UK Energy Research Centre

Enhancing Electricity System Resilience with AI, Digital Twins and Digitalisation Technologies

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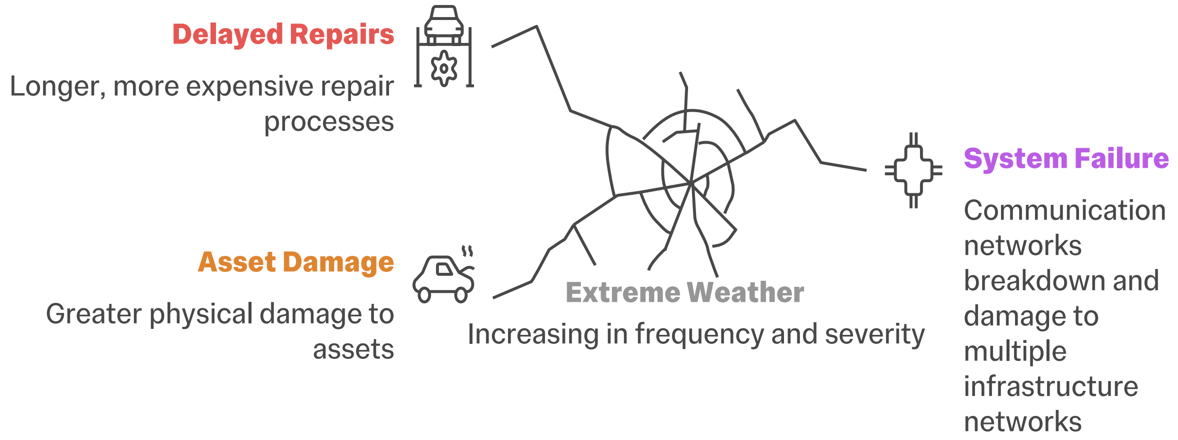
Extreme weather events

Extreme weather events, intensified by climate change, pose a significant and increasing threat to the resilience of electricity systems. They cause direct physical damage to assets like power lines and substations and hinder repair efforts by disrupting communication and transportation networks.



Extreme Weather Impacts Electricity Resilience

Delayed Repairs

Longer, more expensive repair processes

Asset Damage

Greater physical damage to assets

Extreme Weather

Increasing in frequency and severity

System Failure

Communication networks breakdown and damage to multiple infrastructure networks

Storms: Events like hurricanes and cyclones cause widespread damage through high winds that bring down infrastructure. Ice storms are particularly destructive.

Flooding: Heavy flooding, whether from storms or prolonged rain, is especially damaging to ground-based electrical infrastructure like substations. Floodwaters can inundate critical equipment, erode foundations, trigger landslides, and block access for repair crews long after the initial event.

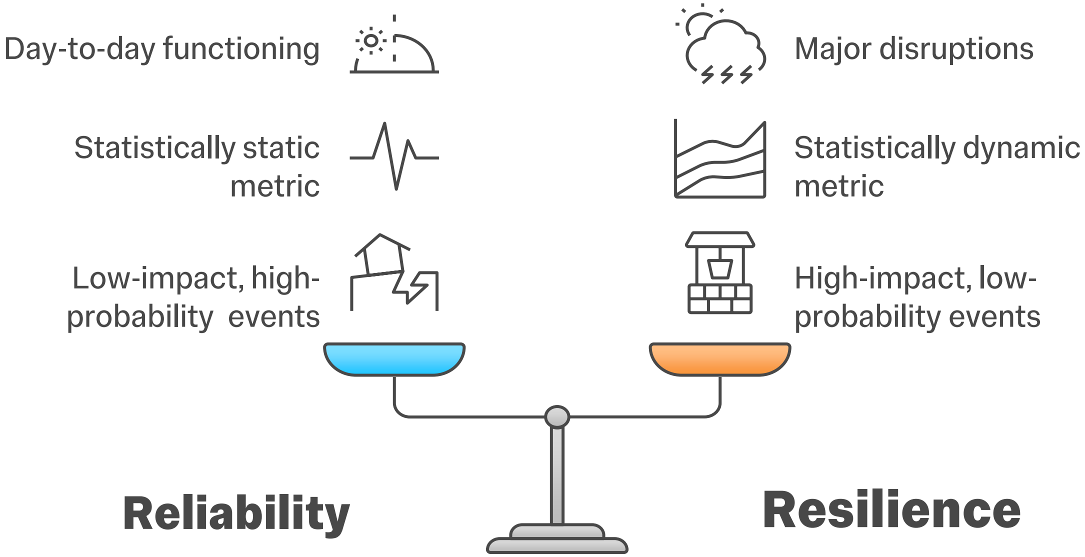
Extreme Heat: Heatwaves strain the grid by increasing electricity demand for cooling while simultaneously reducing the efficiency of thermal power plants and solar panels. High temperatures also cause power lines to sag, creating a serious risk of starting wildfires.

