Assessment of electricity systems, markets, and support mechanisms in the energy transition

May 2026

Summary and key Drax take-aways undertaken by:
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Summary

Electricity systems are changing faster than at any point since modern power grids were first built. For a century, electricity was supplied by large power stations that could be switched on when needed, with markets and networks designed around this model. Today, wind and solar are growing rapidly and are essential for cutting emissions, but they depend on the weather, cannot always meet demand, and at times can produce more electricity than the system can use, creating new challenges for balancing supply and demand. At the same time, electrification of heavy industry, growth in data centres, and the shift to lower carbon technologies such as electric vehicles and heat pumps are increasing electricity demand and changing when and how it is used. Power systems must therefore deliver clean energy, reliable supply during peak demand, and flexibility to manage short term changes; needs that no single technology can meet alone. Existing electricity markets were not designed for this challenge and cannot deliver the right investment signals on their own. As a result, governments and system operators are increasingly combining markets with long term contracts, capacity mechanisms, and grid investment. Different approaches in Great Britain (GB), the European Union (EU), and the United States (US) show how moving towards more complex and hybrid market arrangements is essential, offering lessons for reform.

Key Drax take-aways

1. **The current energy transition necessitates fundamental changes to how electricity systems and markets work to maintain energy security and stability.** The electricity grid is a highly coordinated system that requires continuous balancing, tight frequency control, and secure operation at all times, regardless of the generation mix. As the energy transition reshapes how electricity is generated, maintaining reliability increasingly requires new technologies and explicit support for both power generation and essential system services, leading to more hybrid market arrangements.
2. **As the share of renewables generation on the systems increases, a portfolio of technologies and approaches are needed to maintain a balanced and reliable grid while providing flexibility and dispatchability.** Examples include (not exhaustive):
    a. **Battery storage:** indispensable for fast, short duration flexibility and rapid frequency response.
    b. **Pumped storage hydro:** able to operate as both a flexible and firm resource while also contributing to system stability.
    c. **Sustainable unabated bioenergy:** a reliable, dispatchable resource that can support system stability and balancing when sustainability requirements are met.
    d. **Demand-side flexibility:** the ability of electricity consumers to adjust when and how they use power in response to grid needs or price signals.
3. **Support arrangements reflect the value different technologies provide to the system and apply across all forms of energy generation.** All generation technologies (including coal, gas, nuclear and renewables) have historically received some form of support. The key question is whether arrangements are well designed, proportionate and aligned with the grid services required to maintain security of supply, such as capacity, flexibility, inertia, and system stability.

4. **There are different ways to support market evolution as electricity systems transition to cleaner energy.** To maintain reliable power, governments and system operators in GB, the EU and the US use different forms of public support funded either through consumer bills or taxes, such as long term contracts (e.g., Contracts for Difference in GB), capacity mechanisms (e.g., National capacity mechanisms in parts of the EU) or tax credits (e.g., the US 48E Clean Electricity Investment tax credit). These approaches reflect a shared shift toward hybrid markets rather than reliance on wholesale price signals alone. While these approaches differ in design and funding, they all aim to ensure reliability and investment as electricity systems decarbonise.

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Acronyms

Acronym	Meaning
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CHP	Combined Heat and Power
DOE	Department of Energy (United States)
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emissions Trading Scheme
EU	European Union
GB	Great Britain
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	Independent System Operator
LCA	Life Cycle Analysis
NESO	National Energy System Operator (Great Britain)
RAB	Regulated Asset Base
RIIO	Revenue = Incentives + Innovation + Outputs (UK regulatory framework)
RTO	Regional Transmission Organization
TSO	Transmission System Operator
UK	United Kingdom
US	United States

Glossary

Glossary definitions are adapted from terminology used by NESO, ENTSO-E, NERC, IEA, Ofgem, IPCC, and electricity market literature.

Term	Definition
Adequacy	The ability of the electricity system to meet demand at all times under a defined set of conditions.
Ancillary Services	Non-energy services required to maintain grid stability, including frequency control, voltage support, inertia, and reserves.
Balancing (System Balancing)	The continuous process of matching electricity supply with demand in real time to maintain system stability.
Black Start Capability	The ability of a power plant to restart electricity generation without relying on an external power supply after a system-wide outage.
Capacity Mechanism	A market instrument that provides payments to ensure sufficient generation or demand-side resources are available to meet peak demand and system stress events.
Capacity Credit	A measure of how much a generation or storage resource contributes to system adequacy during peak demand or stress conditions.
Decarbonisation	The process of reducing or eliminating carbon dioxide emissions from electricity generation and energy systems.
Demand-Side Flexibility	The ability of electricity consumers to adjust their demand in response to system conditions, prices, or signals.
Dispatchable Generation	Power generation that can be controlled and scheduled on demand by system operators (e.g., gas, nuclear, hydro).
Energy-Only Market	A market design where generators are paid only for the electricity they produce, without separate payments for capacity or system services.
Fault Current	The current that flows through the network during an electrical fault (such as a short circuit). High fault current levels are essential for the correct operation of protection systems.
Firm Capacity / Firm Generation	Electricity supply that is reliably available regardless of weather, time, or system conditions, especially during scarcity events.
Flexibility (System Flexibility)	The ability of the power system to respond to changes in supply and demand across different timescales.
Frequency (System Frequency)	The rate at which alternating current oscillates (typically 50 Hz in the UK/Europe), which must be tightly controlled to maintain system stability.
Frequency Response	The ability of generators or storage systems to respond rapidly to deviations in system frequency.
Grid Infrastructure	The physical network of transmission lines, substations, and distribution systems that transport electricity.

Term	Definition
Hybrid Market Architecture	A combination of market mechanisms (energy markets, capacity markets, ancillary services, and contracts) used to ensure reliability and investment in electricity systems.
Inertia	The resistance of the power system to changes in frequency, traditionally provided by the rotating mass of synchronous generators.
Interconnector	A transmission link that connects electricity systems between countries or regions, enabling cross-border power flows.
Long-Term Contracting	Mechanisms (e.g., Contracts for Difference) that provide revenue certainty to generators over long periods to support investment.
Life Cycle Analysis	A systematic method for assessing the environmental impacts of a product, process, or system across all stages of its life cycle based on defined system boundaries and a functional unit.
Reactive Power	A component of alternating current power that does not perform useful work but is necessary to maintain voltage levels in the system.
Residual Demand	Electricity demand minus the output of variable renewable generation at a given time.
Resource Adequacy	The ability of the electricity system to reliably meet demand under a range of conditions, including extreme or prolonged stress events.
Synchronous Generation	Electricity generation from rotating machines (e.g., coal, gas, nuclear, hydro) that operate in synchrony with grid frequency and provide inherent stability services.
System Frequency	The rate at which alternating current oscillates across the power system.
System Operator	An entity responsible for managing the real-time operation of the electricity system and ensuring reliability.
System Services	Non-energy services required to ensure the secure and stable operation of the electricity system. These include frequency response, voltage control, inertia, operating reserves, black start capability, and system balancing.
Transmission System Operator (TSO)	An organisation responsible for operating and maintaining the high-voltage transmission network.
Intermittent Renewable Energy	Electricity generation from sources such as wind and solar, whose output depends on weather conditions and cannot be dispatched on demand.
Voltage Control	The management of voltage levels within acceptable limits to ensure safe and reliable operation of the electricity system (NESO, 2025a)

Executive Summary

The electricity system is undergoing its most fundamental transformation since the creation of modern power grids in the early twentieth century, when interconnected networks first enabled reliable, large-scale electricity supply. For a century, the logic of that system held: large, controllable power plants produced dispatchable capacity, system reliability and ancillary services, including frequency regulation, voltage support, and fault current as a package. Markets were built around their behaviour, and the engineering assumptions embedded in grid codes, investment frameworks, and regulatory structures reflected the incumbent status quo. Now, wind and solar account for a growing share of generation across every major economy, and the pace of deployment is accelerating. The imperative is to ensure that the infrastructure of the electricity grid enables the continued transition without compromising security of supply. This report examines how electricity systems, markets, and support mechanisms are evolving to maintain reliability and enable decarbonisation in Great Britain, the European Union, and the United States.

Electricity systems must simultaneously deliver three distinct requirements: adequate firm capacity to reliably meet demand, flexible capacity to balance second-by-second and sub-hourly variations in supply and demand, and bulk low-carbon generation.

Wholesale electricity markets, as originally designed, cannot resolve this challenge. Energy-only markets were calibrated for thermal-dominated systems in which energy production and system reliability were bundled together. High-renewables systems unbundle these, and the revenue signals available through energy markets are insufficient to justify investment in the firm dispatchable capacity, long-duration storage, and synchronous services the system requires. Capacity mechanisms, ancillary service markets, long-term contracts, and network investment programmes have emerged across Great Britain, the European Union, and the United States jurisdictions as the necessary complement to market signals.

Each electricity system examined has strengths and weaknesses: Great Britain has developed one of the most comprehensive hybrid architectures, combining Contracts for Difference, the Capacity Market, and NESO-coordinated ancillary service markets, with more recent instruments including the Regulated Asset Base model and Dispatchable Power Agreements extending coverage to capital-intensive and emerging technologies (DESNZ, 2024; Low Carbon Contracts Company; BEIS, 2022), but its network development is slow. The European Union's approach is more varied across Member States but is converging following the 2024 Electricity Market Design reform (Council of the European Union, 2024). The United States offers the widest internal variation, with nodal pricing in organised wholesale markets providing strong locational investment signals, but state-level policy complexity and the absence of a federal carbon price creating challenges for whole-system coherence (FERC, 2021). Each system offers lessons for the others, whether this is explicit, long-term technology-specific support (UK), harmonization of cross-border connection (EU) or nodal pricing to improve overall economic efficiency (US). The system as a whole must be decarbonized, but affordability and reliability are also central to long-term viability.

