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Review Article

Data Centre Growth, Grid Constraints, and Project Management: A Review of Integrated Delivery Approaches

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ABSTRACT

Data centres have become one of the fastest-growing sources of electricity demand, and their expansion increasingly depends on the capacity, timing, and reliability of the electricity grid. This review examines how project management practice shapes the outcomes of data centre development where grid interaction is a binding constraint. It draws on literature from power systems, energy infrastructure risk, data centre engineering, and programme and project governance, and organises the evidence around four themes: demand growth and its uncertainty, grid connection and demand flexibility, reliability and asset management of energy infrastructure, and the planning and delivery methods used to coordinate multi-party projects. The review finds that conventional project management tools are widely used to control schedule and cost, but the reviewed sources show that they commonly treat grid connection as an external dependency, which can delay the discovery of capacity limits until late in delivery. Approaches that bring utilities, developers, and equipment suppliers into a shared gated schedule, and that treat demand flexibility as a design variable, appear better suited to the problem. The paper proposes an integrated framework that links grid readiness gates to project phases and identifies research gaps in the empirical measurement of connection timelines and in the governance of flexible loads.

1. Introduction

Data centres sit at the meeting point of digital infrastructure and electricity systems. Their load is large, concentrated in a small number of sites, and increasingly expected to grow faster than most other commercial electricity uses. Masanet and colleagues estimated that data centres accounted for roughly 1% of global electricity use in 2018, and they cautioned that efficiency gains had offset a large part of earlier growth [1]. Later assessments show that the picture has shifted. The International Energy Agency [2] reports that electricity demand from data centres is set to roughly double by 2030 as artificial intelligence workloads expand. National assessments in the United States point in the same direction [3].

The grid is the constraint that many developers now meet first. In Dublin, the national transmission system operator EirGrid restricted new data centre connections from 2021 because transmission and distribution capacity could not keep pace with requests [4]. Similar pressures have been reported in parts of northern Virginia, where utility interconnection queues have lengthened as the number of proposed facilities has grown. In both cases the bottleneck is not the building, the equipment, or the land. It is the time required to study, reinforce, and energise a connection to a network that was planned for a different pattern of load.

This pattern matters for project management because most data centre programmes are scheduled around construction and commissioning milestones, with electrical supply treated as a supporting activity. When the supply milestone moves, the project does not simply slip by the same amount. Equipment orders, leases, staffing plans, and customer commitments are often tied to a date that the grid operator has not confirmed. The result is that

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a delay which originates in network planning becomes a commercial and contractual problem for developers, suppliers, and sometimes tenants. Project management practice is therefore part of the answer to the grid question, not a separate matter that follows it.

This review asks a practical question: how should project management practice change when grid capacity, rather than land, capital, or equipment, governs when a facility can operate? The question is practical in two senses. First, developers and utilities need delivery approaches that work under real connection timelines. Second, the energy infrastructure literature has developed tools for reliability, risk, and asset management that could inform data centre delivery, but these tools are rarely connected to the planning and procurement decisions that determine the schedule. The review aims to bring these strands together and to assess what the evidence supports.

Three terms are used throughout the paper and should be defined at the outset. A data centre is a facility whose primary function is to house computing equipment and its associated power and cooling systems. Grid connection refers to the full sequence of studies, reinforcements, agreements, and energisation steps by which a facility is permitted to draw power from, or export power to, an electricity network. Demand flexibility refers to the capacity of a load to shift, reduce, or defer its consumption in response to network conditions or price signals, within limits set by the operator of the load. Project management refers to the planning, scheduling, cost control, risk management, and governance of a temporary endeavour that delivers a defined asset. Each term is used in a sense that is standard in its own literature, and the review's contribution lies in joining them.

The paper makes three contributions. It maps the evidence on data centre electricity demand and its uncertainty, with attention to how that uncertainty reaches planners. It synthesises the literature on grid connection, flexibility, and energy infrastructure reliability, and it assesses how far conventional project management addresses the problems that these literatures identify. It then proposes an integrated framework that links grid readiness gates to project phases, and it sets out a research agenda that follows from the gaps the review identifies.