Extreme Cold: Cold spells increase energy demand for heating while physically damaging infrastructure. Freezing temperatures can disable thermal power plants by affecting cooling water or fuel supplies (as seen with frozen natural gas wells in Texas) and can cause wind turbines to ice up.

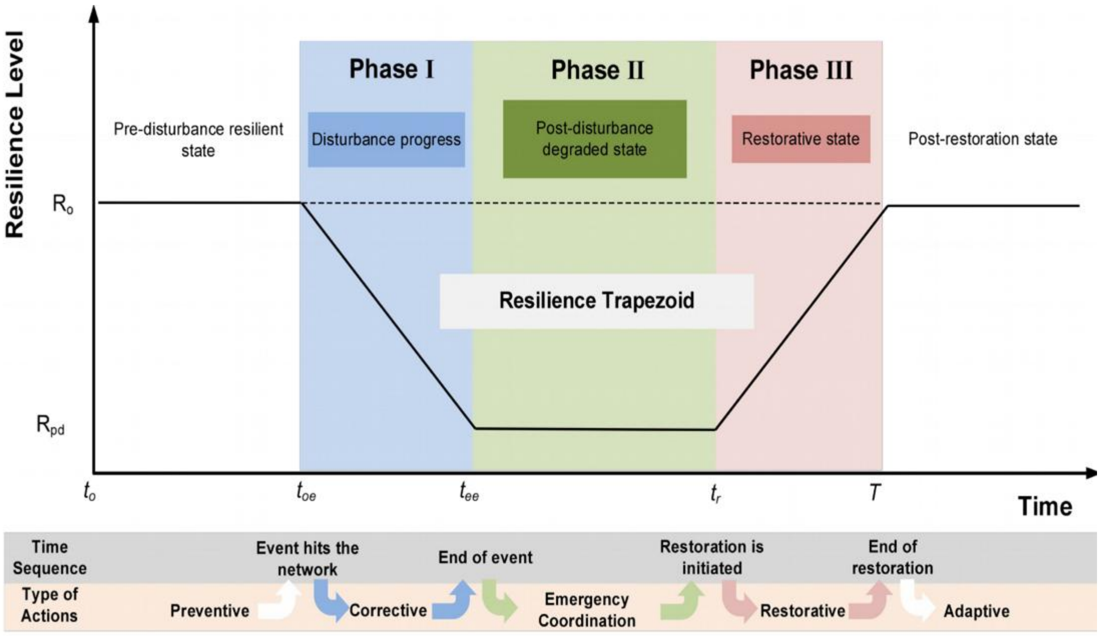
The Concept of Operational Resilience

- The ability of energy systems and technologies to respond to and recover from a serious disruption is known as operational resilience.
- These disruptions are usually classed as **HILP** events, covering extreme weather events, earthquakes and other natural disasters, as well as man-made threats such as cyber-attacks and physical disruptions.

Resilience Vs Reliability



Reliability	Resilience
Day-to-day functioning	Major disruptions
Statistically static metric	Statistically dynamic metric
Low-impact, high-probability events	High-impact, low-probability events



Before an event:

- *Anticipation*
- *Preparation*
- **During an event:**
- *Absorption*
- *Sustainment of critical system operations*
- **After an event:**
- *Rapid recovery*
- *Adaptation*

Conventional Resilience Strategies

- **Physical Hardening -** This involves strengthening vulnerable components like overhead lines and poles, proactive vegetation management, and moving critical assets to safer locations, such as transformers to higher ground.

- **Undergrounding lines -** this provides excellent protection but is often prohibitively expensive, (around ten times the price of overhead lines) limiting its use to the most critical areas.

- **Redundancy –** Adding redundant lines adds flexibility and resilience to network topology. Expensive to build and maintain and would need to be economically justified and targeted at vulnerable line segments and assets.

- **Resilience Planning** is a practical process that prepares the power system for a specific set of likely extreme events, accepting that some outages may occur but ensuring automatic recovery and restoration can begin immediately.

- **Operational Management and Resource Allocation** focuses on maintaining grid functionality during damage, primarily through emergency power supplies or by reconfiguring the network's topology.