1. Introduction

Electricity systems were historically designed around a set of engineering assumptions. Electricity demand exhibited relatively predictable diurnal and seasonal patterns, generation was largely dispatchable and centrally located, and power flowed largely in a single direction from generators through transmission networks to end users (IEA, 2020; Fox-Penner, 2014; Kundur et al., 2004), as is shown in Figure 1. Large synchronous power plants provided not only energy but also a range of essential system services, including inertia, frequency control, voltage regulation, and fault current, as inherent characteristics of their operation. System planning, market structures, and regulatory frameworks evolved within this paradigm of controllable supply and passive demand.

The net zero transition of power systems is altering these foundational characteristics. The rapid expansion of variable generation, the increasing decentralisation of energy resources, and the electrification of end-use sectors are reshaping the operational dynamics of electricity networks (IEA, 2020). In parallel, advances in digitalisation, demand-side participation, and energy storage are introducing new sources of system flexibility (IPCC, 2022; IRENA, 2019). As a result, electricity systems are transitioning from architectures dominated by dispatchable generation toward more complex configurations in which reliability must be maintained through a portfolio of technologies, operational practices, and market mechanisms (IEA, 2023b).

In this evolving context, it is essential to distinguish between the physical requirements of a reliable power system and the economic and regulatory instruments used to deliver them. Regardless of the generation mix, electricity systems must continuously balance supply and demand, maintain frequency within narrow limits, ensure adequate capacity during periods of system stress, and provide the ancillary services necessary to stabilise network operation.

This report examines how electricity systems are currently designed, what physical system requirement must be maintained as generation portfolios change, and how electricity markets and support mechanisms evolve as power systems decarbonise. The analysis focuses on the electricity systems of Great Britain, the European Union, and the United States. These regions represent three of the most developed electricity markets globally and provide instructive examples of how system operators and regulators are adapting market structures to accommodate changing generation portfolios while maintaining security of supply.

2. How Electricity Systems Physically Work

Electricity systems are governed by physical constraints that require supply and demand to be balanced at all times whilst also maintaining frequency stability, voltage limits, and secure network operation. Understanding these physical conditions is essential when evaluating electricity market design, because markets can then procure services that correspond to the operational needs of the system.

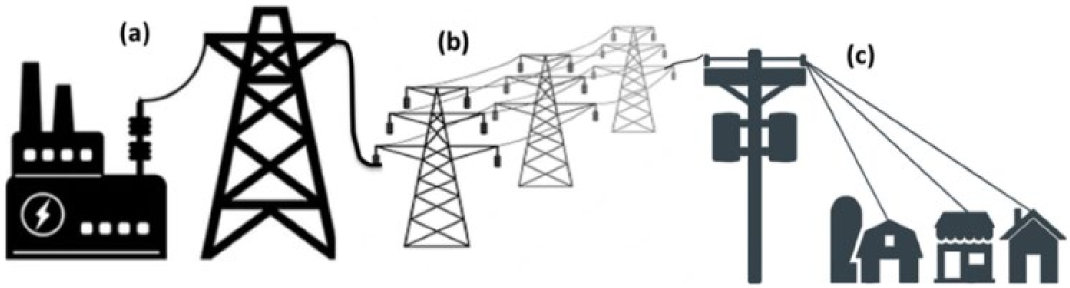

Figure 1: Illustration of electricity generation, transmission, and distribution (a) Electricity generation; (b) transmission system; (c) distribution network. Source: Kgoete, F.M. et al. (2024).

2.1 The Engineering Foundations of Modern Electricity Systems

The architecture of modern electricity systems reflects a set of engineering principles developed to ensure the continuous and reliable delivery of power. At its core, the electricity grid is a synchronised physical system in which generators, transmission infrastructure, and demand must remain in constant equilibrium (Ahlqvist et al, 2022). Although electricity is increasingly being stored through batteries, pumped hydro, and other storage technologies, the power system must maintain a real-time balance between production, flows to and from short-term energy storage, and consumption across the entire interconnected area (IEA, 2020).

This requirement for balance shapes both system design and operational practice. Power system operators must maintain system frequency within narrow tolerances while ensuring that transmission flows remain within the thermal and stability limits of network infrastructure. Achieving this requires a coordinated set of operational controls that respond across multiple timescales, ranging from the instantaneous physical response of generation assets to slower redispatch actions undertaken by system operators as discussed below.

Historically, the technologies used to produce electricity also provided many of the stabilising characteristics required for reliable operation. Large synchronous generators contributed inertia through their rotating mass, helping to resist rapid changes in system frequency following disturbances. They were also capable of delivering frequency response, reactive power, and voltage support as part of normal operation. These properties allowed electricity systems to maintain stability even when subject to fluctuations in demand or unexpected outages of generation or transmission assets (Kundur, 1994; Kundur et al., 2004).

Until relatively recent times, the engineering design of power systems has therefore assumed the persistent availability of these stabilising characteristics. System operators relied on a combination of reserve capacity, automated control systems, and network planning standards to ensure that sufficient flexibility was available to respond to contingencies. Reliability was typically maintained through operating reserves, contingency planning, and reserve margins that ensured additional generation could be deployed rapidly when required.

These operational principles underpin the structure of electricity systems regardless of the generation technologies deployed. While the composition of generation portfolios may evolve over time, the fundamental requirements of frequency stability, voltage control, and network security remain constant. Understanding these physical constraints is therefore essential when evaluating the adequacy of electricity market design and the ability of different resources to contribute to system reliability.

What happens when there is not enough generation?

When total generation falls short of demand, for example, because a large power station trips unexpectedly, frequency begins to fall immediately. The rotating mass of synchronous generators elsewhere on the system provides inertia that resists this fall. Fast frequency response services inject additional power. If frequency continues to fall, protective relays begin disconnecting blocks of demand to prevent a system-wide collapse. Voltage is managed separately: reactive power from generators and network equipment keeps voltage within safe limits at every point in the network. Both frequency and voltage must be controlled simultaneously, at all times, regardless of generation mix. The inertia that provides the first layer of defence comes almost entirely from synchronous machines. As those machines are displaced by wind and solar inverters, which do not naturally provide the same response, the system's tolerance for sudden generation loss narrows, requiring attention to the services provided by synchronous machines.

2.2 System Operators and the Scope of Explicit Procurement

Coordinating the physical operation of electricity systems requires more than generation assets. Great Britain's electricity market, which covers England, Scotland, and Wales but not Northern Ireland, operates as a single bidding zone (Ofgem, 2014). The National Energy System Operator (NESO) in Great Britain (see Figure 2) manages real-time balancing and procures the ancillary services the system needs (NESO, 2024). Across continental Europe, national Transmission System Operators coordinate through ENTSO-E (ENTSO-E, nd). In the United States, Independent System Operators and Regional Transmission Organizations run wholesale markets and manage system balancing across distinct regional footprints, alongside large areas served by vertically integrated regulated utilities (FERC, n.d.; ISO/RTO Council, n.d.).

What has changed in recent years is the scope of what these operators must explicitly procure. A generation ago, frequency response, inertia, and voltage support arrived as automatic consequences of thermal electricity dispatch. Today, as that thermal fleet retires, system operators must go to market for each of these services separately. The range of services being explicitly tendered is expanding, the markets designed to procure them are becoming more granular and technically sophisticated, and the signals they send are increasingly shaping investment decisions across the sector. This shift from implicit to explicit procurement of system services is one of the defining characteristics of electricity market reform in all three regions this report examines.

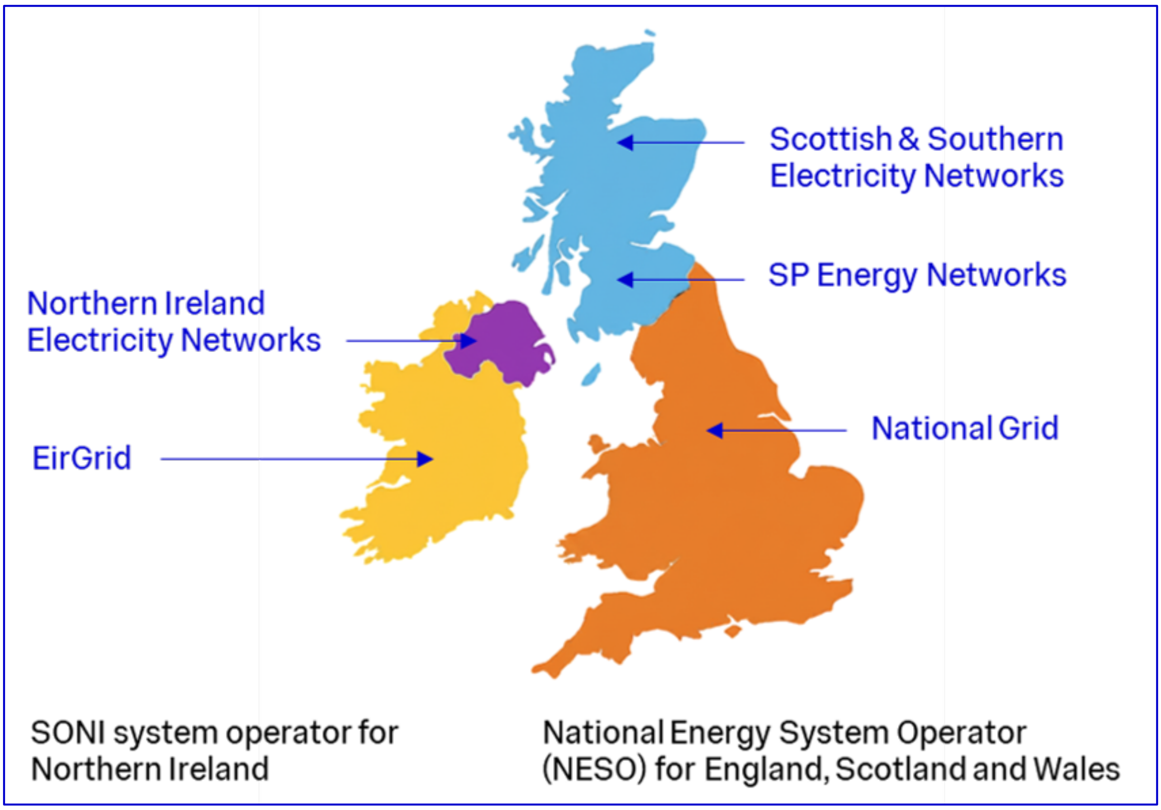

Figure 2: Structure of electricity networks in Great Britain and Ireland, showing roles of transmission operators. Source: Authors' own work.