The paper follows the IMRaD structure. Section 1 introduces the problem, sets out the background on data centres as electricity loads (Section 1.1), and states the contributions. Section 2 describes the review method and the sources consulted. Section 3 reports the results of the synthesis: demand growth and its uncertainty (Section 3.1), grid connection, reliability, and demand flexibility (Section 3.2), asset management and reliability practice in energy infrastructure (Section 3.3), project management approaches to grid-constrained delivery (Section 3.4), and governance, procurement, and supply chain arrangements (Section 3.5). Section 4 discusses the results: it proposes the integrated framework (Section 4.1) and sets out research gaps and an agenda (Section 4.2). Section 5 concludes.

1.1 Background: Data Centres as Electricity Loads

A data centre is an electrical load with several distinctive characteristics. The first is concentration. A single facility may draw tens or hundreds of megawatts from one connection point, which is large relative to most commercial loads and comparable to some industrial processes. The second is continuity. Data centres are designed to operate at high availability, and their load factor, the ratio of average to peak demand, tends to be high. The third is rapid change. Computing equipment is replaced on short cycles, and the load profile of a facility can change substantially within a few years as the mix of workloads shifts between conventional hosting, cloud services, and the training and inference of large models.

These characteristics shape how a data centre appears to the electricity system. A high, steady load at a single node is attractive to a utility in some respects, because it can improve the utilisation of existing assets. But it is also demanding, because the network must be able to deliver that power continuously and must withstand the loss of the facility's supply without cascading effects. Digitalisation more broadly has been identified as a driver of energy demand in its own right [5], and power usage effectiveness, the ratio on which most facility energy comparisons rest, is defined in a common international standard [6]. Reviews of energy-efficient data centre strategies have examined how these choices affect the climate impact of facilities [7]. Reviews of cooling techniques have compared air, liquid, and free cooling systems in terms of their energy consumption and thermal management [8, 9, 10, 11]. Work on cooling control strategies and evaluation metrics [12] and on radiative free cooling as a means of saving energy and water [13] extends this comparison. Earlier reviews of cooling and waste heat recovery [14, 15] and surveys of energy consumption models [16] provide technical background for these choices. Practical design guidance is set out in the U.S. Department of Energy's best practices guide [17], and operating envelopes for equipment are specified in thermal guidelines [18]. An energy standard for data centres sets out design requirements for the facility and its systems [19]. The Green Grid [20] introduced the PUE and DCiE metrics on which many such comparisons rest. Two further parts of the same standard series define the renewable energy factor [21] and the energy efficiency of server equipment [22].

The engineering of a data centre's power supply is also relevant to project management. A typical facility includes

a connection to the grid, transformation and switching equipment, uninterruptible power supply systems, backup generation, and cooling plant, each of which has its own procurement lead time and commissioning sequence. The grid connection is typically the longest lead item, but the other elements must be ready to energise the facility when the connection is available. A project that schedules equipment delivery against a fixed construction programme, without reference to the connection timeline, risks holding expensive equipment on site while the facility waits to be energised.

Energy infrastructure in general has been studied as a system with its own reliability requirements. Adaramola and colleagues examined predictive maintenance and condition monitoring in critical power and energy infrastructure, arguing that the reliability of such systems depends on detecting degradation before it leads to failure [23]. The same logic applies to the supply of a data centre, where an outage can carry a high cost. Reliability engineering therefore bears directly on the design of the supply, on the commissioning plan, and on the way the facility is operated once it is energised. The Uptime Institute [24] analyses the frequency and causes of data centre outages each year, which gives the reliability argument a basis in operating records.

The management of distributed energy resources provides a further point of reference. Komi and Adamolekun [25] reviewed control architectures for distributed energy resources and compared hierarchical, decentralised, and hybrid approaches. Their comparison is relevant to data centres for two reasons. Onsite batteries, generators, and flexible loads are themselves distributed resources that must be coordinated with the network, and the control architecture chosen determines how far the facility can contribute to network stability. A facility designed as a passive load and a facility designed as a managed resource will have different connection requirements, and these differences should be specified early in the project.

The background also includes the question of how power is supplied to a data centre in the first place. In many jurisdictions the facility connects to a distribution or transmission network operated by a utility, and the connection is governed by a set of technical and commercial rules. In some cases the facility is supplied by a dedicated generation or storage asset, and in others it relies on a combination of grid supply and onsite resources. The choice affects the study required for connection, the risk allocation between parties, and the timescale over which capacity is available. The review treats these choices as part of project design rather than as external facts, because they are often made or constrained during early project development.

