For example, whether a global gas price spike or failure of a major contractor develops into unrecoverable costs, extreme delays or critical service failures.

Economic resilience is avoiding scenarios where a lack of financial resilience would undermine the physical resistance of the system. If companies are bankrupted or cannot fund necessary repairs, or if consumers face excessively high energy bills leading to a crisis, the grid's resilience would be at risk.

RIIO is a regulatory price-control framework used by the regulator Ofgem to set how much network companies (electricity transmission, distribution, gas distribution, etc) in Great Britain can earn from customers. Its name stands for *Revenue = Incentives + Innovation + Outputs.*

Ofgem's RIIO framework

Lessons learnt from recent energy supplier collapses (such as Tomato Energy and Rebel Energy) in the retail market led regulators wanting to ensure monopoly networks stay afloat and do not require bailouts.

- Energy networks are natural monopolies: they are regulated, non-competitive, and their income is set by Ofgem through price controls.
- However, even though networks were not in financial trouble, the supplier crisis made regulators, government, and investors aware of how expensive a large-scale failure can be.
- As a result, under the RIIO-ED2 and RIIO-T2 price control, Ofgem brought in more explicit requirements to maintain strong financial resilience (e.g., maintaining healthy debt levels to be able to absorb shocks without taxpayer help) and deliver investment for energy networks.

The RIIO-ED3 framework in Great Britain has explicitly discussed financial resilience of network companies, taking account of tight ring-fenced conditions and restrictions on dividend payments if credit metrics fall.

- ED3 highlights the importance of applying a consistent financial resilience requirement across sectors, particularly given the larger investment required for the transformation of the energy system.

Ofgem's monitoring of network operational and capital expenditure also feeds into resilience.

- Under/overspend against allowances can signal efficiency or inefficiency in delivering reliability

The definition of resilience

Economic resilience - example

CfDs and Interconnectors

Contracts for Difference (CfD)

During the gas price shock in 2022-23, Contracts for Difference (CfD)* cushioned bill payers.

When wholesale prices surged above the CfD strike prices, generators paid money back into the scheme, which led to the below

£18 per household Reduction in government funding required under the Energy Price Guarantee in winter 2022-23

Interconnectors

Interconnectors under Ofgem's cap-and-floor regime stabilise revenues and share upside with consumers.

- Great Britain's regulated model sets a minimum ("floor") and maximum ("cap") revenue level over 25 years.
- **Excess revenues above the cap are returned to consumers**, while the floor limits downside in stressed markets. This supports continued operation and investment through financial shocks

Energy supplier failure

In 2021-22, the GB market suffered a wave of energy supplier failures due to weak financial resilience.

29 suppliers failed

The cost for these failures were ultimately socialised by bill-payers

Parliamentary committees and the National Audit Office attributed this to inadequate capitalisation and poor risk management in the energy retail market

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Outcome of the energy supplier failures

As a result of the energy supplier failures, retail market reforms were brought in by Ofgem.

- Minimum capital requirements were introduced.
- Powers to ring-fence consumer credit balances and Renewables Obligations receipts were also introduced so that capital could not be diverted to other business uses.

Over-reliance on Russia

Prior to 2022, Germany was heavily reliant on the Russian pipeline gas for its energy. When supplies were disrupted following the invasion of Ukraine, the country faced a major supply shock risk.

- The government responded by rapidly contracting for Liquid Natural Gas (LNG) terminals (including Wilhelmshaven and Lubmin) and pivoting their supply chains.
- German policy documents emphasise that LNG import capacity, storage, and diversification of supply routes are critical for resilience.

**CfDs apply to specific types of renewable generation and were implemented to encourage the deployment of renewable generation.*

Quantitative and qualitative value of resilience

Quantifying, valuing and monetising resilience

1

Quantifying resilience

How do we benchmark resilience?

These resilience metrics indicate how resilient an energy system is. Performance-based metrics are often used to incentivise network investment on an annual basis.

2

Valuing resilience

What is the cost of resilience?

The value of resilience involves understanding the direct and indirect costs by the service provider (DSO), the consumer and society as a whole.

3

Monetising resilience

What is the monetary incentive for resilience?

Quantifying the monetary impact can act as regulatory incentive and provide rationale for investment.

Quantifying resilience

Quantifying resilience – metrics used

SAIDI and SAIFI are the most widely used indices for resilience

For the benchmarking of resilience, several different performance-based metrics are used to incentivise network investment on an annual basis:

- Customer outage time
  - Average duration
  - Peak duration
  - Cumulative duration
- Load not served (kWh)
- Number of customers affected
- Time to recovery
- Cost of recovery
- Reliability standards (part of system adequacy): Loss of Load Probability (LOLP) / Loss of Load Expectation (LOLE).
  - NESO publishes their LOLE in their winter outlook. Their base case for 2025/26 is less than 0.1 hours.

SAIDI and SAIFI

System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) quantify how long consumers are without electricity during outages. These metrics are well-established and widely reported in industry today.

SAIDI	The sum of the restoration time for each sustained interruption multiplied by the sum of the number of consumers interrupted, divided by the total number of consumers served for the area. This metric is expressed in average minutes per year.
SAIFI	The sum of the number of interrupted consumers for each power outage (greater than three minutes) during a given period, divided by the total number of consumers served for the area. This metric is expressed in the average number of outages per year.

Lower SAIDI and SAIFI values show greater reliability and therefore higher operational resilience

Great Britain

- SAIDI is reported as *Customer Minutes Lost (CML),* which measures the average minutes lost per customer due to outages lasting more than three minutes.
- SAIFI is reported as *Customer interruptions (CI),* which measures the average number of interruptions per 100 customers longer than three minutes.

Compared to other European countries, Great Britain performs strongly, ranking in the top 10 for both planned and unplanned outages**, including 2nd for planned SAIFI and 3rd for planned SAIDI.

Perceived value metrics

- Willingness to Pay (WTP)
  - This is the maximum amount a consumer would be willing to pay to avoid an electricity outage.
- Willingness to Accept (WTA)
  - This is the minimum amount a consumer would require as compensation to accept an outage.

**This can vary by country, but within Europe, it is typically three minutes. This includes Great Britain. **based on a 2022 report from the Council of European Energy Regulators (CEER)*

Quantifying resilience

Resilience metrics – examples of consequence categories

Direct consequence	*Resilience metric*
Electrical service	Cumulative customer-hours of outages Cumulative customer energy demand not served Average number (or percentage) of customers experiencing outage during a specified time period
Critical electrical service	Cumulative critical customer-hours of outages Critical customer energy demand not served Average number (or percentage) of critical loads that experience an outage
Restoration	Time to recovery Cost of recovery
Monetary	Loss of utility revenue Cost of grid damages (e.g. repair or replace lines, transformers) Cost of recovery Avoided outage cost

Indirect consequence	*Resilience metric*
Community function	Critical services without power (e.g., hospitals, fire stations, police stations) Critical services without power for more than N hours (e.g., N > hours of back up fuel requirement)
Monetary	Loss of assets and perishables Business interruption costs Impact on Gross Municipal Product (GMP) or Gross Regional Product (GRP)
Other critical assets	Key production facilities without power Key military facilities without power

The value of resilience

Economic value is attributed to resilience split between DNO and consumer perspective

DNO investment decisions regarding resilience must consider both the costs and respective values of the technological solution

There is a growing need for resilience and a growing value in providing it. However, it is challenging to attribute a precise value to resilience per se as it varies on the application:

- Some values are tangible, others perceived
- Different applications have different values
- Different countries perceive value differently

But investment decisions require an understanding of both the costs of implementing a solution and the resulting benefits. Benefits may include the avoidance of penalties as well as rewards and improved operational value:

- Regulatory penalties
- Symmetrical regulatory rewards
- Compensation payments to consumers
- Reduced OPEX

**Source: https://www.ofgem.gov.uk/sites/default/files/2025-04/Consumer_Standards_24-7_Metering_Support_Impact_Assessment.pdf*

Residential Value of Lost Load (VoLL)

Residential consumers attribute a perceived value to lost load, and sometimes tangible values:

- Critical consumers on vulnerable connection
- Remote consumers on vulnerable connection
- Perceived value, Willingness-to-accept (WTA) or Willingness-to-pay (WTP).
    - In Great Britain, the most recent WTA value used by Ofgem in 2025 is £26.47 / kWh*
- The value of VoLL varies significantly depending on the consumer groupings, outage attributes such as duration, frequency, time and season, societal / regional factors, valuation method

Non-residential values

Industry and critical infrastructure deliver financial value in many ways, for example by avoiding production losses, equipment damage, safety risks, and reputational harm.

- Business critical functions: data centres, industrial process, food storage
- Life critical infrastructure: operating theatre, intensive care
- Other critical infrastructure: military, transport, emergency services
- Literature reviews by Electricity North West in GB (2016) and Energiforsk in Sweden (2021) find that VoLL range from a few €/kWh to as much as €250/kWh

The value of resilience

The Value of Loss Load (VoLL)

VoLL depends heavily on the methodology used to calculate it

Reported VoLL figures often include:

- Customer category
- Outage duration (e.g., 1 hour)
- Season (e.g., winter)
- Peak or off-peak (or morning, afternoon, evening).
- Whether there was prior warning of the outage
- Region specific

As dependence on a single vector (e.g., electricity) grows then so will its perceived VoLL. There are also a range of methods for calculating the VoLL that consider different aspects.