2.3 How Generation Technologies Differ in Their System Contributions

Not all generation technologies contribute equally to system operation. Their value depends not on energy output and cost of generation alone but on three further properties: whether that output can be controlled and scheduled at the discretion of the system operator; whether the technology contributes to the physical stability of the system through inertia, frequency response, or voltage support; and what greenhouse gas emissions it produces across its lifecycle.

Variable resources, principally wind (as illustrated in Figure 3) and solar, produce electricity whenever weather conditions allow. Their output cannot be increased on demand; it can only be curtailed downward. They provide large volumes of low-carbon energy at very low marginal cost and are central to the economics of decarbonisation (IRENA, 2024). They do not, however, inherently provide dispatchability, inertia, or the ability to sustain output.

The cold weather event in Texas of February 2021 is instructive in this respect. The proximate cause of the system failure was the freezing of gas infrastructure, where wells, pipelines, and gas-fired generation units froze, whereas wind generation continued to operate broadly within its expected seasonal range (Levin et al., 2022), highlighting the importance of fuel supply chain and infrastructure resilience to adverse weather events, and demonstrating that renewables can also assist with security of supply under certain conditions.

Figure 3: An aerial view of the Power County wind farm - Power County, Idaho with Nordex N100/2500 turbines. Source: U.S Department of Energy (2012).

Fast acting flexible resources can adjust output quickly in response to system conditions. This category spans battery storage, pumped hydro, demand response, interconnectors, aggregated industrial loads, unabated bioenergy, and some gas-fired generation, such as Open Cycle Gas Turbines (OCGTs). Flexibility is primarily about response speed and cycling capability at short timescales (IEA, 2020; IEA Wind TCP Task 25, 2025). It is distinct from firmness. A resource may be highly flexible over minutes or hours without being capable of sustaining output for multiple days during a prolonged period of calm, overcast weather (NREL, 2019; Denholm et al, 2021; ESIG, 2024).

Firm resources provide dependable output when required, regardless of weather, time of day, or season. Firmness is a system requirement defined by when it is needed and for how long. Several technologies, including nuclear generation, gas-fired power plants and biomass-fired power plants (with or without carbon capture and storage) dispatchable hydroelectric generation (see Figure 4), and potentially hydrogen-fired turbines where fuel supply is available can provide it. The central policy question is which combination of firm, flexible, and variable resources most reliably and cost-effectively meets the full range of system needs. Some technologies, notably pumped hydro storage, large-scale batteries, biomass-fired power plants, OCGTs and interconnectors, can operate as both firm and flexible resources depending on their state of charge, dispatch position, and contractual obligations.

Figure 4: South side of the dam at the Tillery Hydroelectric Plant. Source: Wikimedia (2020)

2.4 Managing a Weather-Dependent Power Generation System

As renewable penetration increases, system operators increasingly manage what is known as residual demand: total electricity consumption minus the real-time output of wind and solar generation. This quantity can fall to very low levels or even go negative during periods of strong combined output and low demand (Ma, 2026; Hirth, 2013). It can also rise sharply when conditions change: the ramp in residual demand on a calm winter evening, as solar output drops quickly while heating loads remain high, is one of the most operationally demanding scenarios facing system operators in high renewables systems (IEA Wind TCP Task 25, 2025).

The shape of these residual demand patterns reflects the correlation structure of renewable output. Wind and solar generation exhibit some degree of complementarity, which reduces aggregate variability relative to either source alone. However, this does not prevent periods in which both are simultaneously low. These conditions arise under large-scale weather systems, particularly winter high-pressure regimes, that suppress wind speeds and solar irradiance across wide geographic areas (Bett and Thornton, 2016; Miglietta et al., 2017). As a result, the system needs firm capacity most acutely when renewable output is least available across the entire region. Firm capacity is the response to the renewable shortfall, not an additional requirement running in parallel to it. Geographic diversification of renewable plants reduces but does not eliminate this correlation. It is a fundamental property of weather-dependent generation (Bett and Thornton, 2016). Partial complementarity therefore reduces variability in normal conditions but does not eliminate the risk of sustained renewable shortfall.

The practical consequence is the phenomenon referred to in European power markets as *Dunkelflaute*: extended periods during which wind and solar output are simultaneously and persistently low across wide geographic areas. These events are most common between November and January in Europe, when high-pressure blocking patterns bring calm, cloudy conditions that suppress both wind generation and solar irradiance simultaneously. They can persist for one to two weeks or longer (Bett and Thornton, 2016), and recent European winters have provided concrete examples of their market impact: events in November and December 2024 saw combined renewable output fall to a fraction of expected levels across multiple interconnected systems, driving wholesale prices to extreme levels and demonstrating that correlated low-output periods remain a structural feature of weather-dependent generation even at high installed capacities (Otero et al., 2022; Kittel and Schill, 2024; Wilczak et al., 2025). The most extreme *Dunkelflaute* event recorded in European climate data occurred in the winter of 1996/97, and modelling suggests it would have required storage of the order of 351 TWh or 7.1% of the yearly demand (Kittel and Schill, 2024). Their implications for system stability depend on the mix of resources used to cover the shortfall, with inverter-dominated responses potentially requiring additional frequency-stability services to be procured explicitly.

The requirement for firm capacity in this context is therefore not independent of renewable deployment, but arises directly from the need to maintain adequacy during prolonged periods of correlated low renewable output (IEA, 2020; ESIG, 2024). Geographic diversification of renewable plant reduces the frequency and severity of correlated low-output periods by ensuring that blocking patterns affecting one region do not simultaneously affect all generation, but it does not eliminate the risk (Otero et al., 2022). Where blocking events are sufficiently large in spatial extent, as they can extend across the North Sea and Western European wind resource zones (Otero, 2022; Kittel and Schill, 2024), interconnection provides limited relief, since the systems most likely to need imports are simultaneously experiencing the same meteorological conditions as their neighbours. This is a fundamental property of weather-dependent generation, and it defines the system need for firm, dispatchable capacity that operates independently of prevailing atmospheric conditions.

The practical consequence for market design is a structural shift in what the system values. Energy output during periods of abundant renewable generation is worth very little at the margin. The capacity to respond quickly, to sustain output during extended scarcity, and to maintain system stability while doing so is worth considerably more. This shift from valuing energy volume to valuing system services is the central dynamic driving electricity market reform across all three jurisdictions examined in this report, evidenced in practice by the EU's

2024 Electricity Market Design reform (Council of the European Union, 2024), the sustained expansion of GB's Capacity Market and Contracts for Difference programme (DESNZ, 2024), and the technology-neutral clean electricity credits introduced under the US Inflation Reduction Act of 2022, as amended by the One Big Beautiful Bill Act of 2025.

3. What Power System Decarbonisation Requires

The physical analysis in Section 2 generates a specific set of system requirements. These requirements define what any credible electricity market must procure as decarbonisation proceeds. They are technology-neutral: they describe what is needed, not which technologies should provide it. The distinction matters because a great deal of policy confusion arises from conflating the two.

3.1 Grid Infrastructure

Generation capacity has expanded rapidly across most major economies. Grid infrastructure has not kept pace. Transmission networks (as exemplified in Figures 5 and 6), substations, transformers, and connection assets have become constraints on decarbonisation and the pace of capacity expansion that are at least as consequential as any generation challenge (IEA, 2023b). New-build generation projects that are technically ready and economically sound sit in planning and connection queues for years because there is insufficient network capacity to accommodate them (IEA, 2023e; Ofgem, 2025b; NESO, 2025b). In this sense the grid has become a limiting factor in the energy transition, rather than a passive conduit for it.

Figure 5: Anchor pylon of high-voltage overhead power line 750 kV. Source: Dimtryi Novoklimov (2010),

The underlying cause is a mismatch between how transmission investment has historically been planned and what the transition requires (IEA, 2023e). Network planning was built around the location of existing generation, overwhelmingly large thermal stations near fuel sources or cooling water, rather than the dispersed geography of wind and solar resources (Hughes, 1983). Correcting that mismatch requires coordinated planning across generation, networks, and market rules, combined with regulatory frameworks capable of authorising and financing investment at appropriate pace.

The locational dimension of this problem is becoming sharper. Renewable generation is often sited far from major demand centres. Simultaneously, data centre growth and industrial electrification are producing new concentrations of demand in locations determined by land availability, fibre connectivity, and planning conditions rather than by proximity to existing network capacity (IEA, 2025; Ofgem, 2026; NESO, 2025c). Data centres require not only large electricity supply but also water (Mytton, 2021), raising additional siting and infrastructure considerations. The International Energy Agency projects that global electricity demand from data centres could more than double between 2024 and 2030, driven principally by artificial intelligence workloads (IEA, 2025). Adequacy can become locally constrained even when system-wide generation capacity appears sufficient. Transmission expansion is not a supplementary element of the energy transition; it is a precondition for it.