Foundational Digital Technologies for Energy

Big Data

Machine Learning and AI

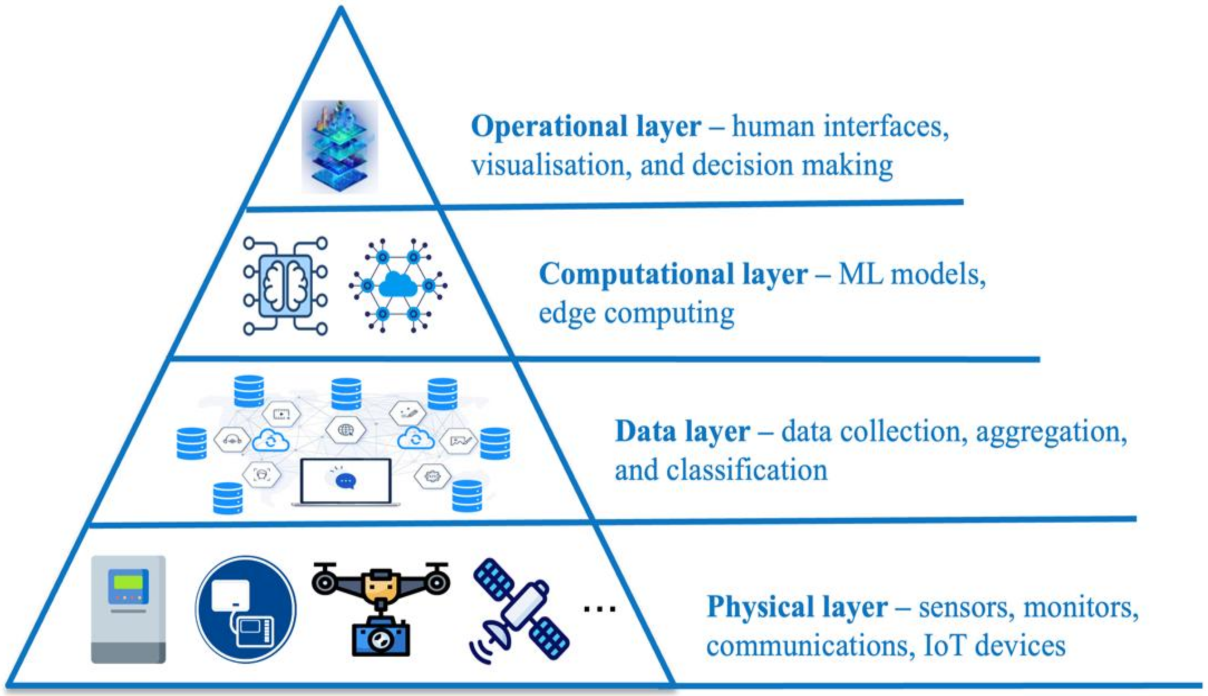
Internet of Things

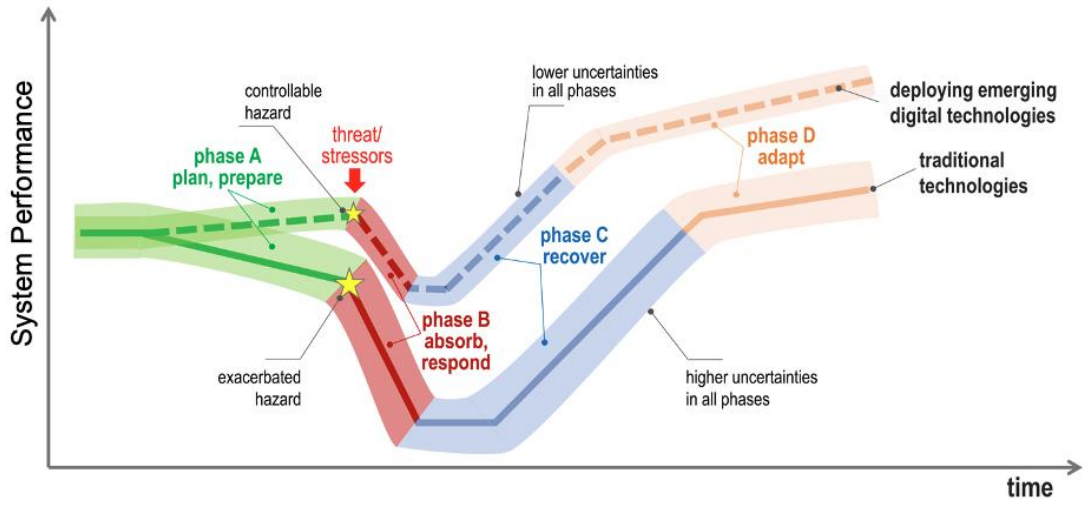
5G, Mesh and Satellite Networks

Cloud and Edge Computing

	Generation	**Transmission**	**Distribution**	**Consumer**
Big Data	Optimisation of operational efficiency through analytics	Forecasting of future load and pricing	Analytics for optimising microgeneration and storage in communities	Advice on usage and saving energy.
AI/Machine Learning	Optimisation of wind farms through wind speed forecasting	Autonomous agents trading energy	Optimisation of networks against physical faults.	Automation of demand response
Internet of Things	Drone inspection of equipment	Smart grid sensing, monitoring and asset management	Enabling local microgrids through embedded control	EVs, in-home/building sensors

Digital Technologies for Resilience





- Digital technologies can address weaknesses in conventional methods by enhancing system visibility and modelling complex interactions between hazards and system performance.