- VoLL heavily depends on methodology used.
- Capturing all costs from industrial outages (including lost product, spoilage, restart costs, etc), VoLL for industry tends to be higher than for households.
- The true outage cost in industry is often underestimated.

01	**Surveys**	Customers report their willingness to pay to avoid or willingness to accept compensation for outages. There are separate surveys for residential, SME and C&I groups.
02	**Cost-based proxies**	Infer outage costs based on observed behaviour or market choices, including cost of backup systems, lost sales, spoilage, or operational data. This is more reliable for C&I compared to residential.
03	**Macroeconomic output**	Economic output loss calculated using industry Gross Value Added / Value Added per Revenue per MWh not served. Focus on C&I.
04	**Meta-analysis**	Combines multiple existing studies to derive cost functions by customer class, duration, notice and seasonality. There are typically steeper cost gradients for C&I with duration and timing.
05	**Administrative parameter**	Market operators or regulators set a VoLL parameter (often a cap or scarcity price in markets) drawing on the other methods together with policy judgement.
06	**Hybrid approach**	A new integrated assessment combining multiple estimation methods such as survey-based VoLL with macroeconomic (value added calculations) and sometimes cost-based proxies to narrow results and address uncertainty.

The value of resilience

Valuing resilience from the perspective of industrial customers

The impact of outages varies by application and perceived value by region; avoiding outages can be worth more than €250/kWh to select commercial customers

There are multiple ways to examine the VoLL for industrial and commercial customers. Typically, cost-based proxies and macroeconomic output are used to calculate a willingness-to-accept that is framed for businesses.

For industrial and commercial sectors, the value of resilience typically ranges from a few €/kWh to as much as €250/kWh.

- The values shown on the right are for the peak values, although in some cases the value can be relatively low or even zero, depending on the criticality of the process affected.

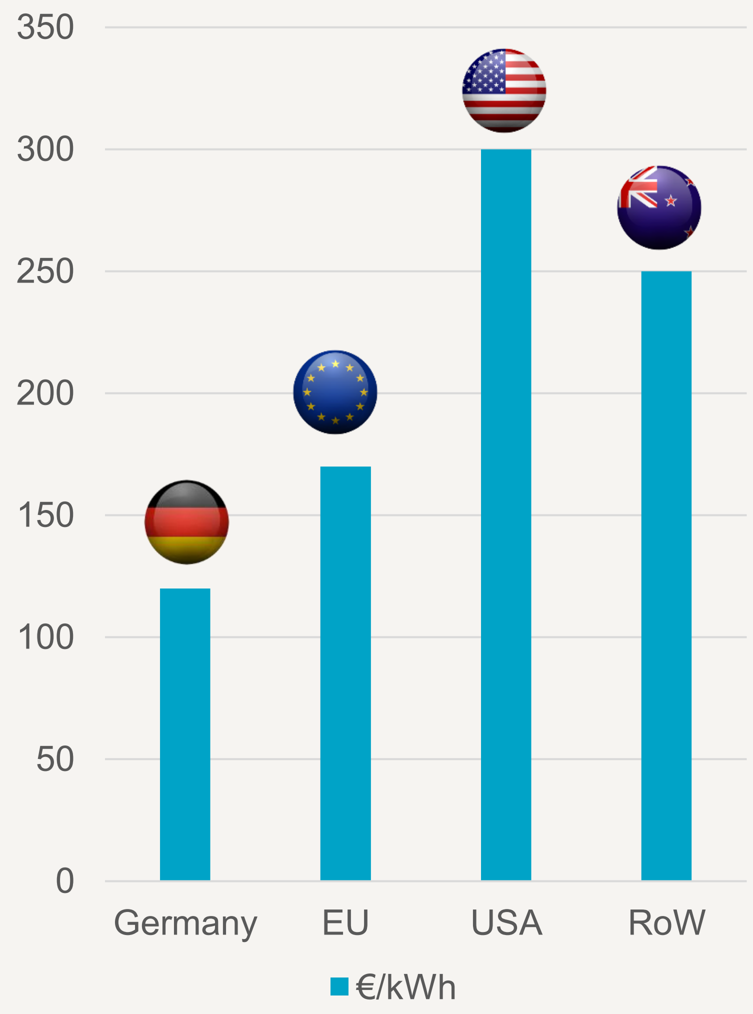
Studies in the US (2009) and New Zealand (2013), found VoLL could even exceed €250/kWh for outage-sensitive sectors like continuous process manufacturing, food processing, and finance, where downtime quickly leads to major economic losses

Industrial VoLL varies across countries, sectors and analyses because of many factors.

- **Real industrial costs differ**. Different processes, shutdown costs etc
- **Outage scenarios differ**. Studies use different assumptions for duration timing, notice, frequency of outages.
- **Customer segmentation differs**. Industrial can mean anything from heavy chemicals to small workshops.
- **Methods and assumptions differ**. This includes different treatments of non-market costs.
- **Country specific context and regulation**. National income, industrial structure and regulatory preferences.

Value of Lost Load (VoLL) for industrial customers is attributable to quantifiable business costs and is typically significantly higher than for residential.

C&I VoLL in different regions



The value of resilience

Data centres

Business disruption, lost revenue and end-user productivity are major economic impacts of an outage for data centres

Data centres' operation underpins essential digital services (the cloud, payments, logistics, public services, etc) and increasingly, AI training and inference, which run 24/7 and have very low tolerance for interruptions.

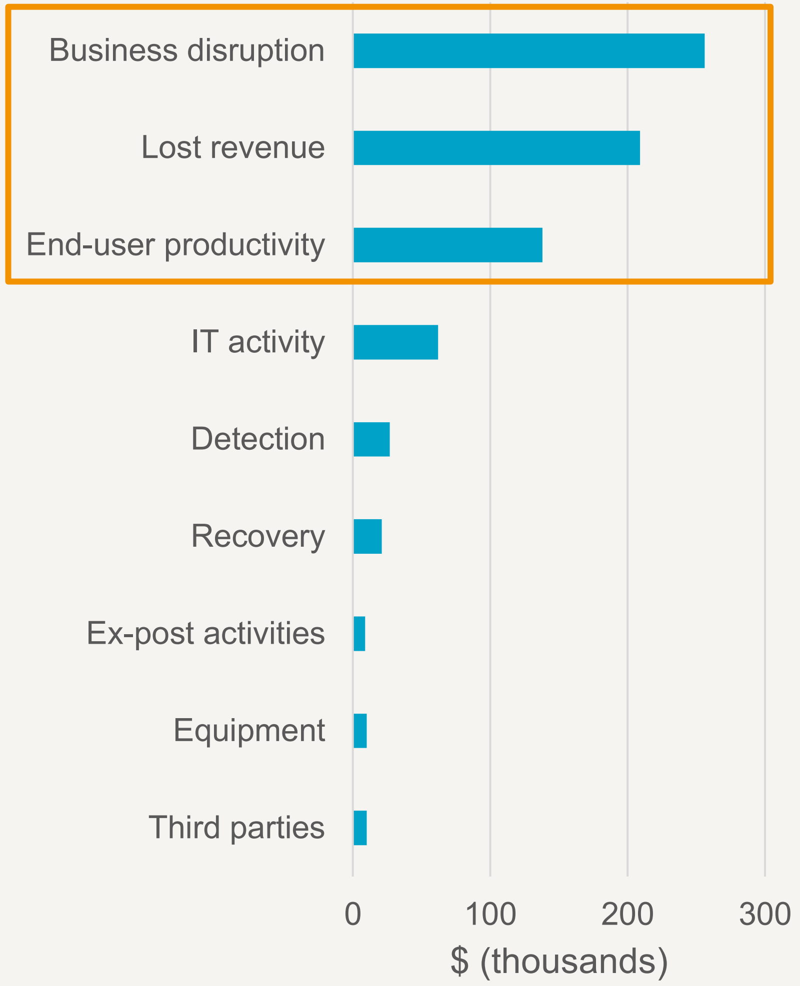
In GB, NESO's "Ten Year Forecasts" in the Future Energy Scenarios 2025 predict that demand from data centres will grow from 7.7 TWh in 2024 to 20.1 TWh in 2030, representing a ~2.5x increase.