2. METHODS

2.1 Review Method and Source Selection

The review followed a scoping approach. Scoping reviews are suited to mapping a field in which the evidence is heterogeneous, in which sources come from several disciplines, and in which the aim is to clarify concepts and identify gaps rather than to estimate a single effect [26]. The framework of Arksey and O'Malley was extended by Levac and colleagues, who recommended that the stages be treated as iterative and that the consultation of stakeholders be made explicit [27]. This review adopted the five stages of the original framework and drew on the later recommendations in its reporting.

The five stages were as follows. The first stage defined the research question, which asks how project management practice should respond to grid-constrained data centre delivery. The second stage identified relevant studies through searches of bibliographic databases, supplemented by searches of institutional repositories and of the reference lists of key sources. The third stage selected studies against explicit criteria. The fourth stage charted the data, recording for each source its discipline, geography, period, method, and the grid, demand, or delivery issue it addressed. The fifth stage collated and summarised the results, organised by theme. The themes are those used in Sections 3.1 to 3.5.

Searches covered peer-reviewed journal articles, conference papers, and government or utility technical reports. The search terms combined data centre, grid connection, interconnection, demand response, flexibility, and project management with planning, scheduling, governance, reliability, and procurement. Because the energy infrastructure literature uses a different vocabulary from the data centre literature, the searches also included terms for power system reliability, predictive maintenance, asset management, and infrastructure risk. Searches were limited to publications between 2010 and 2026, and sources were included or excluded according to the criteria set out in Table 1.

Inclusion required that a source address electricity supply, grid interaction, reliability of energy infrastructure, or the delivery and governance of energy-intensive digital or industrial infrastructure. Sources that addressed data centre cooling or server efficiency alone were excluded unless they reported grid-relevant outcomes such as peak demand, load factor, or energy use at facility level. Sources that addressed renewable generation or storage were included where they bore on grid connection, reliability, or the management of variable loads, since the same technical problems recur in data centre supply.

The review synthesised sources thematically rather than by quantitative pooling, because the studies differ

widely in geography, metric, boundary, and time period. Where a source reported a numerical estimate, the paper reports that estimate together with its year and boundary definition. This approach allows comparison of magnitudes without treating figures from different methods as directly interchangeable. Where two sources reported different estimates for what appears to be the same quantity, the review notes the difference and does not average the figures.

3. RESULTS

3.1 Demand Growth and Its Uncertainty

Demand forecasts for data centres vary widely, and the variation itself affects project planning. Koomey documented rapid growth in data centre electricity use in the years before 2010 and argued that earlier forecasts had overstated growth, in part because they relied on server counts [28]. Masanet and colleagues later showed that improvements in server and facility efficiency had kept global consumption more stable than some earlier projections suggested [1]. The contrast between these two findings illustrates the central difficulty. Demand depends on the number of computing units, on the energy each unit consumes, and on the workloads that run on them, and each of these depends on decisions made by operators and equipment manufacturers over short periods.

Table 1: Source categories and inclusion criteria used in the review

Source category	*Examples in this review*	*Inclusion criterion*	*Role in the synthesis*
Data centre demand and energy use	Koomey [28]; Masanet et al. [1]; Shehabi et al. [3]; International Energy Agency [2]	Reports electricity use, growth, or forecasts for data centres	Establishes scale and uncertainty of demand
Grid connection and flexibility	EirGrid [4]; Strbac [29]; Lund et al. [30]	Addresses network connection, reinforcement, or demand-side flexibility	Establishes connection constraints and flexibility options
Power system reliability and asset management	Adaramola et al. [23]; Dagodzo [31, 32]; Komi and Adamolekun [33]	Addresses reliability, inspection, or predictive maintenance of energy assets	Informs the operational side of grid readiness
Energy infrastructure risk	Asibor and Isong [34]; Asibor et al. [35]; Obriki and Arumosoye [36]	Addresses risk-based engineering or safety of energy infrastructure	Informs risk registers and gate criteria
Project and programme management	Project Management Institute [37]; Makut et al. [38]; Aminu-Ibrahim et al. [39, 40]	Addresses delivery models, scheduling, or programme governance	Informs the delivery-side analysis
Supply chain and governance	Ogunwole et al. [41]; Okonkwo et al. [42, 43]	Addresses supply chain resilience or governance in energy sectors	Informs procurement and commercial arrangements

Source: compiled by the author from the sources cited in the review. The table records the category of each source and the role it plays in the synthesis, not a judgement of the quality of individual studies.