- Power system digitalisation can be structured into four distinct layers: physical (data generation via sensors), data (collection and storage), computational (analysis using ML/edge computing), and operational (human interfaces, visualisation and control)

- These technologies can enhance overall system reliability, enabling more informed decision-making during extreme weather events.

Physical Layer Technologies

Satellite Communication

- **Low-Earth Orbit Satellites:** LEO satellites support grid resilience by enabling monitoring, automation, and post-disaster response. This allows communication when terrestrial networks are damaged, though potential network latency must be managed through adaptive system design.

- **Open Network Technologies:** Technological advancements, such as 4G over satellite, improve interoperability and allow for seamless integration with existing power grid infrastructure.

- **Data and Communication Continuity:** Leveraging satellite communication will be essential for the future security and reliability of smart grids, particularly when facing natural disasters or unexpected disruptions.

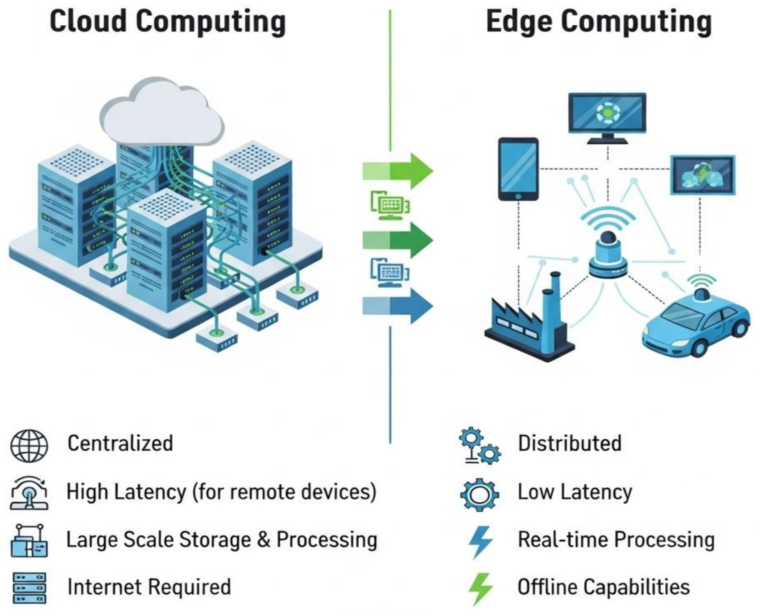
Unmanned Aerial Vehicles (UAVs)

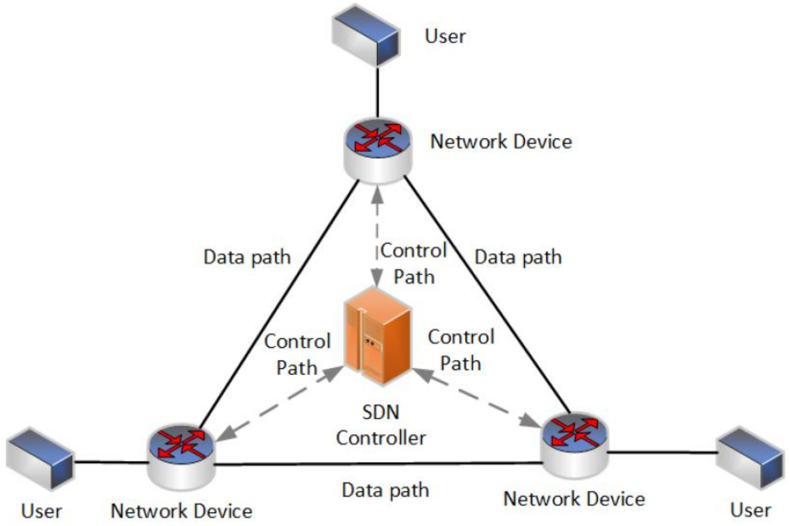
- **Aerial Inspection:** UAVs are commonly used to inspect power plants, substations, overhead transmission lines, and other significant assets. This allows for early detection of issues such as sagging spans, leaning poles, and broken or slack wires.