At the distribution level, constraints are becoming increasingly significant as electrification and decentralisation accelerate. The growth of electric vehicles and heat pumps is increasing local peak demand, while distributed energy resources are introducing bidirectional power flows into networks originally designed for one-way supply (NESO, 2023a). This is transforming distribution systems into actively managed networks, expanding the role of Distribution System Operators in coordinating resources and maintaining reliability. Demand-side flexibility, through smart charging and responsive loads, is therefore becoming essential to manage local constraints and reduce the need for costly network reinforcement.

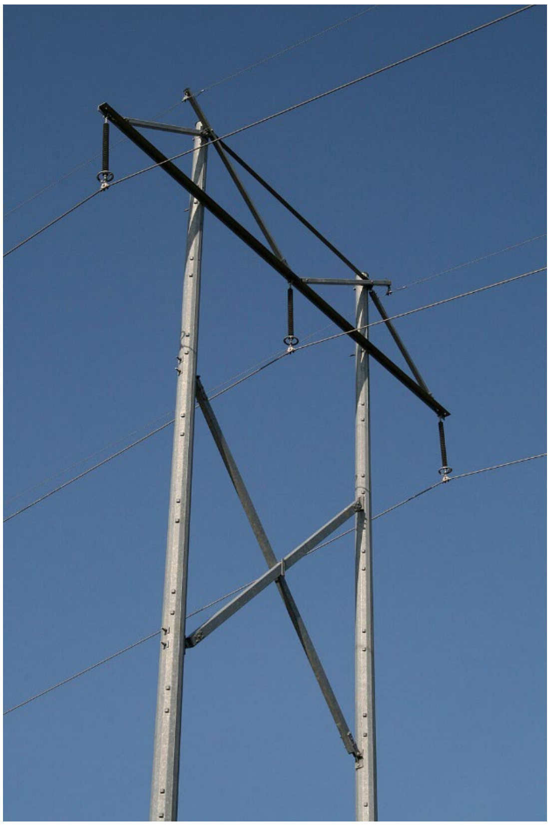

Figure 6: H-frame transmission tower (suspension pylon) along Indiana I-69 Corridor Project, Section 5; Monroe County, Indiana. Source: I-69 Construction Indiana (2017).

3.2 Frequency, Voltage, Inertia, and the Explicit Procurement of Stability

Electricity systems must hold frequency and voltage within narrow tolerances continuously. The physical mechanism through which this was historically achieved was the rotational inertia of large synchronous generators: the stored kinetic energy in their spinning mass resisted sudden changes in system frequency and provided the time necessary for automated protections and reserve dispatch to respond to faults. As synchronous thermal plant retires, this inertia is declining across most major systems.

The consequences are tangible. The rate of frequency change following a fault is increasing, compressing the window within which corrective action must occur (NESO, 2023b). This is already shaping operational practice in Great Britain, Ireland, and parts of continental Europe, where minimum inertia constraints now bind the scheduling of generation. ENTSO-E's work on system flexibility requirements makes clear that grids with high shares of inverter-based resources need more deliberate and systematic procurement of stability services, not less (ENTSO-E, 2024b).

Synchronous condensers, grid-scale batteries with appropriate inverter control, and dispatchable generators can each contribute to stability service provision (ENTSO-E, 2024b; NESO, 2025a). The key point for market design is that these services must be explicitly procured and remunerated through mechanisms that adequately reflect their value to the system. Where such mechanisms are absent or poorly calibrated, systematic under-investment in stability is a predictable result.

3.3 Black Start and System Restoration

Black start capability, the ability to restart the power system following a widespread outage without drawing on an external electricity supply, is a fundamental reliability requirement that becomes harder to guarantee as dispatchable thermal plant retires (NERC, 2024; ENTSO-E, 2024b). Conventional black start was provided by large thermal and hydro units capable of self-starting and energising transmission circuits. In practice, even thermal plants typically rely on auxiliary diesel generators and on-site systems to initiate start-up, meaning black start depends on a chain of fuel availability and mechanical readiness. As that fleet shrinks, system operators must identify and contract alternative providers (NESO, 2025a).

Dispatchable low-carbon plants can fulfil this function while also contributing inertia and other ancillary services during normal operations, which is one reason why their system value extends well beyond the energy it generates. System operators in Great Britain, across Europe, and in several US regions are actively reviewing their black start arrangements as the generation mix changes (NERC, 2024). In Great Britain, the National Energy System Operator is also exploring bottom-up restoration approaches through its Distributed ReStart programme with SP Energy Networks, which investigates the use of distributed energy resources, including renewables, to re-energise the grid (SP Energy Networks, 2022). The requirement is real, growing, and must be addressed through explicit procurement.

3.4 Resource Adequacy in a Weather-Dependent System

Traditional reserve margin analysis assessed adequacy by comparing installed generating capacity with forecast peak demand, adjusted for planned outages and forced outage rates (Denholm et al, 2025). That approach was fit for purpose when the vast majority of generation was dispatchable. It is no longer sufficient on its own.

The relevant question is not whether aggregate installed capacity exceeds expected peak demand but whether the system can reliably serve demand across multi-day periods of correlated low renewable output, across transmission bottlenecks that constrain imports, and through the tail events that simple reserve margin calculations do not capture. The U.S. Department of Energy's 2024 assessment of resource adequacy argues explicitly for moving beyond static capacity counting toward multi-period, energy-constrained analysis (U.S. DOE, 2024), and that is the right direction.

Research from the National Renewable Energy Laboratory demonstrates that the capacity credit of wind, solar, and battery storage varies materially across systems and declines at the margin as deployment increases (Pham, Cole and Gagnon, 2024). This is not an argument against deploying these technologies. It is an argument for designing adequacy mechanisms that assess resources on the basis of their actual contribution under stress conditions, rather than their nameplate capacity or a simplified derating factor.

The requirements identified in this section, reliable network capacity, stability services, black start capability, and firm energy supply during extended scarcity events, define what any electricity market operating in a high renewables environment must procure. The technologies capable of meeting those requirements, and the market instruments designed to incentivise them, are the subjects of the two sections that follow.

4. Technology Roles: A Portfolio Assessment

Although a power system could theoretically be centred on a single technology or fuel source, reliable low-carbon electricity systems in practice require a portfolio of complementary resources with different operational characteristics. This observation is not a criticism of any particular technology; it is a description of physical reality. The appropriate framework for electricity system planning is therefore a portfolio one, and the appropriate policy question is not which technology should win but which combination of technologies most reliably and cost-effectively meets the full set of system needs. This section assesses the principal resource categories against those needs on a technology-neutral basis.

Figure 7: Solar plant in Ameland, Friesland, the Netherlands. Utility-scale solar photovoltaic installation generation electricity for the power grid. Source: Wikimedia (2019).

4.1 Renewable Energy

Wind and solar (such as Figure 7) generation represent important sources of new electricity generation capacity in most major economies and are expected to play a central role in power-sector decarbonisation (IEA, 2023a; IPCC, 2022). Cost reductions over the past two decades have been extraordinary, such as the drop in the levelised cost of utility-scale solar PV by more than 90% between 2010 and 2023 (IRENA, 2024). The continued deployment of renewables at scale is both necessary and inevitable in any credible net-zero scenario. The question this section addresses is not whether to deploy them but how to understand their system characteristics and what complementary resources those characteristics require (IEA, 2021; IPCC, 2022).

On the question of firm supply, variable generation faces an inherent limitation at high system penetration. Output is correlated with meteorological conditions that can persist at low levels for days or weeks across wide geographic areas. A system relying on wind and solar alone would, during such periods, face a substantial and sustained gap between available generation and system demand, regardless of how much installed capacity it contained. No level of geographic diversification fully removes this risk; it reduces it, but the residual is material and must be addressed through other means. It is worth noting that wind and solar can exhibit diurnal and seasonal complementarity in certain geographies, solar output peaks in summer, wind output peaks in winter in many temperate regions, which helps to partially offset aggregate variability. However, this complementarity is geography-dependent and does not eliminate the risk of coincident low output across both technologies during prolonged adverse weather.

On stability, inverter-based wind and solar do not inherently provide synchronous inertia, meaning the kinetic energy stored in the rotating mass of synchronised generators that resists rapid changes in system frequency following disturbances (ENTSO-E, 2024b; Denholm et al, 2021). Modern installations can provide fast frequency response and some forms of synthetic inertia through inverter control systems (NREL, 2021b), but these require deliberate specification and remuneration. They do not arrive automatically as a by-product of generation, which is a material difference from how stability services were historically supplied by thermal plant.

None of this diminishes the central importance of variable generation to the energy transition. It does make clear why they must be complemented by resources with different system characteristics, and why market design that treats energy output as the only product worth procuring and pricing will systematically fail to deliver a reliable system.

Curtailment becomes more frequent as renewable penetration rises (Hirth, 2013; IEA, 2025), occurring when generation exceeds demand or network capacity, often during low or negative prices. It is not just a technical constraint but an economic signal of declining marginal value as output becomes more abundant and correlated. For this reason, there is a growing trend in Europe for renewables projects to be built as hybridised projects coupled to energy storage (Chatzigeorgiou et al, 2024) (see next section). As shown by Hirth (2013), the market value of wind and solar falls with higher penetration, and curtailment reflects this effect by highlighting that system value depends on when and where generation is delivered.

This effect is illustrated in Figure 8 from Bui et al, 2018: as larger quantities of low-carbon generation are added, total system costs begin to rise despite further emissions reductions. The effect is particularly visible for weather-dependent generation technologies such as wind and solar, although integration costs and system-value effects are not unique to those technologies and depend on the operational characteristics of the resource being deployed.