While published in 2016, analysis of U.S. data centres* indicates a break down of the outage costs:

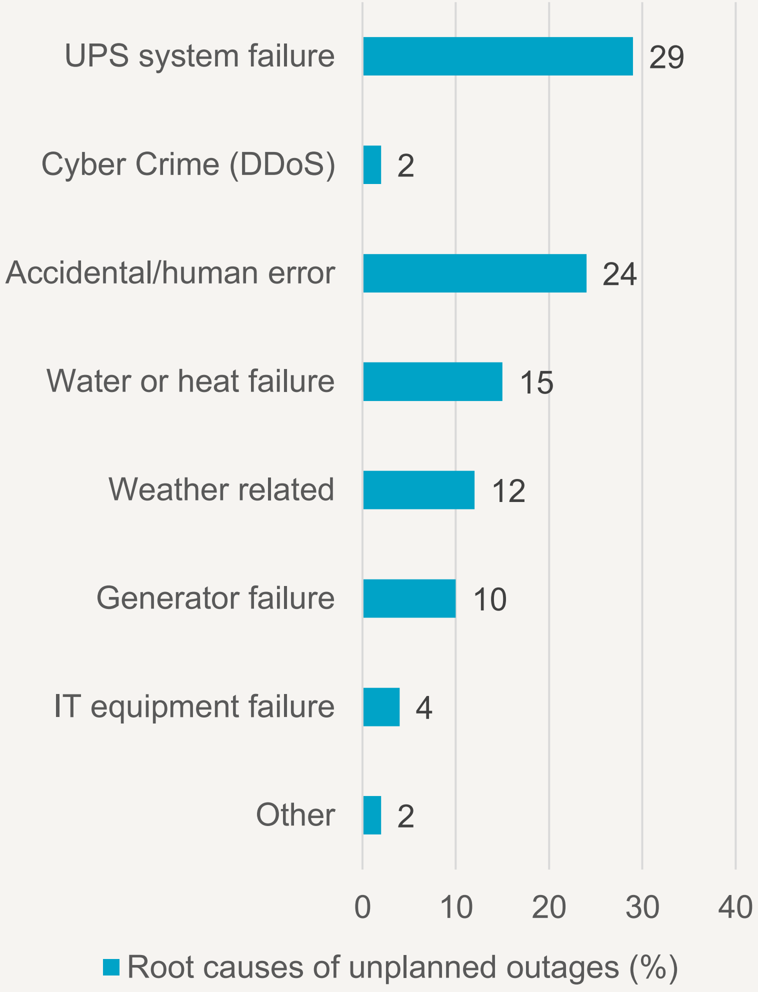
- Direct costs (cash expenses for recovery): 36%
- Indirect costs (time, effort, and internal resources): 51%
- Opportunity costs (lost business from reputational damage): 13%

More recent analysis from 2024 shows that while outage frequency has declined, costs per incident have increased, with over half of outages exceeding $100k, and over 16% exceed $1 million. The cost structure remains unchanged.

Breakdown of unplanned outage costs by category*



Root causes of unplanned outages*



*from Ponemon Institute. (2016, January). Cost of Data Center Outages. Sponsored by Emerson Network Power.

The value of resilience

Valuing resilience from the perspective of residential consumers

The value of resilience to residential consumers depends on their perception of value. There is little tangible value or loss.

For residential consumers, there are two main ways that consumers perceive value:

- Willingness to pay (WTP): the maximum amount a consumer would be willing to pay to avoid an electricity outage.
- Willingness to accept (WTA): the minimum amount a consumer would require as compensation to accept an outage.

In practice, WTA is often higher than WTP. In Ofgem research from 2013, a WTA estimate for domestic users during winter peak at the weekend is £11.82/kWh compared to a WTP estimate of ~£1.65/kWh. This is roughly a seven-fold difference.

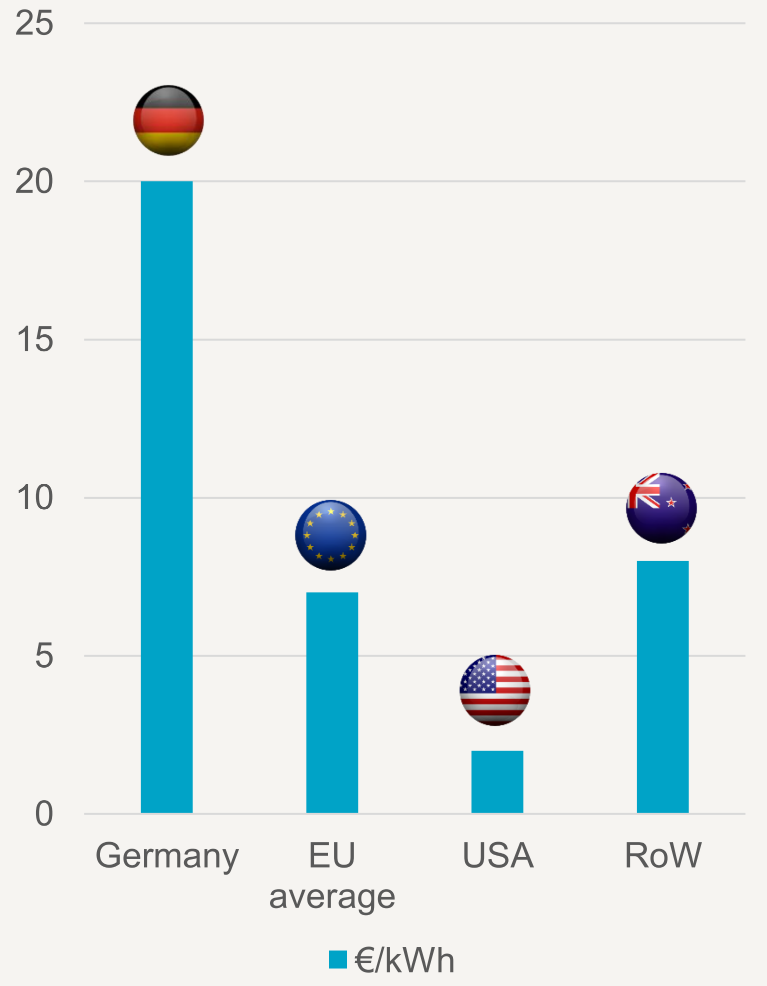
- When it comes to energy supply, consumers expect the grid to be resilient and therefore believe they should be compensated for outages (WTA) but are unwilling to pay as much for it (WTP).

For residential consumers, the values range from a few £/kWh up to about £40/kWh. Structural differences, such as country-specific, time of year, differences in income, may provide an explanation. The residential Value of Lost Load (VoLL) tends to be lower than for industrial and commercial VoLL, although this varies based on the I&C segment.

The value of VoLL also has a cultural element with different values even between EU states.

+ *£17 / kWh*	Headline load-weighted average VoLL value (WTA) from Ofgem's 2013 research for domestic and small-to-medium business consumers during peak winter workdays
+ *£21 / kWh*	Value of VoLL in current price control period RIIO-ED2 (April 2023 to March 2028). This is Ofgem's 2013 research adjusted by inflation.
+ *£26.47 / kWh*	Value of VoLL in a 2025 impact assessment study from Ofgem, also based on Ofgem's 2013 research and a **65% increase** over the original £17/kWh.

Average VoLL in different regions



The value of resilience

Reasons for the difference between Willingness-to-accept (WTA) and Willingness-to-pay (WTP)

Income / budget constraints

Willingness-to-pay (WTP) is limited by what consumers can afford or expect to pay. On the other hand, Willingness-to-accept (WTA) is a hypothetical compensation number, less bounded by immediate budget constraints. This tends to widen the gap between WTP and WTA.

Loss aversion

Consumers fear losing something, such as their electricity service, more than they value gaining the same service. So, WTA, which asks consumers about “giving up” a service, tends to be higher than WTP, which asks about “paying to avoid losing”.

Substitutability

If there are few good substitutes for the good, for example having uninterrupted electricity supply during a peak winter period, then the compensation required for loss might be high because the consumer anticipates higher cost or difficulty of replacement.

Survey framing

Estimated the VoLL through stated preference methods is sensitive to how questions are asked, to the respondents’ perception of the scenario, the compensation, and consumers sense of ownership or entitlement. WTP estimates have a well-documented downward bias due to “entitlement”.

When consumers are asked how much they might pay to avoid an outage, they may think about income, budget and say a more modest number. Whereas when asked how much compensation they would require in the event of an outage, they inflate the number, thinking about how bad it would be.

In studies such as Ofgem’s VoLL research, the results are used to inform security of supply policy including feeding into how much capacity they should hold to avoid outages. In this case consumers may not be willing to pay more to improve a service but when an outage occurs, they may feel that the involuntary disruption is worth some form of payment for the service they provide.

Monetising resilience

DNO perspective

Just as the value of resilience varies depending on the user, there are also a range of economic mechanisms imposed to incentivise appropriate service standards in different markets

Australia

In Australia, the Australian Energy Regulator has a scheme called the Service Target Performance Incentive Scheme (STPIS) for DNOs.

- The scheme is primarily aimed at maintaining and improving service performance and incorporates the reliability metrics SAIDI and SAIFI.
- This is a symmetrical scheme that rewards DNOs for exceeding targets and penalises DNOs for missing targets.

Finland

Finland has a penalty for non-delivered energy.

- The utility pays between 10% and 200% of the annual grid fee as consumer compensation for between 12 and 288 hours of interruption

Duration of outage	**% compensation**
12 – 24 hours	10%
24 – 48 hours	25%
48 – 72 hours	50%
72 – 120 hours	100%
120 – 288 hours	150%
>288 hours (12 days)	200%, (max €2,000)

- Consumers may also claim for damages for other events.
- There are exceptions for exceptional circumstances, such as storms.

Great Britain

Great Britain operates on a compensation basis for power outages. Ofgem monitors and enforces this. Under normal conditions, consumers receive automatic payments if outages exceed set thresholds:

- For example, £95 for each consumer if <5,000 households are without power for more than 12 hours
- For more than four power cuts in a year (each of more than three hours), consumers can claim an additional £95.

For severe weather condition outages, compensation is dependent on the category of storm and duration of the event.

- Initial payments are £85 with an additional £45 every 6 hours, up to a maximum £2,165.