- **3D Mapping:** Advances in laser technology now enable UAVs to perform remote distance measurements, which is invaluable for monitoring the right-of-way of high-voltage lines and controlling tree encroachment.

- **Post-Disaster Damage Assessment and Restoration:** UAVs can significantly speed up and improve the accuracy of damage assessments and restoration efforts after a disaster. Aerial inspections of suspected damage areas enable repair crews to quickly determine the extent of the damage and the necessary repairs.

Processing Data: Edge Computing and Software-defined Networking





- Edge computing boosts power system resilience by processing data locally on distributed devices, a significant advantage during emergencies.

- By operating closer to the data source, it enables faster detection and reaction to grid disturbances, a critical factor in ensuring service continuity.

- The technology lessens the reliance on central communication networks, allowing localised decision-making to keep essential grid functions.

- Software-defined networking technology enables a central controller to collect real-time data and dynamically adjust network pathways based on fault detections.

- When a failure occurs on a data pathway, the controller automatically reroutes traffic through alternative paths, ensuring uninterrupted communication.

Computational Layer Technologies: Machine Learning Based Technologies

There are two major drivers incentivising the integration of ML/AI into power system resilience:

Data Proliferation: The advent of wide area monitoring systems, which monitor the health of the network in real-time, and the ubiquity of sensors and other EIoT devices have resulted in an exponential increase in data availability, providing a rich substrate for machine learning algorithms.

AI and Computational Evolution: The rapid progression in AI algorithmic sophistication, paralleled by an exponential augmentation in computational capacity, has significantly enhanced the predictive accuracy and decision-making process of machine-learning based technologies (MLBTs).

- **Reliability Management**: MLBTs can use predictive maintenance and failure detection algorithms to predict when equipment might fail, ensuring a more dependable power supply.
- **System Stability Assessment and Control**: MLBTs use state estimation and dynamic simulation to maintain the stability of the power system under changing conditions. This involves continuously monitoring the system's state and simulating different scenarios to ensure it remains stable and operational.
- **Frequency Analysis and Control**: By applying Fourier transforms and spectral analysis, MLBTs can help maintain the system's frequency within the desired range. This is crucial for the smooth operation of the power grid, as frequency deviations can lead to power outages or equipment damage.
- **Contingency Analysis**: MLBTs can evaluate the potential impact of system disruptions using probabilistic risk assessment. This involves analyzing various possible disruptions and their likelihood.

Machine Learning during a resilience event

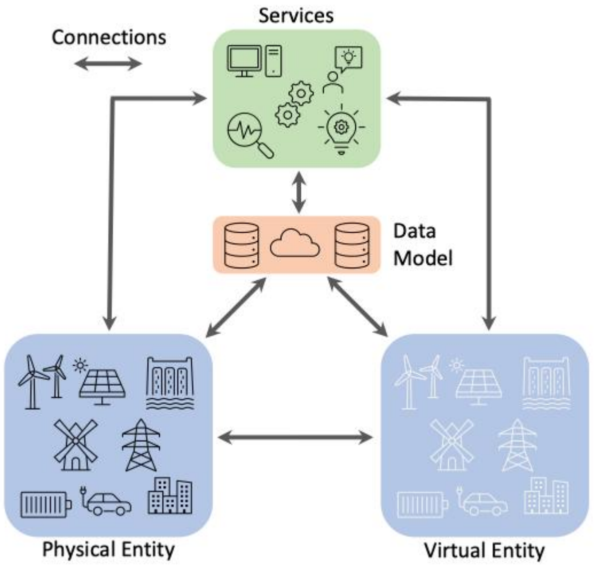
- **Pre-event:** Machine learning (ML) technologies can improve the accuracy of dynamic security assessments, giving operators a better understanding of the grid's resilience before an incident occurs.

- **During-event:** By predicting outages and classifying power disturbances, ML enhances an operator's situational awareness, enabling them to take prompt corrective actions as an event unfolds.

- **Post-event:** Reinforcement learning (RL) helps in making fast, accurate decisions for stability control and service restoration, which is particularly useful when the grid is behaving unpredictably.