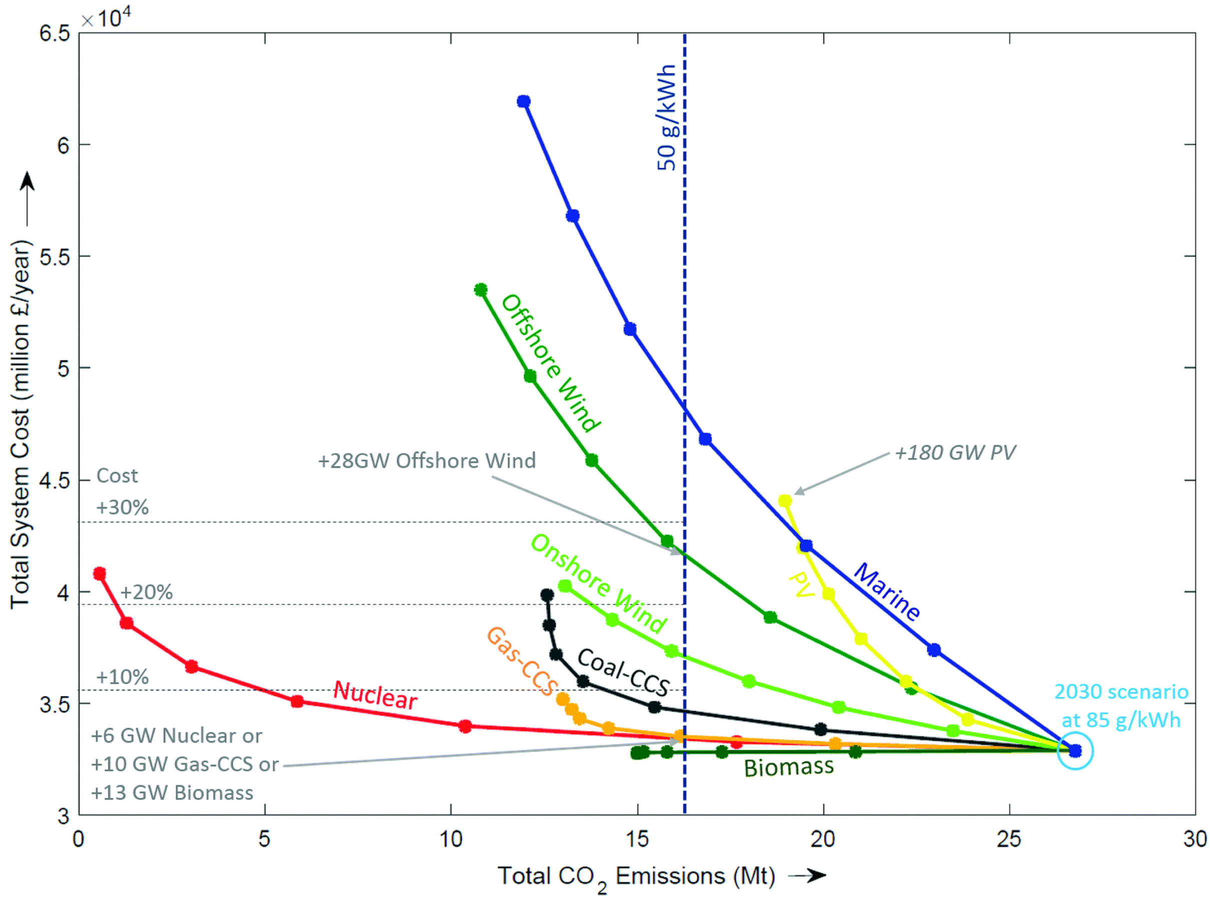

Figure 8: Illustrative system cost and emissions effects of adding low-carbon generation technologies in 5GW increments to a central 2030 UK electricity-system scenario. The figure demonstrates how additional deployment can reduce emissions while also increasing total system costs where integration, balancing, network, or adequacy requirements become more significant. Source: Bui et al (2018).

The policy implication is that renewable deployment cannot be assessed on generation cost alone. At low and moderate penetration, falling technology costs make wind and solar the lowest-cost route to decarbonising large parts of electricity supply. At higher penetration, however, the binding constraint shifts from producing enough low-carbon electricity to maintaining adequacy, flexibility, and system stability during periods when renewable output is either excessive or scarce. A credible electricity-market design must therefore procure not only low-carbon energy, but also the complementary capabilities required to make a renewables-heavy system reliable.

4.2 Storage

Battery storage (such as that shown in Figure 9) has transformed the operational flexibility available to system operators over the past decade. Sub-second response times, the ability to shift energy across intra-day periods, and rapidly declining costs have made batteries an indispensable component of high-renewable grids (Denholm et al, 2021); NREL, 2019). Their value in managing short-cycle variability and providing fast frequency response is well established and widely recognised.

The adequacy limitation of short and medium-duration battery storage is equally well established, though it receives less policy attention than it deserves. Most deployed systems provide two to four hours of storage, which is ample for managing the evening demand peak or the morning ramp, but insufficient to cover a multi-day period of low wind and solar output (NREL, 2021b; IEA, 2024b; ESIG, 2024). The distinction between flexibility for short-cycle balancing, at which batteries excel, and firm capacity for sustained scarcity events, which requires either long-duration storage or dispatchable generation, is among the most important distinctions in contemporary adequacy analysis. It is not a distinction that simple reserve margin calculations make visible, which is one reason it is under-appreciated in policy discussions.

Long-duration storage technologies, including pumped hydro, compressed air energy storage, thermal storage, and long-duration flow batteries, could in principle address the multi-day adequacy challenges, although most remain insufficiently developed at system scale. Pumped hydro also contributes synchronous inertia directly from its rotating machinery, which adds further system value (Kundur, 1994). The commercial maturity of these technologies varies considerably. Pumped hydro storage represents a highly reliable black start resource in generation mode, since the release of stored gravitational potential energy enables turbine start-up and electricity generation without external power input, although pumping operations remain dependent on grid-supplied electricity. Most other long-duration options remain expensive relative to alternatives and are not yet deployed at the scale required to substitute for firm dispatchable generation at the system level.

Figure 9: A large battery storage power station with a capacity of 6.24 MWh and an output of 5 megawatts (Tesvolt TPS-E). Source: Wikimedia (2024)

4.3 Demand-Side Flexibility

Electrification is creating flexible loads at scale that did not previously exist. Electric vehicle charging, heat pump operation, and a growing range of industrial processes can shift their electricity consumption in time without compromising their primary function. As smart metering and control infrastructure extends, the practical potential of demand-side flexibility is increasing.

For system planning purposes, demand-side flexibility contributes most usefully to short-cycle balancing and to the management of peak demand (IEA, 2020). Its contribution to multi-day adequacy is limited by the same logic that limits short-duration storage: it can defer consumption, but it cannot create energy that is not there. During an extended period when wind and solar output is low across a wide area, demand flexibility postpones the problem rather than solving it. Its contribution to physical stability services is also limited; it does not provide inertia, black start capability, or voltage support.

These limitations do not diminish the value of demand-side flexibility as a component of the portfolio. They do place it in the right context: a necessary and cost-effective tool for managing variability and reducing peak requirements, but not a substitute for firm generation capacity when the system faces extended scarcity.

Demand-side flexibility is also evolving beyond its traditional industrial and commercial form. The growing deployment of electric vehicles, domestic battery storage, smart heat systems, and distributed solar generation is creating a large pool of price-responsive and potentially dispatchable demand-side resources (NESO, 2023a). Smart tariffs already incentivise consumers to shift electricity consumption toward periods of lower system demand and higher renewable output, reducing peak stress and improving system utilisation. Vehicle-to-grid capability and aggregated domestic storage further expand the potential for distributed flexibility provision.

A parallel trend is occurring in distributed generation. Regulatory reforms in several European jurisdictions, including Germany's expansion of small-scale "balcony solar" (German Federal Network Agency; Reuter, 2025), demonstrate how rapidly decentralised household generation can scale once planning and connection barriers are reduced. Great Britain has begun moving in a similar direction. While these resources do not remove the need for firm generation capacity during extended scarcity events, they materially increase system flexibility, reduce peak demand pressure, and strengthen the role of consumers as active participants in electricity system operation.

4.4 Firm Low-Carbon Dispatchable Generation

Firm dispatchable low-carbon generation directly addresses the adequacy and stability gap that storage and demand flexibility cannot close at current technology costs and deployment levels. The defining characteristic is the ability to produce dependable output on demand, across extended periods and regardless of weather conditions, while meeting decarbonisation requirements. This is a system service requirement, not a technology specification. Several technologies can meet it, and the appropriate policy position is to procure the service and allow technology competition to determine how it is delivered.

Nuclear power (see Figure 10) provides near-zero-carbon output at high-capacity factors and, as a synchronous technology, contributes inertia and voltage support as inherent features of operation. Its adequacy contribution is substantial and well-established. Flexibility is more constrained than gas-fired plant, though modern reactor designs demonstrate considerably greater load-following capability than early assumptions suggested (IAEA, 2018). The primary constraints on nuclear deployment are capital cost, construction timescales, and supply chain depth rather than technical performance (IEA, 2022). Where these can be addressed, nuclear offers one of the most complete responses to the adequacy and stability problem in a decarbonised system.

Figure 10: Taishan Nuclear Power Plant, Units 1 & 2, Guangdong, China. Source: EDF Energy (2019).

Fossil generation with carbon capture and storage provides flexible firm capacity with substantially lower emissions than unabated operation. As a synchronous technology, it contributes inertia and can provide black start services. Residual emissions depend on the capture rate and the upstream carbon intensity of the fuel supply chain; the label CCS covers a wide range of actual emissions performance, and claims about carbon intensity should be verified against operational data rather than design assumptions. Where capture rates are high and fuel supply chains have low upstream emissions, this technology category can deliver genuinely low-carbon firm generation at commercially available timescales.

Bioenergy with carbon capture and storage combines the operational characteristics of dispatchable thermal generation with the potential for net-negative emissions, subject to biomass sustainability requirements and the permanent geological storage of captured carbon being verified. From a power system perspective, a BECCS plant operates as a synchronous thermal generator: it provides inertia, frequency response, and black start capability alongside dispatchable firm output. Integrated assessment models consistently identify a role for BECCS in cost-effective net-zero pathways (Bui et al, 2018), principally because it is one of very few technologies capable of delivering firm low-carbon power while simultaneously removing carbon dioxide from the atmosphere (IPCC, 2022). Its actual performance depends critically on supply chain sustainability verification and storage permanence, both of which require rigorous independent assessment.