Under the Interruptions Incentive Scheme as part of Ofgem's RIIO-ED2, the performance of DNOs is measured against targets, including customer interruptions (equivalent to SAIFI) and customer minutes lost (equivalent to SAIDI).

- If they outperform, they can be rewarded and if they under-perform, they may be penalised.

> Resilience today means combining hard assets with smart intelligence. Every smart meter installed strengthens the grid, reduces costs, and makes the UK's energy system more sustainable.

2. *Delivering resilience*

Delivering resilience has traditionally meant pouring concrete and laying cables, capital-intensive projects like Ofgem's **£9 billion upgrade** to Britain's high-voltage network, the largest since the 1960s. That investment will add £74 to consumer bills by 2031, but it's expected to save £80 per household by reducing curtailment costs and maximising renewable energy use.

Yet physical infrastructure alone can't keep pace with the demands of a decentralised, electrified grid. Non-infrastructure solutions such as smart meters, digital twins, and flexibility platforms are the game-changers. Smart meters act as a nationwide sensor network, enabling timely fault detection, demand-side flexibility, and predictive maintenance. Without them, we pay the price: in 2025, curtailment cost Great Britain **around £1.9 billion**, a stark reminder that data-driven resilience is cheaper than wasted clean energy.

This section reviews the current approaches to grid resilience and their respective merits and challenges

Overview of current approaches for delivering resilience

In this section we explore 4 core current approaches to grid resilience and their respective merits and shortcomings

Traditional infrastructure investments

Building resilience through physical infrastructure is capital intensive, but essential for capacity growth and long asset life.

Measures to increase resilience of the grid that are applied to **power lines, substations and transformers** include physical hardening of assets, integrating redundancy (alternative route) and fault isolation design, and upgrading or expanding capacity.

Backup generation supports resilience by providing reserve power but face high operating costs and under-utilisation.

Microgrids

Microgrids assist the integration of renewables and offer power resilience by interconnecting DERs which can be operated in isolation from the main grid.

Microgrids can operate in **island-mode** from the wider grid, providing resilience both locally and to the system when the grid fails.

However, microgrids, as a **microcosm of the wider grid**, face the same challenges as the wider grid such as load balancing, managing voltage and frequency stability, managing faults, and cybersecurity.

Non-infrastructure solutions

Non-infrastructure solutions such as network software and digital solutions that provide resilience with near real-time data.

However, Smart Meter Operations Center (SMOC) and Distributed Energy Resource Management System (DERMS) are expensive and data intensive systems.

Operational and System processes that provide resilience include curtailment and flexibility services. Curtailment cost GB almost £1 billion last year, a high price to pay for inadequate network capacity.

Black Start

Black Start is the ultimate disaster recovery mechanism when there is a total or partial system shutdown or “black out”.

NESO ensures the system can be restored, by dispatching isolated power stations to start individually and gradually reconnect to each other to form an interconnected, restored system.

Large synchronous power plants have traditionally provided Black Start. However, with fewer thermal plants in operation, GB will become increasingly **dependent on inverter-connected assets** for Black Start.

Delivering resilience: Traditional infrastructure investments

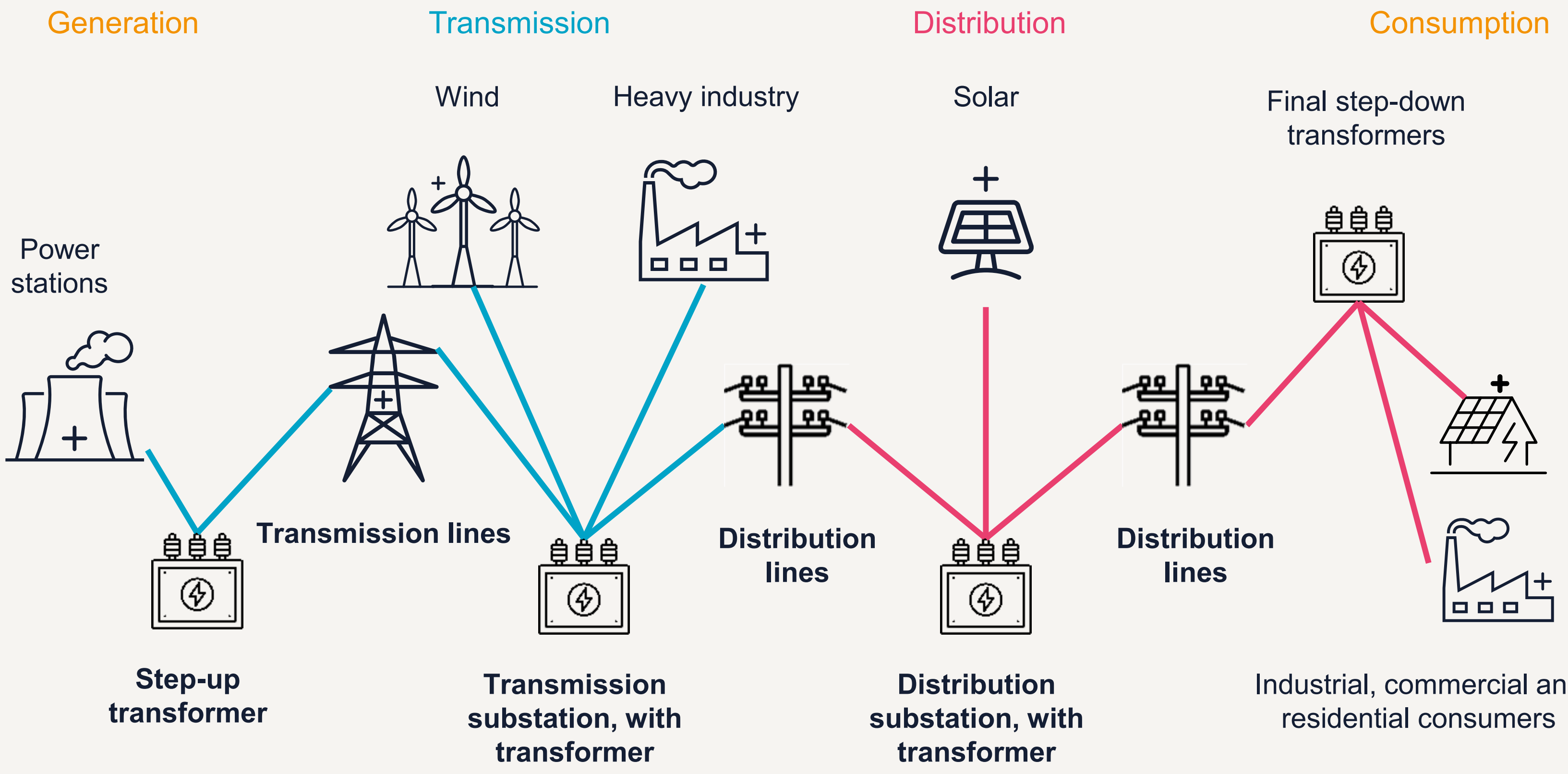
Building resilience through physical infrastructure is capital intensive, but essential for capacity growth and long asset life

Traditional infrastructure investments for resilience are capital-intensive projects focused on physical assets that expand or reinforce the grid

Key components to physical grid infrastructure related to resilience:

- Transmission and distribution Lines
- Substations and transformers
- Backup generation

Illustrative grid components (components in bold are the focus of this section)



Delivering resilience: Traditional infrastructure investments

Building resilience through physical infrastructure is capital intensive, but essential for capacity growth and long asset life