	Dynamic Security Assessment	Outage prediction	PQD classification	Attack detection	System restoration
Main task	Assess power grid's ability to withstand and recover from a set of contingencies	Predict the time, place, and duration of outages	Root cause investigation of sudden deviations from standard ratings	Detect anomalous activities in the SCADA network	Decision-making process preserving and recovering performance in during-/post-event
Input data	PMU measurements, waveform angle and rotor speed	Weather data, Electricity dataset,	Voltage/current waveform magnitude, phase angle and frequency	SCADA network traffic, open dataset	Operating condition, device status, PMU data, etc.
Data process and ML methods	Decision tree, SVM, NN, etc.	Ensemble learning, etc.	Wavelet transform, SVM, etc.	SVM, NN, etc.	RL, deep RL, Multi-agent RL, etc.
Resilience enhancement	Pre-event system robustness understanding	In-event situation awareness	In-event situation awareness	In-event situation awareness	Post-event decision making process

Operational Layer Technologies – Digital Twins



Five-dimensional structure of a digital twin system

Monitoring and Prediction

Pre-Event outage monitoring and prediction for energy assets
- Dynamic data collection and aggregation
- Risk metric development and computation

Decision Support

During-Event deceision support for mitigation and recovery
- Proactive/Corrective control, resource coordination, and repair crew route
- Real-time recovery time prediction

Planning and Analysis

Post/Pre-Event asset and infrastructure planning and resilience assessment
- Prelocation of mobile generation and communication vehicles
- Real-time assessment of resiliency level

1. Pre-Event: Predictive Monitoring & Situational Awareness

- Predicts infrastructure outages several hours before an extreme event.
- Provides crucial situational intelligence, identifying the type and location of potential failures

2. During-Event: Automated Decision Support & Dynamic Recovery

- Automatically deploys proactive and corrective control methods
- Coordinates mobile resources and repair crews
- Adapts to new or escalating events during the recovery process,

3. Post-Event: Analysis, Learning & Future Planning

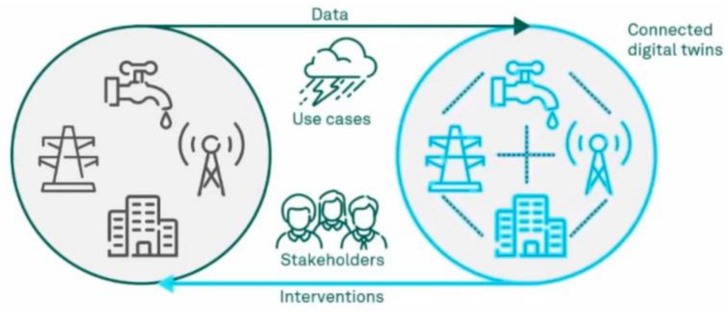
- Analyses data from past events to generate recommendations for enhancing future resilience
- Enables operators to build a global understanding of system resilience to better anticipate and react to future incidents.

Challenges of Digital Twin Implementation

- ***Connectivity:*** Connectivity-related challenges, including software errors and power outages during real-time monitoring can significantly impact digital twin accuracy. Implementing robust methods to recover lost data and ensure reliable connections and data transfer is essential.

- ***Cyber Security.*** Digital twins are vulnerable to cyber-attacks due to the vast volume of data and information exchange. Creating a secure platform is necessary to ensure a reliable digital twin model. Blockchain technology or another token-based authentication system can address this issues and help digital twins maintain coherence.

- ***Standardisation.*** Various infrastructure systems such as electricity, water, and gas will require interoperable platforms to effectively monitor and resolve large scale events . This could be addressed using Using standard data formats to define, save, and execute digital twin models, along with Semantic Web technology or a standard digital twin definition language.



CReDo Implementation Overview

CReDo is a pioneering climate change adaptation digital twin project in the UK that brings together data across energy, water, and telecoms networks from Anglian Water, UK Power Networks and BT.

A distributed data sharing architecture, a system where data is stored and accessed across multiple, networked computers or nodes to allow resource sharing, is developed to enable interoperability, data security and privacy, and scalability.

Asset owners have full control privilege over their own data and can get a clear overview of the interactions between their own assets and others.

Bringing It All Together

Storm Darragh struck the UK in early December 2024 with wind speeds exceeding 96 mph, triggering widespread flooding, fallen trees, and transport disruptions.

Before The Event

- Preparing for an extreme storm involves forecasting its scale, including wind speed and rainfall. AI and machine-learning weather models provide effective predictions.
- This data can be combined with a digital twin to model storm impacts with high precision.
- By integrating forecasts with historical outage and asset data, these systems identify high-risk network areas before the event.

During The Event

- As the storm hits the UK, IoT-connected sensors and monitoring devices send real-time data to control centres, including stress points such as wire tensions, transformer temperatures and tower vibrations.
- Satellite communications can provide redundancy in case of terrestrial communication failure.
- Power can be dynamically rerouted around failure points, either manually or by AI intervention, allowing the grid to remain stable even in the case of significant asset damage.