Unabated bioenergy also warrants recognition as a distinct firm and dispatchable resource. Where biomass sustainability requirements are met, unabated bioenergy generation operates as a controllable thermal plant with low lifecycle carbon emissions (IPCC, 2022). It contributes firm capacity, synchronous inertia, and flexible dispatch, and in some systems plays an important role in grid stabilisation and balancing. Unlike BECCS, it does not require carbon capture infrastructure and does not offer net-negative emissions, implying a more limited and potentially transitional role within decarbonisation pathways. Its net carbon position depends on supply chain verification and lifecycle carbon accounting, and it should be assessed within a whole-system framework.

Low-carbon hydrogen-fired generation provides fast-ramping flexible capacity and can contribute synchronous inertia through modified gas turbine technology. Its adequacy contribution depends on hydrogen availability and storage infrastructure at the scale required for power system applications, both of which are at early commercial stages. Emissions performance depends entirely on the production pathway; hydrogen produced from low-carbon electrolysis or from natural gas with CCS can underpin genuinely low-carbon generation (IEA, 2021; IEA, 2024a), but that chain of custody must be established and verified rather than assumed from the fuel label alone.

Across all of these options, the system-level conclusion is consistent: Firm low-carbon dispatchable generation is a category of service requirement, not a technology mandate. Policy frameworks should specify what the system needs: sustained output during scarcity events, synchronous stability services, black start capability, and verified low-carbon credentials, and allow competitive procurement within those specifications. Technology-neutral capacity mechanisms, long-term contracts, and well-designed ancillary service markets are the instruments through which that procurement should occur.

4.5 Sector-Coupled Resources: Thermal and Electrical Integration

Combined heat and power systems occupy a distinctive position in electricity system analysis. Their thermodynamic efficiency, producing both electricity and useful heat from a single fuel input, is their most commonly cited characteristic, and it is genuinely high relative to separate heat and power generation. For electricity system purposes, however, thermodynamic efficiency is not the relevant measure. What matters is whether the electrical output can be scheduled to meet system needs, and in most configurations, it cannot provide this capability independently (IEA, 2020; IPCC, 2022).

In conventional heat-led CHP, electricity generation follows thermal demand (IEA, 2020). The unit runs when the connected building(s) or process needs heat, and electricity is produced as a consequence. When heat demand is low, the unit is off regardless of prevailing system conditions. This means that heat-led CHP cannot be relied upon to provide firm capacity during electricity-system stress events; it may equally be generating at times when surplus renewable output is already driving system prices below cost. Assessed against the system requirements identified in Section 3, heat-led CHP operating on fossil fuels offers limited and declining value.

The picture changes materially when CHP is connected to thermal storage or flexible district-heating networks. Thermal storage allows the heat and power decisions to be decoupled:

the unit can run when the electricity system needs it, store the heat for later use, and reduce output when the system is long. In this configuration, CHP becomes a genuinely flexible electricity-system asset. Its stability contribution, synchronous inertia and frequency response from the rotating plant, is present in either configuration and is a system value that is routinely understated in assessments focused on fuel efficiency.

The fuel supply matters as much as the operational design. Gas-fired CHP produces lower carbon intensity than separate generation and heating, but it remains a fossil source with a finite role in a net-zero system. CHP fuelled by verified low-carbon hydrogen or sustainably sourced bioenergy can deliver substantially lower lifecycle emissions, though the same verification requirements that apply to other fuel-dependent technologies apply here. The appropriate conclusion for policy is to assess each CHP configuration on its actual operational design, fuel supply, and system contribution rather than treating the technology category as having a fixed and predetermined role in the transition.

4.6 Portfolio Characteristics

The analysis across Sections 4.1 to 4.5 establishes several conclusions about the portfolio characteristics a net-zero electricity system requires. Variable renewables provide the majority of energy at low marginal cost but cannot on their own deliver the adequacy, stability, or firm capacity services the system needs at high penetration. Short-duration storage provides indispensable short-cycle flexibility but cannot substitute for multi-day firm capacity. Demand-side flexibility is valuable for peak management and short-cycle balancing but is subject to the same duration constraints. Firm dispatchable low-carbon generation, across several competing technologies, provides the adequacy and stability attributes that the other categories cannot supply.

A useful way to compare resource contributions on a technology-neutral basis is through Equivalent Firm Power (Helm, 2017b; Helm, 2019). This framework expresses different technologies in terms of the amount of firm, dispatchable power they can effectively provide under conditions of scarcity. Rather than relying on installed capacity or average output, it assesses their contribution to reliability based on dependable delivery when it is most needed. In doing so, it provides a common metric across variable generation, storage, demand-side flexibility, and firm generation, and highlights that resources with similar capacities can have very different system value.

Table 1, below summarises the system characteristics of each category. Ratings are indicative and technology-neutral, reflecting the inherent properties of each category rather than the performance of any specific installation. The purpose is to make the portfolio trade-offs visible rather than to score or rank technologies.

Table 1: Summary of Resource Category Characteristics

Resource Category	Firm Adequacy	Flexibility	Stability Services	LCA Performance
Variable renewables	Low at high penetration	Curtailment only	Via inverter control	Excellent
Short/medium-duration storage	Low, duration constrained	High	Inverter-based (no inherent inertia)	Excellent in operation
Long-duration storage and pumped hydro	High, subject to cost maturity	Moderate	High for pumped hydro	Excellent
Demand-side flexibility	Partial, short timescales	Moderate to high	Low	Good
Nuclear	High	Moderate	High, synchronous	Excellent
Fossil with CCS	High	High	High, synchronous	Good to excellent at high capture rates
BECCS	High	Moderate to high	High, synchronous	Net-negative potential
Unabated Bioenergy	High	Moderate to high	High synchronous	Highly variable (sustainability-dependent)
Low-carbon hydrogen	Moderate, fuel dependent	High	Moderate, turbine type	Good, pathway dependent
CHP, thermally decoupled, low-carbon fuel	Partial	Moderate	Moderate, synchronous	Fuel dependent

Reading across the table, no single category scores well on all dimensions; most involve inherent trade-offs. The categories that score well on firm adequacy and stability, nuclear, fossil with CCS, BECCS, and to a lesser extent long-duration storage, are those that address the system requirements that variable generation and short-duration storage cannot reliably meet. This is the technical basis for the conclusion that a net-zero electricity system requires a portfolio drawing on all categories, and that market design must be structured to procure all of the relevant system attributes rather than relying on energy prices and carbon pricing alone.

5. Markets and Support Mechanisms

The analysis in Sections 3 and 4 establishes what electricity systems must procure, and which resource categories can provide it. This section examines how market frameworks and support mechanisms are designed to deliver those outcomes across the UK, EU, and US, and why the energy-only market model that prevailed during the first generation of liberalisation is structurally inadequate for the task.

Two points of frequent public misunderstanding warrant clarification. First, the cost of support mechanisms in the United Kingdom has historically fallen on primarily on energy consumers through supplier obligations and levies, rather than on general taxation. This is a significant distinction: support costs are embedded in electricity bills rather than drawn from public expenditure, and the institutional and political accountability for those costs differs accordingly. The same distinction applies, with variations, across the EU and US jurisdictions examined in this section. Second, support of some kind is not exceptional to any one technology. All forms of generation have historically benefited from public subsidy, policy protection, or below-market financing at some stage of their development, including coal, gas, nuclear, and renewables (IEA, 2023c; Mazzucato, 2013; Helm, 2017a). The question is not whether a technology receives support, but whether the support is well-designed, proportionate, and time-limited relative to the system value delivered.

5.1 The Structural Inadequacy of Energy-Only Markets

Wholesale electricity markets were designed to price energy on the basis of short-run marginal cost. In thermal-dominated systems this was workable, because the resources that produced energy were the same resources that provided reliability, inertia, and stability as bundled by-products of synchronous operation. Revenue from energy sales was broadly sufficient to justify investment in the full range of system capabilities. The Electric Reliability Council of Texas (ERCOT) is a contemporary example of a large grid operating as an energy-only market without a formal capacity mechanism. It is instructive about the theoretical appeal of scarcity pricing and its practical limitations under system stress, as experienced in the February 2021 winter storm event (Prete & Seth, 2023).

High renewables systems unbundle functions that were historically co-delivered by thermal generation. Wind and solar generation depress average wholesale prices during periods of abundant output, reducing the revenue available to all generators (Hirth, 2013). Wholesale markets based on uniform marginal pricing ensure efficient short-run dispatch, with all dispatched units receiving the system marginal price. Scarcity price spikes, which in theory should incentivise investment in firm capacity, in practice, have become politically difficult to sustain and are often capped or intervened upon (Joskow, 2008). As a result, the resources most needed for system reliability, firm dispatchable generation, long-duration storage, and synchronous stability services, earn insufficient revenue from energy markets to justify investment at the scale required. This is the missing money problem, and it widens as renewable penetration increases rather than resolving itself (Joskow, 2008; Cramton and Stoft, 2005).

Carbon pricing through emissions trading schemes makes an important contribution by raising the relative cost of carbon-intensive generation and improving the investment case for lower-emission alternatives. Both the UK ETS and the EU ETS play genuine roles in shifting the merit order and in aligning long-run investment incentives with decarbonisation objectives (Ellerman et al, 2016; UK ETS Authority, 2023; European Commission, 2024). But an emissions trading scheme does not procure adequacy, ensure sufficient inertia nor guarantee black start capability. Carbon pricing is one necessary component of the policy architecture, not a complete response to the problem.