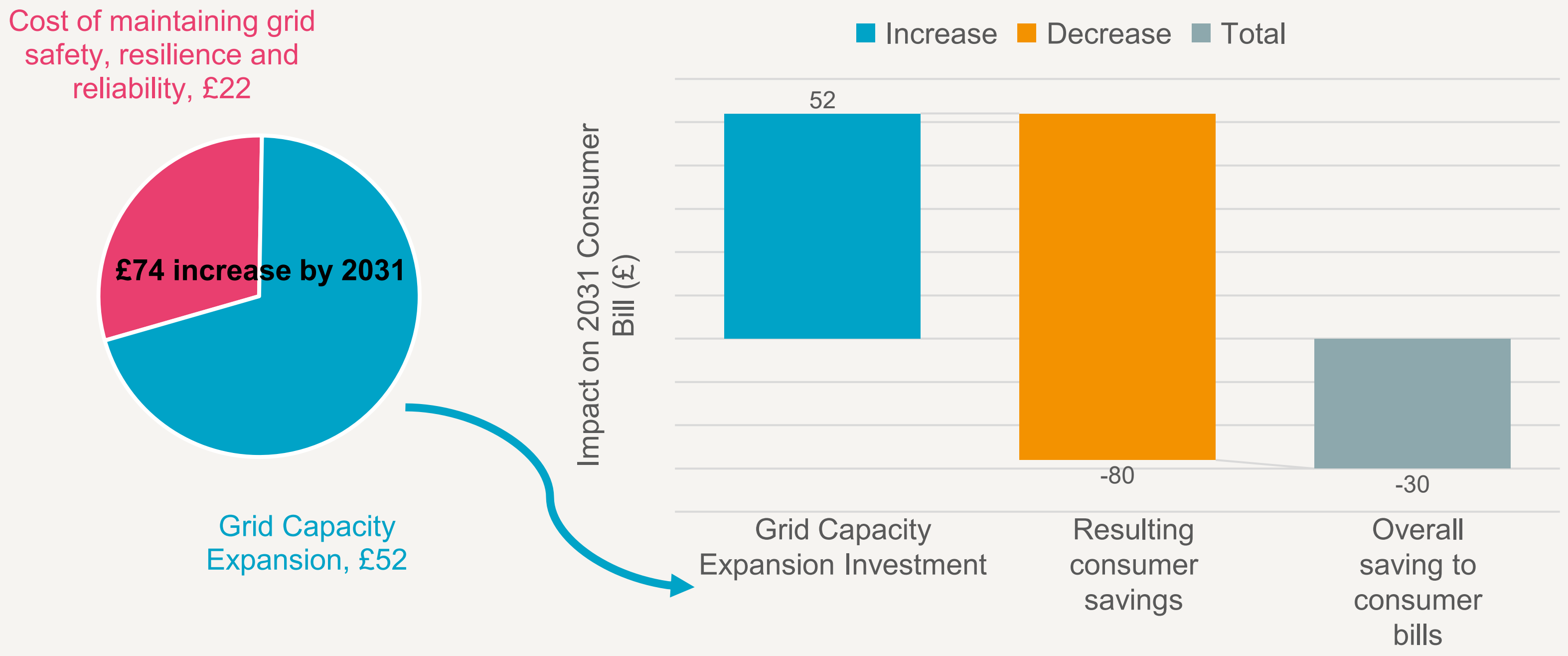
Great Britain

Case study

In July 2025, Ofgem approved a **£9bn investment programme** to upgrade Britain's high-voltage network, **the largest grid expansion since the 1960s.** Ofgem estimate the investment will result in **increased electricity network charges on consumer bills of £74 by 2031,** but this cost is offset by savings.

The grid capacity expansion investment is expected to result in **£80 of savings for consumers by 2031**, by:

1. **Reducing constraint costs** – cutting payments to wind farms that are forced to curtail output because the grid cannot transmit their power.
2. **Maximising renewable energy use** – ensuring clean generation meets demand, reducing reliance on expensive gas-fired plants.



Delivering resilience: Traditional infrastructure investments

Building resilience through physical infrastructure is capital intensive, but essential for capacity growth and long asset life

Transmission and distribution lines

Transmission lines carry electricity from power plants to substations and distribution lines carry it onto homes and businesses. Upgrading lines to boost grid resilience requires significant capital with long permitting and construction timelines:

- **Line hardening** – materials or coatings to improve weather resistance against corrosion, extending asset life and reducing outages.
- **Redundancy lines** – alternative paths to reduce single points of failure. Measures include extra feeders (alternative paths), sectionalised switches (dividing feeders into sections to isolate faults) and reclosers (automatic response after fault detection).
- **Increasing line capacity** – eases congestion and thermal overload. Dynamic line rating sensors like "smart thermometers" allow lines to carry more capacity when safe to (e.g., in cool and windy conditions). Reconductoring is another method, where cables are replaced with advanced materials of higher-capacity.
- **Relocating lines** – undergrounding or elevating lines to protect against extreme weather or flooding.

Substations and transformers

Transformers change voltage levels (steps up or steps down), for efficient power transmission and distribution. Substations house transformers and other equipment to support the same purpose. They form vital grid 'nodes' that manage voltage, direct power and isolate faults.

Infrastructure investments in these grid 'nodes' that deliver resilience include:

- **Equipment upgrades** – power transformers with on-load tap changers, voltage regulators, and capacitor banks are used to maintain voltage.
- **Fault isolation design** – circuit breakers and protective relays limit fault propagation.
- **Physical hardening** – elevating substations above flood levels, adding fire-resistant coatings, and adding seismic reinforcement.
- **Redundancy design** – multiple transformers and feeders exist for back-up, providing improved response during equipment failure.

While expensive, these improvements help prevent outages, allow for faster repairs, and support the growing use of renewable energy.

Backup generation

Backup generation assets provide the reserve power when main generation or the grid fail but can have high operating costs and be under-utilised assets.

Relevant applications that can provide grid resilience include utility-scale generators at substations, front-of-the-meter generators (e.g., community-scale), and microgrid generators. This does not include small residential generators.

Diesel or gas generators and battery storage, are often located at critical facilities and support resilience by:

- **Ramping up in minutes** to stabilise the grid in sudden demand spikes or generation shortfalls.
- **Providing firm capacity** during extreme weather or renewable intermittency.
- **Supplying emergency power.**

Delivering resilience: Microgrids

Microgrids are a microcosm of the wider grid

Microgrids assist the integration of renewables and offer power resilience by interconnecting DERs which can be operated in isolation from the main grid

A microgrid provides resilience when the grid fails

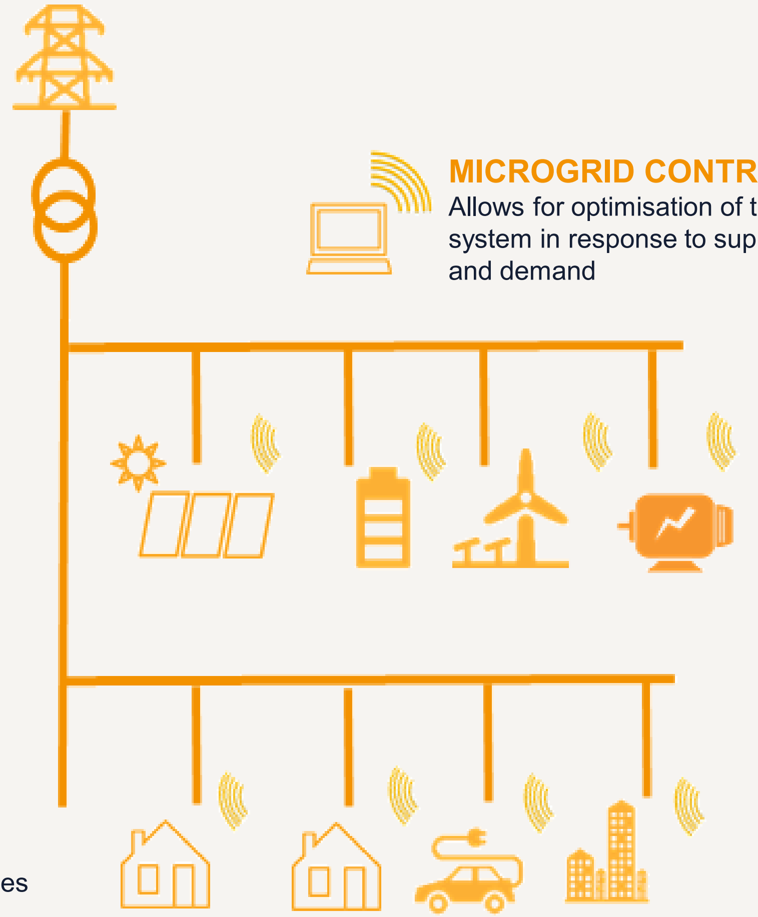
A microgrid is a system of interconnected energy loads and at least two distributed energy resources (DERs) within a clearly defined boundary, and with a single point of coupling to the wider electricity distribution grid.

It can connect and disconnect from the grid to enable it to operate in grid -connected or island-mode. The speed of response to an outage and the duration of islanded operation depend on the intended application and the generation technologies connected to the microgrid.

There are various use cases for microgrids, including industrial and commercial microgrids, utility microgrids, community microgrids, critical infrastructure microgrids (e.g. for hospitals or military bases) and remote or weak grid applications.

While microgrids can operate in island-mode from the wider grid and operate with fewer resources, they face the same challenges as the wider grid such as load balancing, managing voltage and frequency stability, managing faults, and cybersecurity.

Components of a microgrid



POWER GRID
The wider electricity distribution grid

SUBSTATION
A single point of coupling to the wider electricity distribution grid, to connect / disconnect from the grid

MICROGRID CONTROL
Allows for optimisation of the system in response to supply and demand

DISTRIBUTED ENERGY RESOURCES
Generation sources such as renewables (solar PV, onshore wind), firm power sources (gas or diesel generators) or energy storage (Lithium-ion batteries)

CONSUMER LOAD
Connecting the generation sources to the end-consumer

Delivering resilience: Microgrids

How do microgrids deliver resilience? What opportunities are there for smart meters?

Microgrids deliver resilience both locally and to the system

Local resilience

The ability of microgrids to operate in isolation from the main grid protects its users from loss of power and disruptive events that impact the main grid.

System resilience

Microgrids also support the resilience of the wider electricity grid, by:

- **Helping reduce peak load** by locating generators close to point of consumption
- **Acting as a Black Start anchor** in case of an outage
- **Minimising reconnection peaks** via soft synchronisation, staggered load reconnection, energy storage buffering or generator ramp-up control.
- **Disconnecting** users from the main grid when it uses fossil generation and preserve carbon-free power supply for users, without destabilising the main grid.

Smart meters play a vital role in the efficient operation and management of microgrids

Smart meters can benefit microgrids through:

- **Near real-time monitoring and control** – by enabling operators to monitor power quality, detect islanding, and identify inefficiencies to optimise energy flows and control voltage within the microgrid.
- **Enabling demand response** – by receiving demand response (DR) instruction signals from operators (for end-users or automated assets to change demand) and providing accurate measurement of DR event participation for fair compensation
- **Detecting and diagnosing faults** – by enabling operators to identify and respond quickly to issues, preventing outages
- **Helping integrate distributed renewable energy resources** – by providing data on their intermittency and variability, which can contribute valuable data for forecasting
- **Enhancing billing accuracy** – by ensuring more accurate billing with detailed data on consumption.