After The Event

- Data from connected devices and sensors can assist in pinpointing the most critically damaged assets.
- Drones can be used to survey wire lengths for fallen trees and other debris damage, and specialised robots can be used to locate and fix faults in infrastructure that is difficult to access.
- To adapt to future events, AI models can assess data to pre-position repair crews for future storms, as well as to understand exposed and vulnerable assets that would benefit from further physical hardening.

Risk factors for implementation

Digital Technologies

- Resilience over years or decades
- Interoperability (hardware and software)
- Support and updates through lifecycle

Security

- Security against malicious cyberattack
- Physical infrastructure connected to and controlled by software
- Greater amount of stakeholders connected and sharing data

Personnel

- Greater number of personnel with access to critical systems
- New skillsets, ways of working and knowledge required.
- Risk assessment of employees in a digitalised energy system

Consumers

- Ability of the consumer to affect the electricity system through digitally enabled actions

Regulatory

- Ability of regulators to keep pace with digitalisation
- Regulatory changes could increase operation risk unintentionally

Recommendations

- **Standardised Assessment:** Standardised national/global frameworks are needed to measure the value of digital technologies in improving resilience, allowing for data-driven investment decisions.

- **Regulatory Incentives:** Policies should be updated to provide financial incentives, such as subsidies or tax benefits, to encourage utilities to adopt digital resilience solutions where appropriate.

- **Comparative Analysis:** A cost-benefit analysis comparing digital and traditional resilience methods is required to determine the most effective and resource-efficient strategy.

- **Data Privacy:** Strong data governance and security protocols must be established to protect the sensitive information of multiple stakeholders as digital implementation increases.

- **Cyber Resilience:** As digital dependencies grow, cyber security must be a core priority, requiring the introduction of integrated advanced threat detection technologies and algorithms.

- **Cross-Sector Collaboration:** Understanding the interdependence between different energy and other infrastructure sectors through data sharing is crucial for quantifying and enhancing overall system resilience.

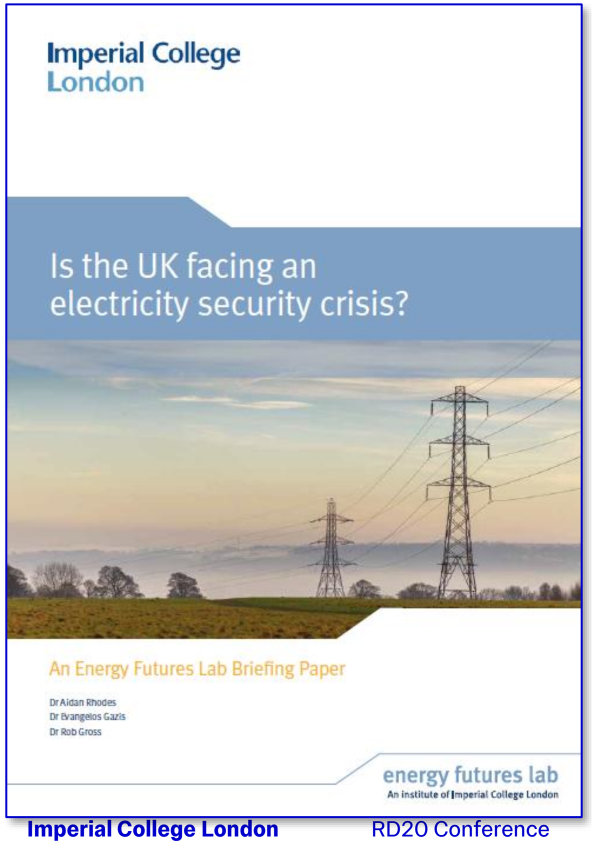
- **Skilled Workforce:** Investment in training and upskilling programmes is essential to equip the workforce with the necessary data analytics and cyber security skills to manage new digital systems.

Thank you!

Thanks to my coauthors:

- Dr Mengxiang Liu
- Dr Fei Teng

https://www.imperial.ac.uk/energy-futures-lab/reports/briefing-papers/



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Is the UK facing an electricity security crisis?