More recent work has shifted attention towards the effect of artificial intelligence on demand. Shehabi and colleagues examined the energy use of data centres in the United States and discussed the uncertainty that surrounds projections of their growth [3]. Earlier work by Shehabi and colleagues [44] examined how the demand for data centre services in the United States had been decoupled from electricity use. The International Energy Agency [2] estimated the contribution of data centres to global electricity demand and considered how the expansion of artificial intelligence might change it, presenting a range of scenarios rather than a single forecast. The agency's wider outlook for the energy system provides the context for these projections [45]. The agency's annual electricity analyses place data centre demand within wider forecasts for the power system [46, 47]. Earlier estimates of electricity use in data centres provide the baseline for this series [48, 49].

The lesson for planners is that the same facility can appear in utility forecasts as a large, certain load or as a speculative request, depending on the assumptions behind the forecast. A utility that receives many requests for capacity in a single service area must decide which of them to plan for, and its decision will depend on the evidence each developer provides. A developer that does not understand this process may find its request treated as speculative, even where the project is well advanced. The result is a mismatch between the information developers hold and the information planners can use.

Table 2 summarises the main sources of demand uncertainty identified in the reviewed literature and the planning response each suggests. The categories are not mutually exclusive. A single request may be affected by all four, and the responses interact. For example, a developer that commits to a particular workload mix may reduce the uncertainty about load shape but increase the uncertainty about the efficiency trajectory if the hardware specification is not fixed.

The planning responses in Table 2 share one feature. Each converts a forecast uncertainty into a decision point that a project schedule can represent. Where a planner cannot represent the uncertainty as a milestone, the uncertainty tends to surface late, when changing it is most costly. This is the central argument of Section 3.4 applied to demand. A scenario range that is carried into the schedule as a set of alternative phasing plans can be managed. A single forecast that is treated as fixed cannot be managed when it turns out to be wrong.

The literature on forecasting in energy systems offers a useful analogy. Komi and Adeniji [50] described a tiered digital twin for predictive diagnostics at renewable energy sites, in which models operate at several levels and feed information back into operational decisions. The same principle can be applied to demand. A demand model that is updated as project information becomes available, and that is linked to the schedule, allows the planner to see when a forecast has moved outside the range assumed in the grid application. The model does not remove uncertainty, but it makes the timing of uncertainty visible.

Table 2: Sources of demand uncertainty in data centre grid planning and associated planning responses

Source of uncertainty	*Description*	*Planning response reported in the literature*
Workload type	Shifts between training, inference, and conventional hosting change load shape and peak behaviour	Design for a range of load factors and document assumptions for each workload class
Efficiency trajectory	Hardware and facility efficiency gains can reduce energy per unit of computation	Use scenario ranges rather than a single forecast, and tie efficiency assumptions to specified equipment
Speculative requests	Multiple developers may request the same capacity in one service area	Require financial commitment or milestone evidence before reserving capacity
Siting and policy	Local permitting and tariff changes alter where and when load connects	Include regulatory review as a scheduled project activity

Source: synthesis of the reviewed literature [1, 2, 3, 28].

Komi [51] examined hybrid deep learning for wind power forecasting, with attention to grid stability and to the position of smaller generators. The paper is concerned with generation rather than demand, but its central concern carries over. Forecasting models that are accurate on average may be poorly calibrated in the periods that matter most to the grid, and the cost of error is not symmetric. For data centre planning, this suggests that the forecast that matters is the one for the peak and the ramp, not the one for average energy use. A forecast of annual consumption that is accurate on average may still be inadequate for network planning, because the network must be designed for the peak.

The question of speculative requests deserves particular attention. Where several developers request capacity in the same area, the utility faces a problem of allocation. If it plans for all requests, it may reinforce the network for load that never materialises. If it plans for only a few, it may leave viable projects waiting. Some jurisdictions have responded by requiring financial commitment, milestone evidence, or capacity reservation fees before reserving capacity. These mechanisms reduce the speculative element, but they also raise the cost of entry for developers, and they shift risk onto the developers that is otherwise held by the utility. The project management implication is that the developer must be able to demonstrate commitment early in the project, which requires that its own planning be sufficiently mature to support the evidence.