Great Britain

The **Isle of Skye** is connected to the national electricity grid but also uses microgrids to support communities during power outages.

The SSEN **resilience-as-a-Service (RaaS)** project on the Isle of Skye is trialling a new solution which uses a battery energy storage system with local distributed energy resources to quickly and automatically restore power when a fault occurs on the upstream network.

By temporarily **operating in island mode** during an outage, RaaS will maintain supply to the local community while the DNO repairs the fault or dispatches a diesel generator for a longer-term issue.

The battery can also provide **additional revenue streams** from the provision of flexibility services, **reducing the cost of resilience service.** As the battery is owned by the energy supplier, E.ON, this also avoids challenges around DNO energy storage asset ownership.

Delivering resilience: Non-infrastructure resilience solutions

Network software and digital solutions can provide resilience, but are often complex, expensive and data intensive

Smart Meter Operations Center (SMOC) acts as a command center for operational intelligence

SMOC provides a centralised platform for managing smart meters

- Providing real-time visibility of meter performance and the ability to detect anomalies.
- Aggregating data from Head-End Systems (HES), Meter Data Management Systems (MDMS), billing systems, and grid monitoring systems (SCADA).
- Automating incident response and predictive maintenance using machine learning.

SMOC provides grid resilience by

- Enabling operators to detect overloads and voltage issues, and respond quickly.
- Detecting outages and anomalies in near real -time and automating incident response.
- Supporting predictive maintenance by analysing voltage fluctuations and device health over asset life.

Distributed Energy Resource Management System (DERMS) acts as a command center for DER

DERMS is a digital platform designed to monitor, control, and optimise distributed energy resources (DER)

- Providing near real-time visibility of DER assets across the network
- Helping coordinate DER dispatch to avoid overloads and voltage issues
- Enabling DER to provide ancillary services and supporting DER bidding into energy markets, where allowed

DERMS provides grid stability, congestion management, and voltage control, which is critical during extreme weather or high DER penetration. DERMS supports grid resilience by:

- Sending commands to DER to adjust output or consumption based on grid needs.
- Using algorithms to predict DER availability and optimise their contribution to grid stability.

These technologies help energy companies spot problems faster, keep the lights on during unexpected events, and make better decisions about repairs and upgrades.

Digital Twin can act as a virtual replica of physical network components

A digital twin is a virtual model of the network built from data on cables, transformers, meters, and sensors.

- It allows network operators to simulate scenarios without risking real infrastructure.
- It enables modelling of extreme weather, outage impact analysis, DER and load integration, and cybersecurity events.

Digital twin development can support in providing grid resilience by

- Predicting failure points of the physical asset, reducing asset downtime or failure.
- Improving planning for climate resilience and integration of renewables and DER.

Delivering resilience: Non-infrastructure resilience solutions

Flexibility achieved through operational and system processes also provides resilience to the grid

Curtailment is a flexibility solution that provides resilience, but also signals grid constraints

Curtailment is where the output of a generator (usually renewable) is reduced to maintain system stability. It is a tool network operators use to manage imbalances.

Curtailment supports grid resilience by:

- **Preventing overloading** – by reducing load on equipment during periods of high generation.
- **Maintaining grid stability** – helping balance frequency and voltage when renewables spike.

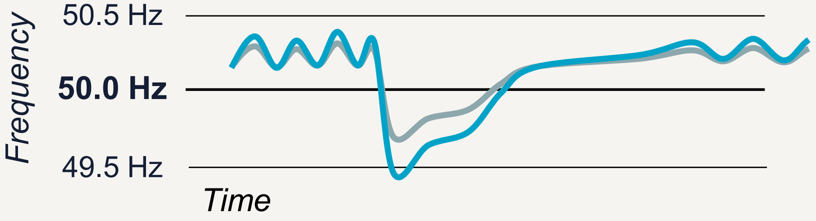
Great Britain

Last year, GB lost close to £1 billion in curtailment compensation payments, a high price to pay for inadequate network capacity.

Curtailment is a live issue in GB due to inadequate capacity at both distribution and transmission levels. This results in wasted clean energy, lost revenues for generators, and inefficient use of assets that sit idle.

Flexibility can support short-term resilience

Flexibility is the ability to **dynamically balance fluctuations in supply and demand** under varying conditions. Frequency reflects the balance between supply and demand. Frequency falls if demand is greater than supply, and rises if supply is greater. NESO is responsible for keeping the frequency within ±1% of 50Hz, illustrated below.



Grid **frequency is becoming more unstable** due to increased renewable generation, which risks damaging equipment or causing blackouts. There is a role for short-term flexibility to balance the grid in real-time to help with short-term issues (i.e., ancillary services, intraday market). Traditionally, flexibility has been sourced from supply side assets. However, **'demand-side' assets are increasingly relied on**. This means decentralised, distributed assets, like batteries or EVs, can respond to grid signals to provide flexibility.

Flexibility can also prevent or delay the need for investment

Flexibility, whether in the form of **load shifting** or provision of **local grid services** by consumers, helps **avoid or defer capital-intensive network reinforcement** by:

- **Lowering peak demand** – by incentivising consumers with dynamic tariffs to shift the time at which they use energy away from peak hours. This reduces the peak load which minimises the need for network reinforcement.
- **Maximising use of existing infrastructure, reducing the cost of generation and grid-scale storage** – by using flexible assets to reduce curtailment of renewables and shifting loads to utilise grid assets outside peak hours.
- **Helping balance the grid and reduce network constraints** – by providing a specific flexibility service to a network operator via a market mechanism.

Based on modelling, the Clean Power 2030 Action Plan finds that flexibility could reduce system costs by up to £70 billion by 2050. (UK GOV)

Delivering Resilience: Black Start

Black Start is the ultimate disaster recovery mechanism when there is a total or partial system shutdown or “black out”

Black Start is the procedure of recovering the National Electricity Transmission System (NETS) from a total or partial outage which has caused an extensive loss of supplies

Black Start, also known as Restoration, is where isolated power stations are started individually and gradually reconnected to each other to form an interconnected system again.

While the event of total or partial shutdown of the NETS is unlikely, NESO is responsible for ensuring the system can be restored following such an event.

NESO contracts with generators and providers for Black Start capability. Providers need to meet three basic requirements for Black Start, including

1. start up independently from external supplies,
2. be able to energise the transmission network,
3. be able to provide block loading of local demand (i.e., gradual reconnection of groups of consumers to the grid).

Black Start is a critical part of system resilience for restoration

Traditionally, Black Start services have been provided by large synchronous power plants, connected at transmission level. As the UK moves away from thermal power plants to cleaner and more decentralised energy, new options for Black Start are being considered.

NESO’s modernisation strategy plans include integrating DER into Black Start, shifting to inverter-connected distribution network assets for Black Start services. However, there are complexities and technical challenges to be overcome.

Smart meters can provide critical support functions that speed up restoration during Black Start.

1. **Rapid fault detection and location** via power outage alert message.
2. **Controlled re-energisation** via randomised offset feature to allow controlled, delayed asset reconnection after an outage.

Great Britain

Distributed ReStart is a £11.7m UK innovation project led by NESO in partnership with industry stakeholders. The goal of the project is to **develop processes and technology to restart the electricity system using distributed energy resources** after total or partial blackout.

Distributed ReStart explores how smaller, distributed assets like onshore wind, solar PV, batteries and demand-side resources can restore power, instead of traditional, large fossil-fuel generators. The project seeks to:

1. demonstrate the **technical feasibility** of DERs to support system restoration,
2. develop **new operational processes** for stakeholders (NESO, DNOs and DER owners),
3. establish **market arrangements and incentives** for DER participation in restoration services,
4. implement **advanced control systems** to manage DER participation safely and efficiently.

Smart meters act as the heartbeat monitor of the grid, turning blind spots into a resilient, data-driven grid.

3. *Dimensioning resilience*

Resilience isn't just about hardening infrastructure, it's about visibility, flexibility, and foresight. Today, network operators still fly partially blind at the low-voltage edge, relying on customer calls to detect faults. Without granular, real-time data, outages linger, vulnerable consumers face greater risk, and investment decisions lean on outdated assumptions.

Smart meters change that. They provide half-hourly consumption data, "last-gasp" outage alerts, and voltage monitoring, creating a nationwide sensing and control fabric. This enables faster fault detection (often 10-15 minutes quicker than traditional methods), targeted restoration, and predictive maintenance.

The opportunity is clear: with around 70% of homes equipped, nearly 30% of Britain remains outside this digital safety net. Closing that gap means moving from reactive fixes to proactive resilience, and thus anticipating risks, optimising investments, and protecting consumers. Every smart meter installed strengthens detection, flexibility, and planning, making resilience not just a concept but a reality.

This section identifies the gaps in current approaches to resilience and the potential role(s) for smart meters in delivering components or addressing gaps. This also notes aspects presenting challenges to smart meters to help in prioritisation of focus areas for further analysis and eventual investment.

Dimensioning resilience

How and where can smart meters support the energy system?

Smart meters in GB

A secure, digital electricity or gas meter that automatically transmits half-hourly consumption data, supports two-way tariff & control commands, and provides near-real-time cost feedback to customers.