An Energy Futures Lab Briefing Paper

Dr Aidan Rhodes
Dr Evangelos Gazis
Dr Rob Gross

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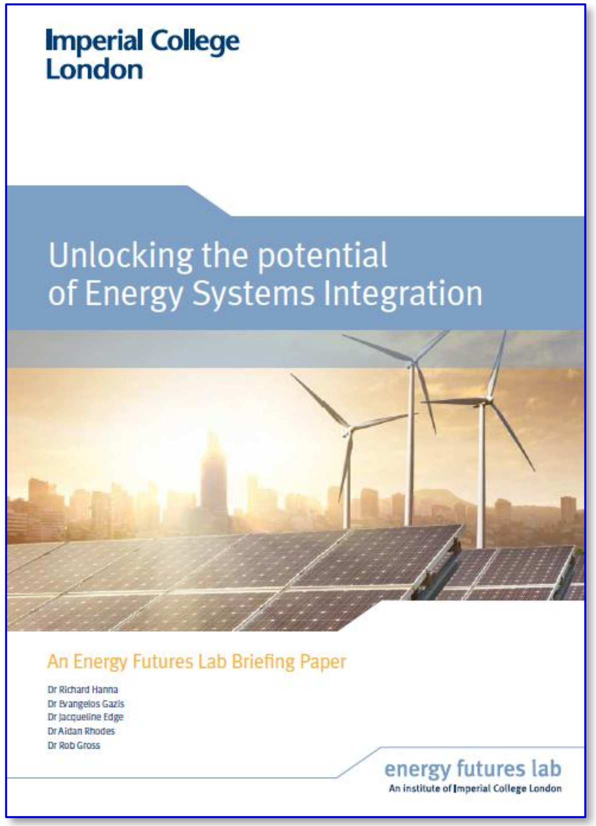

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Unlocking the potential of Energy Systems Integration

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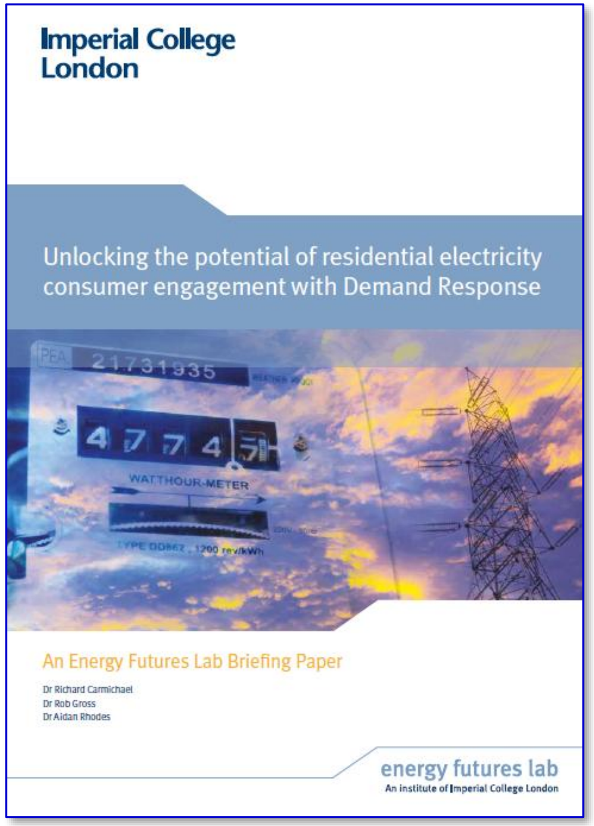

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Unlocking the potential of residential electricity consumer engagement with Demand Response

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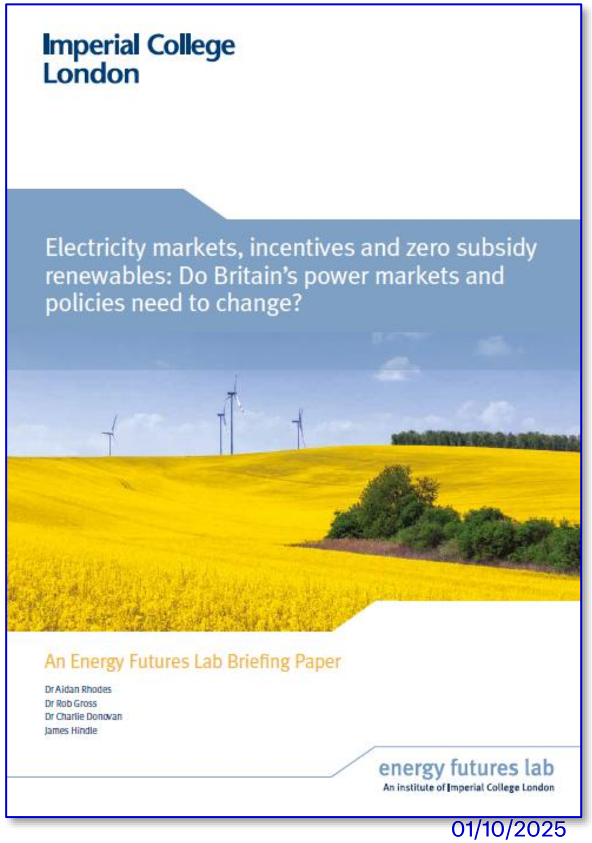

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Electricity markets, incentives and zero subsidy renewables: Do Britain's power markets and policies need to change?

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