3.2 Grid Connection, Reliability, and Demand Flexibility

Grid connection is a sequence of studies, reinforcements, and agreements, and its duration depends on the state of the network at the point of connection. Strbac observed that demand-side measures can defer network reinforcement when they are scheduled with network needs in mind, and that the value of such measures depends on how precisely their timing and location are matched to the network constraint [29]. Lund and colleagues extended this argument to integrated energy systems, showing that flexibility in one sector can support balancing in others, and that the value of flexibility increases when it is coordinated across sectors [30]. These findings establish the principle on which the data centre case rests: a load that can change its behaviour in response to network conditions is a resource, not only a demand. Standardised, multi-layer frameworks have been proposed for integrating intelligent substations, fibre-based communication networks, and grid control systems, with the aim of improving interoperability and resilience in the United States electricity system [52].

For data centres, flexibility is most credible where workloads can be deferred or shifted. Batch training, backup and storage operations, and some non-urgent processing are candidates, because they tolerate delay. Flexibility is less credible for latency-sensitive services, such as real-time inference for consumer applications, where a delay is visible to the user. Table 3 sets out the main types of flexibility and the conditions under which

each is credible. The table is a synthesis of the reviewed literature, and the boundaries it draws should be tested against the operational data of individual facilities.

The literature suggests that a facility's connection application is stronger when it specifies which loads are flexible, under what conditions, and with what verification. Utilities that receive such specifications can model the facility as a resource rather than only as a demand, which may shorten the path to connection. The reasoning is straightforward. A utility that knows a facility can reduce its load by a specified amount, within a specified time, and that this reduction can be verified, can include that reduction in its planning. This may allow it to defer or reduce the reinforcement that would otherwise be required for the full load.

This reasoning remains largely conceptual in the reviewed sources. The principle is widely accepted, and there are examples of flexible connection arrangements, but few published studies report measured connection timelines for flexible and inflexible facilities in the same network. That absence is one of the research gaps identified in Section 4.2. Without paired data, it is difficult to estimate how much time flexibility saves, under what conditions, and at what cost. The review therefore treats the flexibility argument as a reasoned expectation supported by principle and by limited case evidence.

Table 3: Types of demand flexibility in data centres, conditions for credibility, and verification requirements

Flexibility type	*Workload or asset examples*	*Conditions for credibility*	*Verification requirement*
Deferrable computation	Batch training, scheduled analytics	Work can be queued without service impact	Recorded queue behaviour and committed deferral windows
Shiftable storage operations	Backup, replication, archival	Storage and transfer windows are not time-critical	Documented schedules and metered response
Load reduction	Non-essential processing, cooling setpoints	Reduction is within agreed limits and service levels	Measured reduction against a baseline
Onsite storage dispatch	Batteries co-located with the facility	Asset is controllable and sized for the event	Dispatch logs and state-of-charge records
Onsite generation	Backup generators run for grid support	Emissions, fuel, and permit limits are met	Permit compliance and fuel supply evidence

Source: synthesis of the reviewed literature [29, 30, 53].

Komi and Ganiu [53] examined grid-connected battery storage in hot and weak-grid regions, highlighting degradation challenges and lifecycle considerations. Their work is concerned with storage in distributed settings rather than with data centres, but the constraints they identify apply to facilities that rely on onsite batteries for peak management. Battery performance degrades with temperature and with cycling, and a battery that is sized for initial conditions may not provide the same support after several years. A project plan that treats storage as a fixed grid asset without considering its degradation may overstate the flexibility it provides.

Onsite generation and storage offer a second route to reducing grid demand at the connection point. Some operators pair facilities with batteries or backup generators to reduce peak imports, and a few have proposed using backup generation to support the network during stress events. The reviewed sources differ on whether such assets reduce connection queues or merely shift the burden to permitting, air quality, and fuel supply. Backup generation in particular raises emissions and permit questions that can take as long to resolve as the grid study itself. A project plan that treats onsite assets as a grid solution without assessing those secondary constraints risks repeating the late discovery problem described in Section 3.4. Studies of microgrids for rural electrification show how locally managed generation can be modelled and governed [54], and studies of distributed generation and grid-connected hybrid systems, including a university campus, have examined their economic and environmental performance [55, 56].