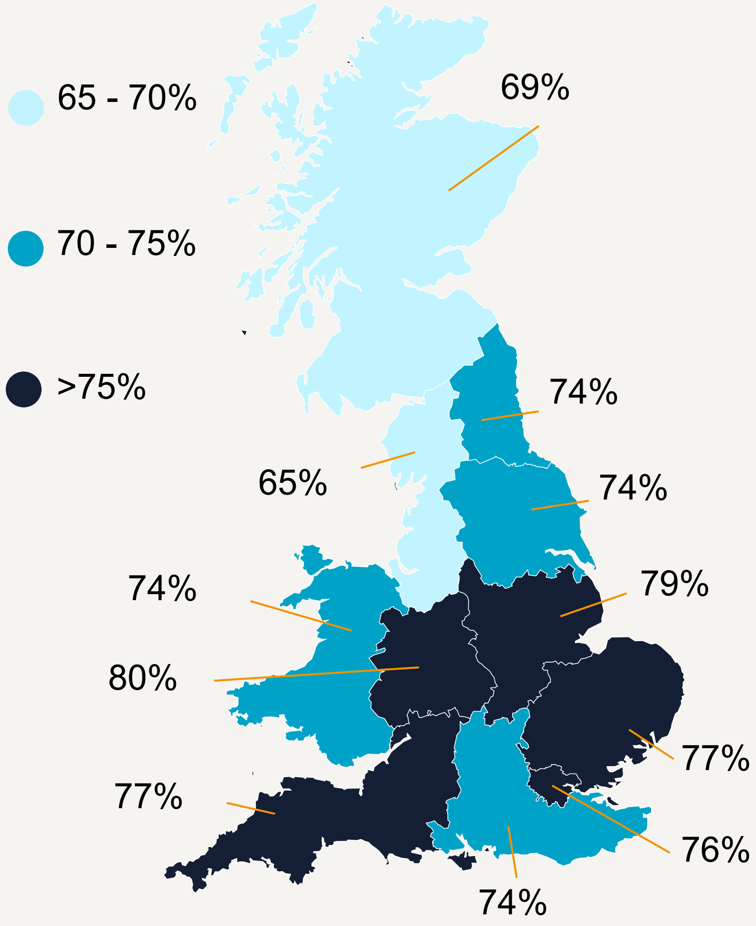
Key use cases for smart meters

1. Replaces manual reads and estimated bills with more accurate, half-hourly settlement data

2. Creates a nationwide sensing and control fabric for flexible demand, outage detection and low-voltage network analytics.

3. Forms the data backbone for the UK's carbon-neutral, electrified energy system.

Rollout of smart meters in GB



GB is behind most Western European countries on the roll-out of smart meters, with only about 70% of meters being smart-enabled. Other countries, including Spain, Italy or France, can leverage the considerably higher installed base of smart meters and the data they provide to operate their electricity grid more efficiently.

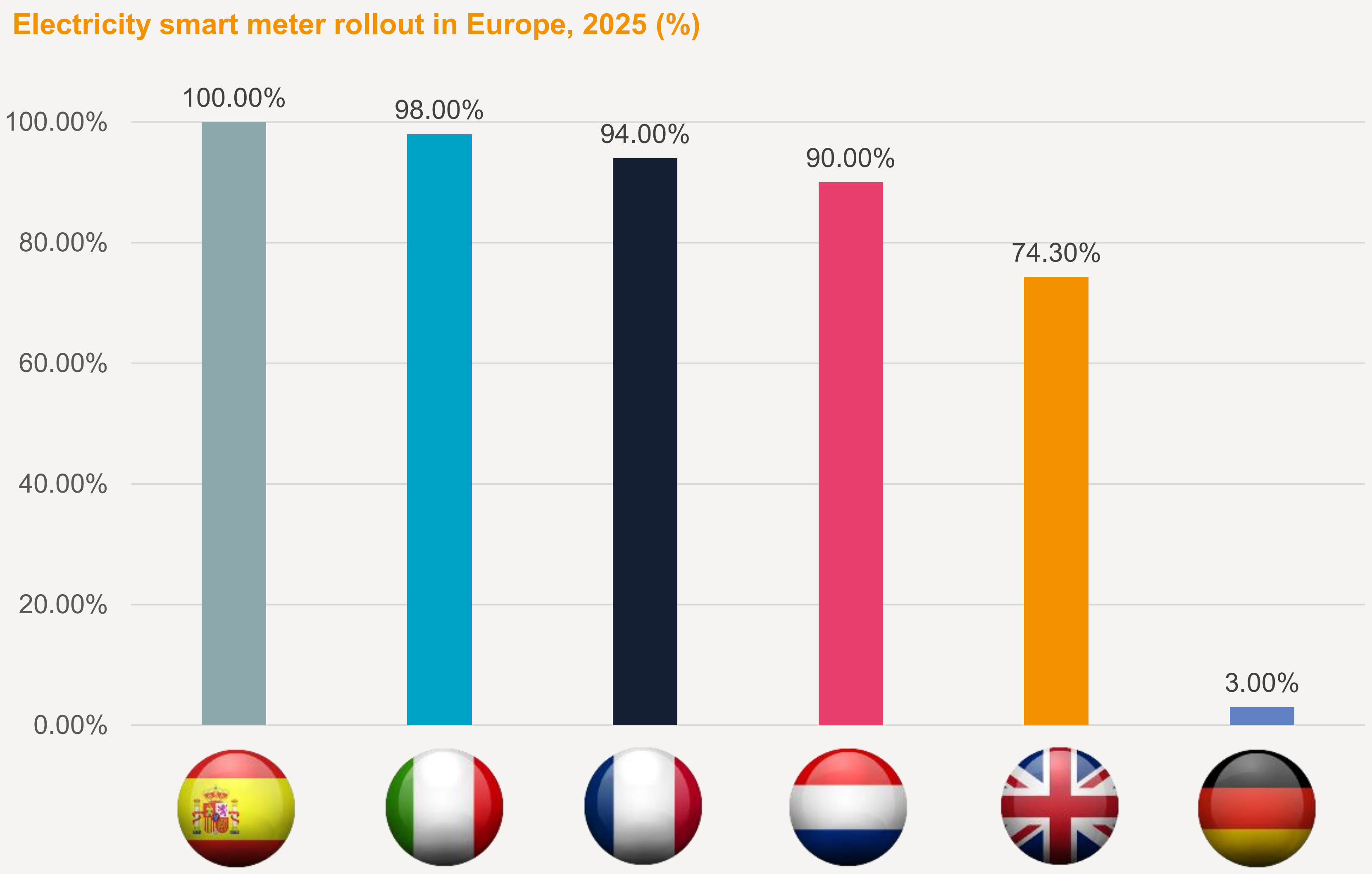
Smart meters have historically been installed at a steady pace across GB, with around 2 million added each year. However, there are disparities in the deployment within the country and installation rates are expected to slow as the remaining properties are harder to access or have barriers like landlord/tenant. Strengthening the importance of smart meters among all stakeholders is key to completing the roll-out as quickly as possible, paving the way for a more flexible, more sustainable and futureproof electricity system.

Smart meter rollout in GB

Generally, higher smart meter penetration aligns with shorter outage durations (SAIDI).

Dimensioning resilience

How and where can smart meters support the energy system?



Dimensioning resilience

How and where can smart meters support the energy system?

Grid resilience components

Over the previous sections, we showed that resilience is multidimensional: it is as much about **seeing** faults in real-time as it is about **adapting** the system, **keeping power flowing**, **planning** the network of tomorrow and **protecting** the data and assets that underpin it. For this section, we map those dimensions onto five components of grid resilience:

1. **Detection and response**
2. **Flexibility and adaptability**
3. **Operational continuity**
4. **Data-driven planning**
5. **Cyber and physical security**

Summary of gaps in existing resilience approaches

Detection and response

Network operators still fly partially blind at the low-voltage edge; faults are often inferred from customer calls rather than observed directly which slows down the first wave of corrective action.

Flexibility and adaptability

While large-scale generation can be dispatched, most behind-the-meter flexibility remains untapped because the system can't see, value or coordinate millions of small assets in real time.

Operational continuity

Outage management is reactive and manually prioritised. Without granular load and condition data, crews can't target the highest-impact fixes or pre-empt cascading failures.

Data-driven planning

Investment decisions still lean on annual peak estimates and simple growth factors, leaving planners blind to emerging load shapes such as clustered EV charging or rooftop PV backfeed.

Cyber and physical security

Legacy field devices and fragmented communication channels create weak points that are difficult to monitor continuously, exposing the grid to escalating cyber and tampering risks.

This section signposts new or existing (and under-utilised) smart-meter use-cases that can help close these gaps.

Detection and response

Detection and response is the real-time awareness and contingency management of the energy system

As the energy system becomes more electrified and complex, rapid detection and response to faults is essential for maintaining resilience. Traditionally, network operators have relied on customer phone calls to identify low-voltage (LV) faults, which can delay corrective action and leave vulnerable customers at risk. While smart meters are now widespread, their advanced capabilities for near real-time fault detection and network monitoring remain under-utilised. Key gaps in grid resilience approaches on detection and response include:

- Most LV faults are still discovered reactively, after customers report outages, rather than through direct observation.
- “Last-gasp” outage alerts (i.e., high-priority messages sent by smart meters when power is lost) are not yet fully integrated into operational workflows, meaning valuable near real-time data is often missed.
- There is limited ability to triage and prioritise support for vulnerable customers during outages, which can lead to inequitable outcomes.