5.2 The Case for Hybrid Market Architecture

The response to the structural limitations of energy-only pricing, observable across all three jurisdictions examined in this report, has been the development of hybrid market architectures that procure multiple system attributes through complementary instruments operating in parallel. This is not a theoretical recommendation that emerges from this analysis. It is a description of what has actually occurred in practice as systems have decarbonised and the inadequacies of pure energy pricing have become operationally apparent. The specific instruments differ by jurisdiction, but the underlying logic is consistent.

5.2.1 Capacity Mechanisms

Capacity markets and equivalent adequacy constructs provide explicit revenue for firm capacity availability, addressing the gap between what energy markets pay and what is needed to justify investment in resources that serve the system during scarcity events. They are sometimes characterised as temporary corrections to market failure. The evidence does not support that characterisation.

Forward capacity auctions in Great Britain (DESNZ, 2024), national capacity mechanisms across EU Member States, and resource adequacy constructs in US Independent System Operators (ISOs) and Regional Transmission Organisations (RTOs) all reflect a shared recognition that as renewables penetration increases (FERC, 2021), the adequacy problem does not become easier. It becomes harder. The marginal system value of firm dispatchable capacity rises as weather-driven scarcity events grow more consequential and as the thermal plant that historically provided adequacy retires (Pham, Cole and Gagnon, 2024; Denholm et al, 2025). Capacity mechanisms address a structural and widening gap, not a temporary one.

Capacity mechanisms are often framed as technology-neutral, with eligibility defined in terms of deliverability and verified reliability contribution rather than fuel type. In practice, however, this neutrality is qualified by design features such as technology-specific de-rating factors, differentiated contract lengths, and emissions constraints, all of which shape participation and investment outcomes. As a result, capacity mechanisms function less as neutral markets and more as structured procurement frameworks, reflecting policy choices about cost, risk allocation, and system priorities. Their ability to support low-carbon firm capacity therefore depends on whether these design features align reliability procurement with decarbonisation objectives.

5.2.2 Ancillary Service Markets

As synchronous thermal generation retires, the stability services it once provided automatically must be procured through formal market arrangements. Fast frequency response, inertia services, reactive power, reserve capacity, and black start are all being brought into competitive procurement processes across the three regions. These markets are becoming more granular in their product definitions, more sophisticated in their technical requirements, and more significant as a source of revenue for assets capable of providing multiple services simultaneously.

The investment implication is considerable. An asset's revenue no longer depends solely on nameplate electricity output. It depends on the full portfolio of system services it can provide and the market mechanisms that remunerate them. Technologies capable of contributing across energy, capacity, and ancillary service markets simultaneously are structurally advantaged in this environment, and that structural advantage is increasing as ancillary service markets develop.

5.2.3 Long-Term Contracting

The technologies most needed for decarbonisation share a common financial characteristic: they are capital-intensive, with high upfront costs relative to their operating costs (Grubb and Newbery, 2018). Renewables, nuclear, long-duration storage, and firm low-carbon dispatchable generation all face significant merchant revenue risk in spot wholesale markets that price at short-run marginal cost (World Nuclear Association, 2026; Simshauser, 2020). That risk raises the cost of capital and, in some cases, makes projects that are socially valuable but commercially marginal impossible to finance at all (Billimoria and Simshauser, 2023).

Long-term contracting mechanisms address this directly. By reducing revenue uncertainty over the investment horizon, they lower the cost of capital and thereby reduce the total system cost of achieving decarbonisation targets. Contracts for Difference, Regulated Asset Base models, production and investment tax credits, and long-term capacity agreements serve this function in different ways across different jurisdictions. They transfer risk from investors to consumers and the state, which creates legitimate questions about governance and affordability that must be taken seriously. The alternative, attempting to finance long-lived capital-intensive assets entirely through merchant revenue, has not delivered the required investment at the required pace in any major jurisdiction where it has been tried.

5.2.4 Affordability and Political Durability

The price events of 2021 and 2022 provided a sharp reminder that electricity markets operate within political limits as well as economic ones. Consumer tolerance for the full pass-through of commodity-linked marginal pricing has proved to be lower than market design architects assumed. Governments across Europe and North America intervened extensively to protect consumers from prices that markets were generating legitimately according to their own rules. UK energy suppliers that failed to hedge their wholesale price exposure went bankrupt, transferring costs to consumers and illustrating that market design without adequate hedging requirements creates systemic as well as political fragility, requiring government support (UK Gov, 2022).

The lesson for market design is not that prices should be administratively suppressed, but that mechanisms which expose consumers to extreme spot price volatility without mitigation are politically fragile. Support frameworks that cannot survive across electoral cycles cannot anchor the long-horizon investment decisions that decarbonisation requires. Affordability, distributional effects, and industrial competitiveness are therefore not external constraints on electricity market design. They are conditions within which it must function if it is to remain durable.

The design of cost recovery mechanisms has important implications beyond political durability. In Great Britain, a substantial proportion of low-carbon support costs has historically been recovered through electricity bills via supplier obligations and levies, whereas the United States relies more heavily on tax-credit frameworks funded through federal expenditure. This contributes to materially higher electricity prices in Great Britain relative to several competing industrial economies (DESNZ, 2026; ONS, 2025).

The issue is particularly significant because many decarbonisation pathways depend on electrification. Heat pumps, electric vehicles, data centres, and electrolytic hydrogen production all become more economically attractive when electricity prices are low relative to fossil fuels. Where policy design embeds a significant decarbonisation cost premium within electricity bills, it can weaken the economic incentive to switch away from gas and oil even where electrified technologies are physically more efficient. This creates a structural tension between the objective of rapid electrification and the fiscal architecture used to fund decarbonisation. Proposals to rebalance policy costs between electricity bills, general taxation, and alternative recovery mechanisms therefore have implications not only for affordability and competitiveness, but for the pace of the transition itself.

5.3 Great Britain

Great Britain's electricity market is among the most developed examples of the hybrid architecture that this section describes. The UK ETS prices carbon in generation and investment. Contracts for Difference provide revenue certainty for low-carbon plant against a strike price, with settlement costs recovered through supplier obligations passed on to consumers (DESNZ, 2024). The Capacity Market explicitly procures firm capacity through competitive forward auctions on a technology-neutral basis. Ancillary service markets, coordinated by NESO, procure inertia, frequency response, reserve, and black start services.

Regulated network investment under the RIIO framework funds transmission and distribution expansion.

Two instruments introduced more recently illustrate the direction of policy development. The Regulated Asset Base model is being applied to qualifying nuclear projects, providing a route for capital-intensive low-carbon generation to access regulated rather than merchant financing and thereby materially reducing its cost of capital. Dispatchable Power Agreements provide contractual revenue support for dispatchable low-carbon plant with carbon capture, filling a gap that neither Contracts for Difference nor the Capacity Market was originally designed to address (BEIS, 2022). The elaboration of these instruments reflects a growing recognition that different technology categories require different support structures, and that the architecture must be capable of accommodating technologies at varying stages of commercial maturity.

A further design question concerns the spatial granularity of wholesale pricing, specifically zonal versus nodal approaches. Great Britain and the European Union use zonal pricing, with a single price per bidding zone and constraints managed through redispatch, while U.S. markets such as Pennsylvania-New Jersey (PJM) Interconnection use nodal pricing that reflects local network conditions. The UK’s Review of Electricity Market Arrangements assessed whether more granular pricing could improve efficiency, concluding in 2025 with a decision to retain a single national wholesale price (DESNZ, 2025). Alternative pricing reforms are now being considered under the Reformed National Pricing (RNP) programme (Ofgem, 2026). The underlying trade-off between accuracy and complexity remains: nodal pricing delivers stronger locational signals but is more complex and can create uneven regional outcomes, whereas zonal pricing is simpler but can mask constraints and increase system costs.

The UK's trading relationship with EU electricity markets is a live strategic issue with material system cost implications. Since Brexit, Great Britain participates in cross-border electricity trade through arrangements that are less efficient than the implicit coupling used within the Internal Energy Market. The 2025 UK-EU common understanding identified possible UK participation in EU trading platforms as a subject for detailed further exploration (Cabinet Office, 2025). Closer market integration would improve interconnector utilisation, reduce system balancing costs, and enable better integration of North Sea renewable resources across the wider regional market. The case for pursuing this is strong on system efficiency grounds. The future direction of carbon pricing policy is also under active consideration: formal linking of the UK ETS and EU ETS is currently being explored as part of broader UK-EU negotiations, which could materially affect relative carbon prices, cross-border investment incentives, and the competitiveness of low-carbon generation on both sides. Table 2 summarises the principal support mechanisms in the UK.

Table 2: Principal Support Mechanisms, United Kingdom

Mechanism	Purpose	Who Pays	Governance	Payment Basis	Status
Contracts for Difference	Revenue stabilisation for low-carbon generation against a reference wholesale price	Consumers via supplier obligation	Low Carbon Contracts Company	Two-way difference payments against strike and reference prices	Ongoing
Capacity Market	Explicit adequacy procurement through competitive technology-neutral forward auctions	Consumers via supplier recovery	Delivery Body, Ofgem oversight	Auction-based capacity agreements; T-4 cleared at approximately £2.58bn per year in 2024/25	Ongoing
UK Emissions Trading Scheme	Carbon pricing to internalise climate cost in dispatch and investment decisions	Generators, passed through to prices	UK Government and Environment Agency	Price on covered emissions	Ongoing
Ancillary and balancing services including black start and inertia	Explicit competitive procurement of stability, operability, frequency response, and reserve services	Consumers via system charges	NESO procurement	Tendered and competitive procurement with availability and utilisation payments	Ongoing
Dispatchable Power Agreement	Revenue stabilisation for dispatchable low-carbon plant with carbon capture	Consumers via levy-funded support framework	Low Carbon Contracts Company	Contractual payment against a reference electricity price	Long-term contracts
Regulated Asset Base model	Financing framework for capital-intensive low-carbon infrastructure, specifically nuclear	Consumers via regulated charges	Ofgem and UK Government	Regulated allowed revenue with de-risked capital structure	Project specific
RIIO Price Controls for transmission and distribution	Regulated returns to incentivise network investment and operational efficiency	Network users and consumers	Ofgem	Allowed revenues against outputs-based performance regulation	RIIO price control periods

5.4 European Union

EU electricity markets operate within the Internal Energy Market framework: an integrated architecture of cross-border trade, harmonised wholesale market rules (Ahlqvist et al, 2022), and the EU ETS as the primary carbon pricing instrument. Member States retain substantial discretion over national support mechanisms, subject to state-aid rules that require demonstrating genuine system need. The resulting architecture is both its strength and its limitation: cross-border integration materially improves system efficiency and reduces the cost of managing variability (Ahlqvist et al, 2022), while the diversity of national mechanisms creates potential for distortions where support schemes, capacity mechanisms, and carbon pricing interact across borders.