Komi [51] examined the stability of grid operation under variable generation, and the concerns raised there apply in a modified form to large loads. A load that changes rapidly, or that responds to a control signal in a way the network does not expect, can create instability. The network operator therefore needs assurance not only that flexibility exists but that it will behave as specified when called. This is a question of control and verification rather than of capacity, and it is one reason that the verification requirements in Table 3 matter as much as the flexibility itself.

The control architecture of the facility is central to this question. Komi and Adamolekun [25] compared hierarchical, decentralised, and hybrid control architectures for distributed energy resources. A hierarchical architecture, in which a central controller issues setpoints to all resources, offers strong coordination but depends on reliable communication. A decentralised architecture, in which resources respond to local signals, is more robust to communication failure but may be harder to coordinate with the network. A hybrid architecture attempts to combine the two. For a data centre, the choice affects how quickly the facility can respond, how it behaves

if communication fails, and how easily its behaviour can be verified. These are design decisions that should be made early, because they affect the equipment specification and the commissioning plan.

Grid connection is also shaped by the way the network is studied. A connection study typically assesses the thermal, voltage, and stability effects of the new load under a defined set of conditions, and it identifies the reinforcements required. The duration of the study depends on the number of conditions considered, the quality of the network model, and the number of other requests in the queue. A developer that provides a detailed and accurate load profile can reduce the study effort, while one that provides a vague or changing specification may cause the study to be repeated. The project management consequence is that the load specification is a deliverable with its own quality requirements, not a by-product of design. Grid connection barriers have been documented for generation in the United States [57], and successive editions of the Berkeley Lab queue analysis report the characteristics of plants seeking transmission interconnection [58, 59]. These queues concern generation rather than data centre load, so they indicate the scale of the interconnection problem without measuring it for data centres. Electricity grids are also identified as a central constraint in secure energy transitions [60], and variable renewable generation and storage are expanding quickly [61]. The North American Electric Reliability Corporation [62] reports that electricity demand growth is accelerating and that substantial new resource additions are needed over the next decade. Reliability assessments add to this picture. The seasonal assessment identifies regions at elevated risk of supply shortfalls under extreme conditions [63], and the state of reliability report tracks performance across the system [64]. Scenario studies of the electricity sector [65] and the annual outlook [66] set out assumptions that connection studies can draw on, and historical generation and capacity data are published each year [67]. Reviews of smart grid architectures for high renewable penetration [68] and of automation for grid operation [69] describe how monitoring and control are being added to distribution networks.

Renewable generation now accounts for most new capacity additions. The International Renewable Energy Agency [70] reports record growth in renewable capacity, and its analysis of costs shows that most of the renewable additions made in 2023 were cheaper than fossil fuel alternatives [71]. The agency's transition outlook describes a 1.5°C pathway that depends on electrification and on the flexibility of the power system [72]. Microgrid designs for underserved regions must balance technical performance against community affordability [73].

The timing of grid reinforcement presents a further difficulty. Reinforcement projects are themselves long, and they are often scheduled by the utility on a programme of its own. A connection may depend on a reinforcement that is due for completion several years after the developer's construction programme. Where the reinforcement is not yet committed, the connection date is uncertain, and the developer must decide whether to proceed. The reviewed literature suggests that developers who understand the utility's reinforcement programme, and who can align their phasing with it, are better placed than those who do not. This requires regular contact with the utility, which is a theme returned to in Section 3.4.

3.3 Reliability and Asset Management in Energy Infrastructure

The energy infrastructure literature contains substantial work on reliability, inspection, and asset management that has not yet been widely applied to data centre delivery. Its central concern is how to detect and respond to degradation in assets before it causes failure, and how to allocate inspection and maintenance effort across a network of assets with different risks and consequences. These concerns bear on data centres in two ways. They inform the design of the facility's own electrical infrastructure, and they inform the way the facility's supply is connected to and maintained within the wider network.