Use cases for smart meters

Smart meters have the potential to transform detection and response by acting as a distributed network of sensors. Key use cases would include:

- **Outage detection:** When a smart meter loses supply for more than 3 minutes, it sends a “last-gasp” (AD-1) alert over the secure DCC network, time-stamped and geo-located to the premise. This allows operators to pinpoint faults within minutes, often **10-15 minutes faster** than waiting for customer calls.
- **Voltage and power quality monitoring:** Advanced meters continuously sample voltage and log power quality events such as frequency deviations and phase angle changes. Aggregating this data gives network operators a live, granular view of the LV network, enabling them to **anticipate and spot issues** like conductor faults or voltage sags before they escalate.
- **Supporting vulnerable consumers:** Smart meters can be used to help identify potential vulnerable customers based on consumption patterns to ensure sufficient support is provided.
- Smart meters monitoring energy usage could be used to help vulnerable consumers stay in their homes longer by providing an early detection of risk.

The benefits of smart meters

Detection and response is the foundation for a resilient grid. By harnessing smart meter data, operators can move from reactive fault-finding to proactive network management. This not only speeds up recovery and reduces disruption, but it also lays the groundwork for other resilience components such as enabling flexibility, improving operational continuity, and supporting data-driven planning.

Flexibility and adaptability

Flexibility and adaptability is the grid's ability to adjust in real-time to changing supply and demand

As the energy system evolves, the ability to flex and adapt in real-time is increasingly vital for grid resilience. Historically, flexibility has been provided by large, centralised generators, but the rise of DERs and smart technologies means that millions of small assets, such as EV chargers and heat pumps, can now play a role. However, much of this potential remains untapped due to siloed coordination and weak price signals. Key gaps in this resilience component include:

- Demand-side flexibility is still a niche offering, with most households and businesses unable to participate easily.
- Coordination between distributed assets is fragmented, with DSOs and NESO operating in silos, lacking a unified approach.
- Price signals for flexibility are inconsistent, making it difficult for consumers to respond effectively.

Use cases for smart meters

Smart meters are central to orchestrating flexibility behind the meter, enabling new ways for consumers and suppliers to interact with the grid. Key use cases would include:

- **Half-hourly settlement data**: Every smart meter records energy usage in half-hour intervals, creating a robust audit trail. During a Demand Flexibility Service event, suppliers can identify exactly which premises delivered a reduction in consumption and settle rebates with confidence. This eliminates the need for statistical estimates and reduces risk for all parties.
- **Remote tariff switching**: Smart meters can store up to 48 different time-of-use tariffs. Suppliers can remotely activate special tariffs during periods of grid stress (a "red-alert" evening) and revert to standard rates automatically. This provides strong, targeted price signals without the need for manual intervention or costly upgrades.
- **Load control via HAN devices**: SMETS2 meters support command-and-control of paired devices using ZigBee technology. Suppliers can issue curtailment commands that are enacted locally, even if the household's broadband connection is down, enabling reliable and responsive demand management.
- **Real-time usage feedback**: In-home displays connected to smart meters provide immediate feedback on energy use and cost. Studies show that simply visualising this information can reduce peak demand by 3-5%, delivering "organic" flexibility across the system.

The benefits of smart meters

Flexibility and adaptability are the bridge between detection and response, and operational continuity. By enabling millions of consumers to participate in demand-side flexibility, smart meters help balance supply and demand, reduce the need for costly network reinforcement, and maximise the use of renewable energy. This strengthens technical resilience and empowers consumers to play an active role in the energy transition.

Operational continuity

Operational continuity is ensuring electricity is kept flowing even when something goes wrong

Operational continuity is the ability to deliver electricity reliably under normal and foreseeable conditions. It remains critical to grid resilience and part of operational resilience discussed in Section 1: Defining resilience. Traditionally, it has been achieved through centralised planning, robust transmission standards (e.g. N-1 security standards), and scheduled maintenance. However, the energy transition introduced new complexities. Key gaps in this resilience component include:

- Limited visibility at the grid edge. Traditional systems lack granular, real-time data for low-voltage networks where most distributed energy assets and consumer technologies connect.
- Slow fault detection and restoration. Manual processes and limited automation delay response during outages.
- Fragmented coordination. Transmission and distribution operators (NESO and DSOs) often operate in silos, with limited integration of operational data
- Static operational models that are designed for predictable, centralised generation, rather than dynamic bidirectional flows from distributed energy assets.

Use cases for smart meters

Smart meters can improve operational continuity by providing near real-time, granular insights and enable proactive management. Key potential use cases include:

- **Automated outage restoration**: As mentioned in the detection and response dimension, smart meters in GB send a “last gasp” (AD-1) alert when the smart meter loses power for more than 3 minutes. Combined with the data on the smart meter’s location, these alerts enable faster switching and sectionalising of the network, reducing downtime.
- **Grid islanding support**: Smart meter data makes it possible to pre-define a set of LV “island candidates” with known load and asset characteristics, helping system operators determine know which zones are technically plausible microgrids in case of an outage.
- **Post-event diagnostics**: Voltage and power quality logs assist in root-cause analysis, improving restoration strategies for future events and the understanding of the system.

The benefits of smart meters

Operational continuity ensures that electricity supply remains stable and reliable, even under stress. Smart meters play a pivotal role by providing near real-time visibility into consumption and grid conditions, enabling utilities to anticipate issues and maintain service without interruption. Through smart meters, operators can remotely monitor voltage, detect outages instantly, and execute rapid restoration strategies. This reduces outage duration, improves asset management, and lowers operational costs.

Data-driven planning

Data-driven planning is using real data to plan ahead so the grid can cope with future changes

As the grid becomes more decentralised and dynamic, planning based on historical averages is no longer sufficient. Extreme weather, electrification and the integration of distributed energy assets require predictive, data-driven strategies to anticipate risks and optimise investments. Key gaps in the data-driven planning dimension include:

- Fragmented datasets and outdated models limiting visibility into real-time conditions on the grid.
- Limited integration of customer vulnerability and asset health data, leading to inequitable resilience outcomes.
- Reactive investment prioritisation makes it hard to justify and optimise resilience spending.

Use cases for smart meters

Smart meters provide granular, time-stamped data that can transform planning. Key use cases would include:

- **Load forecasting**: Half-hourly consumption data from smart meters enables accurate demand projections at feeder level, supporting local energy planning. As there is not yet a full smart meter rollout in GB, NESO does not use smart meter data in their Distribution Future Energy Scenarios (D-FES) and instead rely on transmission metered data.
- **Asset health insights**: Voltage and power quality data from smart meters help identify stress points in LV networks, informing targeted reinforcement before failures occur. Ofgem's RIIO-ED2 framework encourages DNOs to use this data for predictive maintenance.
- **Distributed asset integration modelling**: Smart meter data reveals behind-the-meter generation and storage patterns, allowing planners to simulate grid behaviour under high penetration of distributed energy assets.
- **Societal resilience mapping**: Linking consumption data with vulnerability registers helps planners prioritise upgrades for critical services and vulnerable communities.

The benefits of smart meters

By leveraging smart meter data, utilities can move from static, compliance-driven planning to dynamic, risk-based strategies. This improves investment efficiency, enhances equity, and enables proactive reinforcement of weak points which ultimately reduces outage risk and supports long-term resilience.

Cyber and physical security

Cyber and physical security protects the grid from hackers, keeping the grid safe and reliable

Digitalisation expands the grid's attack surface, making cyber and physical security inseparable. Threats range from ransomware targeting operational technology systems (including, for example, SCADA systems, sensors, and controllers in power grids) to physical sabotage of substations. A layered, integrated approach to cyber and physical security is essential to maintain operational continuity. Key gaps in this dimension include:

- Legacy SCADA systems and remote assets often lack modern security controls.
- Millions of connected devices create multiple entry points for potential attackers.
- Hybrid threats can disable monitoring systems and damage physical infrastructure simultaneously.

Use cases for smart meters

Smart meters can play a critical role in strengthening cyber-physical security dimension of resilience.
Key use cases include:

- **Tamper detection**: Smart meters log and report physical tampering attempts, alerting operators to potential sabotage. This helps detect energy theft or interference quickly.
- **Anomaly detection**: Consumption and voltage anomalies can indicate cyber intrusions. Abnormal events could reflect meter tampering, data manipulation, meter malfunction or other irregularities.
- **Secure communications**: Smart meters in GB operate on a closed, dedicated communication network with security by design. They do this via encrypted channels (through the DCC network) reducing the risk of data interception. The DCC also has 24/7 monitoring of the network for anomalies.
- **Network segmentation**: Acting as secure endpoints, smart meters help maintain integrity between consumer premises and core grid systems.

The benefits of smart meters

Smart meters enhance situational awareness and provide a secure, distributed sensing layer. By detecting tampering and anomalies early, they reduce the likelihood of cascading failures and support rapid incident response. Their encrypted communication protocols also strengthen the grid's cyber defence posture.

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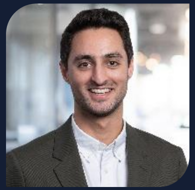

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