The EU's 2024 electricity market design reform moved substantively in the direction of the hybrid architecture this report describes. Long-term contracting arrangements, including two-way contracts for difference and power purchase agreements, were strengthened as investment support instruments (Council of the European Union, 2024). Capacity mechanism approvals were brought into closer alignment with system adequacy evidence and decarbonisation objectives. Flexibility and demand response received greater policy attention and clearer market arrangements. These reforms reflect a recognition, now well established in EU policy, that energy and carbon pricing alone are insufficient to deliver the investment in firm low-carbon capacity, network infrastructure, and stability services that decarbonising systems require. Table 3 summarises the principal support mechanisms in the EU.

Table 3: Principal Support Mechanisms, European Union

Mechanism	Purpose	Who Pays	Governance	Status
Renewable support schemes at Member State level	Long-term revenue certainty for renewables through competitive auctions, feed-in premiums, or contract for difference arrangements, subject to state-aid approval	Consumers and taxpayers, varies by Member State	National authorities subject to European Commission state-aid rules	Active
Capacity mechanisms at Member State level	Explicit adequacy procurement where energy-only markets do not deliver sufficient firm capacity, subject to demonstrated need and EC approval	Electricity consumers	National authorities with European Commission oversight	Active in qualifying Member States
EU Emissions Trading System	Carbon pricing to shift the dispatch merit order and send long-run investment	Generators, with costs passed	European Commission	Active

Mechanism	Purpose	Who Pays	Governance	Status
	signals toward lower-emission resources	through to electricity prices		
Two-way CfDs and power purchase agreements under 2024 reform	Revenue stabilisation and investment support for low-carbon assets, providing greater price certainty for both investors and consumers	Consumers via regulated charges or supplier obligations	National authorities under the 2024 Electricity Market Design Regulation	Expanding
Ancillary and balancing markets	Explicit competitive procurement of flexibility and stability services, with increasing cross-border scope through ENTSO-E coordination	Electricity consumers	National TSOs coordinated through ENTSO-E	Active

5.5 United States

The US electricity system is more fragmented in structure than the UK or EU, combining federal tax policy with regional wholesale markets operated by ISOs and RTOs, vertically integrated regulated utilities serving substantial parts of the country, and a wide range of state-level clean energy standards. Federal and state-level instruments interact in ways that are sometimes complementary and sometimes contradictory, and the absence of a single national market means that experiences of the energy transition, and the policy responses to it, vary considerably across regions.

The Inflation Reduction Act of 2022 is the most significant federal intervention in US energy policy in generations (Columbia CGEP, 2022). Its expansion of tax credits for clean electricity investment and production, including specific provisions for carbon capture and storage and clean hydrogen, represents a substantial federal commitment to clean energy investment. The technology-neutral structure of the clean electricity credits, which are available to any qualifying low-carbon generation technology rather than specified technologies, is particularly significant for enabling competition across the portfolio of firm low-carbon options. However, subsequent amendments under the One Big Beautiful Bill Act of 2025 tightened domestic-content and supply-chain requirements for some technologies, reflecting a broader shift toward industrial strategy and energy security considerations (Reuters, 2025; Columbia CGEP, 2025).

Regional wholesale markets are under growing operational and adequacy pressure from multiple directions simultaneously. Rising renewables penetration is changing both the economics and the physics of system operation. Load growth from electrification and data centre expansion is adding demand substantially faster than many planning forecasts anticipated (IEA, 2025). The retirement of dispatchable thermal capacity is proceeding in some regions without adequate replacement coming online. Capacity market accreditation reforms, moving from nameplate-based derating toward probabilistic and weather-adjusted adequacy assessment, are underway in several ISOs and represent a methodologically important advance in how resource adequacy is measured and procured (Pham, Cole and Gagnon, 2024; Denholm et al, 2025; Anwar et al, 2024). Table 4 summarises the principal support mechanisms in the USA.

Table 4: Principal Support Mechanisms, United States

Mechanism	Purpose	Who Pays	Governance	Status
Clean Electricity Investment Tax Credit (48E)	Reduces upfront capital cost of qualifying clean power projects through a federal tax credit available to a wide range of low-carbon generation technologies	Federal budget funded by taxpayers	Internal Revenue Service and U.S. Department of Energy	Active from 2025
Clean Electricity Production Credit (45Y)	Pays qualifying clean generators per unit of electricity produced, scaled to emissions intensity with zero-emissions generation receiving the full credit	Federal budget funded by taxpayers	Internal Revenue Service and U.S. Department of Energy	Active from 2025
Carbon Capture Tax Credit (45Q)	Pays per tonne of carbon dioxide captured and permanently stored, expanded significantly under IRA 2022 to cover a wider range of capture projects	Federal budget funded by taxpayers	Internal Revenue Service and U.S. Department of Energy	Active
Capacity markets in organised wholesale regions including PJM, ISO-NE, MISO, and NYISO	Explicit adequacy procurement through competitive auctions with accreditation methodologies under reform to reflect probabilistic resource contributions	Electricity consumers in organised market regions	ISO and RTO governance bodies with FERC oversight	Active with regional variation
Ancillary service markets	Explicit competitive procurement of frequency control, operating reserves, reactive power, and voltage support	Electricity consumers	ISO and RTO governance bodies	Active

Mechanism	Purpose	Who Pays	Governance	Status
State renewable portfolio standards and clean energy standards	Require utilities to source a specified proportion of supply from renewable or clean electricity, driving long-term procurement contracts for qualifying resources	Electricity consumers, structure and cost varies by state	State public utility commissions	Active across many states

6. Conclusions

Three conclusions emerge from this analysis. First, the energy transition is changing the physical requirements of electricity systems, not just their generation mix. Adequacy is becoming probabilistic and weather-dependent. Stability services are being explicitly procured for the first time at scale. Transmission has become a strategic constraint on decarbonisation pace. New loads from electrification and data centres are adding demand precisely as dispatchable thermal capacity retires. These are not temporary features of a transitional period. They are the permanent operational characteristics of decarbonised electricity systems, and market design must reflect them.

Second, no single technology category meets all system requirements. Variable generation is indispensable for cost-effective decarbonisation but cannot on their own provide the firm adequacy and physical stability services that a reliable system requires with high renewable penetration. Short-duration storage and demand flexibility are essential for managing short-cycle variability but cannot substitute for multi-day firm capacity. Firm low-carbon dispatchable generation, across the range of technologies capable of providing it, addresses the gap that other resources leave. A credible net-zero electricity system is a portfolio system. Any market design that fails to explicitly procure all required system attributes, rather than relying on energy prices and carbon pricing to do the full job, will systematically under-deliver on reliability.

Third, the policy architecture required is a hybrid one. Energy-only markets and emissions trading are necessary, but structurally insufficient. The emerging model across the UK, EU, and US combines carbon pricing, capacity mechanisms, ancillary service markets, long-term contracts, and network investment, each instrument targeting a specific set of system requirements and operating in parallel with the others. The central design challenge is coherence: ensuring that these layers complement rather than contradict one another, and that together they provide the investment certainty and operational reliability that decarbonisation at the required pace and scale demands.

Comparing the three systems examined in this paper, a number of relative strengths and weaknesses are apparent. Great Britain’s architecture is among the most comprehensively developed: the combination of the UK ETS, Contracts for Difference, the Capacity Market, and NESO-coordinated ancillary service markets constitutes a largely coherent hybrid, with the Regulated Asset Base model and Dispatchable Power Agreements extending coverage to capital-intensive and emerging technologies. Its principal weakness is the pace of network development, which has not matched the ambition of generation policy. The European Union's approach is more fragmented, with capacity mechanisms varying substantially across Member States and carbon pricing exposure uneven due to State aid interventions; however, the 2024 Electricity Market Design reform and the deepening of EU ETS coverage represent significant steps toward greater coherence. The United States presents the widest internal variation: nodal pricing in organised wholesale markets such as Pennsylvania-New Jersey delivers strong locational investment signals and efficient dispatch, but state-level policy overlays, the fragmentation between organised and non-organised markets, and the absence of a federal carbon price create complexity that can work against whole-system efficiency. Each model offers lessons: the GB experience demonstrates the value of explicit, technology-specific long-term contracts for new technologies; the US nodal model demonstrates the efficiency gains available from granular locational pricing; and the EU's cross-border coordination architecture offers a template for coordinating interconnected systems, together defining the complementary building blocks of an effective electricity market design.

Decarbonisation through electrification ultimately depends on electricity being affordable enough that switching from fossil fuels becomes economically rational for households and businesses. Market reform, network expansion, and low-carbon generation investment are therefore not only questions of system reliability and emissions reduction, but of whether the transition can deliver electricity at costs compatible with industrial competitiveness and mass electrification. The affordability challenge is consequently not peripheral to electricity market design. It is central to its long-term viability.

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