Adaramola and colleagues examined predictive maintenance and condition monitoring in critical power and energy infrastructure, and they framed condition-based maintenance as an alternative to periodic maintenance [23]. Asset management systems more generally are covered by ISO 55001 [74], which provides a management framework against which an operator's asset practice can be assessed. The argument is relevant to data centres because the supply infrastructure of a facility is often maintained on fixed schedules that do not reflect its actual condition. A facility that installs condition monitoring on transformers, switchgear, and generators from the outset can use the data to plan maintenance, to schedule outages around operational needs, and to demonstrate reliability to the network operator. Predictive maintenance models have also been applied to processing equipment outside the power sector, including a cassava pulveriser [75].

The inspection of transmission and distribution assets has been studied with unmanned aerial vehicles. Dagodzo [31] proposed a conceptual framework for integrating such vehicles into national power grid inspection programmes, and Dagodzo [32] reviewed their application to electrical transmission line inspection, identifying methods, technologies, and challenges. These studies concern the wider network rather than the facility, but they bear on how the network operator maintains the capacity to which the facility connects. A connection to a

network with a poor inspection record carries a different risk from a connection to a well-maintained network, and developers should understand that risk when they plan their connection and their contingency arrangements.

Asset information systems are a second area of relevance. Dagodzo and Ahiaeke Patrick [76] reviewed geographic information system applications in utility asset management and infrastructure planning. Their review emphasises the value of spatially referenced asset data for planning reinforcement and for coordinating works across a network. For data centre projects, the same data can inform the choice of site, the route of the connection, and the sequence of works. A project that has access to accurate asset data can identify constraints earlier, and it can present the utility with a more precise request. The data also supports the risk assessment discussed in Section 3.4, because it allows the project to link specific network assets to specific study outcomes.

Dagodzo and Ahiaeke Patrick [77] proposed an integrated framework combining unmanned aerial vehicles, light detection and ranging, and geographic information systems for infrastructure corridor management. A later paper by the same authors proposed a framework for national-scale unmanned aerial vehicle deployment in power infrastructure, with lessons drawn from developing economies [78]. These works suggest that the tools for monitoring large networks are becoming more integrated, and that the boundary between network monitoring and project management is narrowing. A data centre project that connects to a network monitored in this way may be able to access more information about the condition of the connection route than was previously available.

Komi and Adamolekun [33] examined interpretable machine learning for early failure prediction in distributed renewable energy assets. The emphasis on interpretability is relevant to data centre reliability because a maintenance decision based on a model must be justified to the people who bear its consequences. An operator that cannot explain why a transformer has been flagged for inspection may find that the inspection is not scheduled, or that it is scheduled without the necessary preparation. For maintenance models in this setting, interpretability is therefore a design requirement rather than an optional feature.

Asibor and Isong [34] proposed a risk-based process engineering framework for strengthening reliability across complex natural gas infrastructure systems. Asibor and colleagues [35] extended this line of work by integrating hazard and operability analysis, reliability analysis, and risk-based decision-making into the design of critical energy infrastructure. The central idea is that design decisions should be informed by a structured assessment of hazards and their consequences, and that the assessment should be carried through to the operational phase. For data centre projects, the same approach can be applied to the electrical supply, to the cooling system, and to the backup arrangements. The output of the assessment can then inform the gate criteria described in Section 4.1.

Risk in energy infrastructure projects also includes occupational safety. Obriki and Arumosoye [36] developed a conceptual model for data-driven occupational safety risk control in large-scale energy infrastructure projects. Their emphasis on data-driven control is relevant to construction and commissioning, where high-voltage work and the energisation of large equipment carry significant hazards. A project that is delayed by a grid milestone may also face changes in its construction sequence, and those changes can introduce new safety risks if they are not assessed. The safety risk register should therefore be updated when the connection schedule changes.

Environmental compliance is a further dimension of risk. Obogo and colleagues [79] proposed a conceptual environmental safety compliance framework for construction and infrastructure projects. Data centre projects may require permits for backup generation, for water use, for land disturbance, and for connection works. The timing of these permits can determine when a project is able to proceed, and permits that are not coordinated with the grid schedule can introduce delay. The compliance framework suggests that these requirements should be mapped early and linked to the project schedule, so that their effects are visible to the team.

Taken together, the reliability and risk literature suggests that data centre grid readiness is not only a matter of obtaining a connection agreement. It is also a matter of demonstrating that the connection route, the supply infrastructure, and the facility's own assets can be operated and maintained to the required standard. A project that can show this evidence early is better placed to negotiate a connection date and to respond to changes in the network. A project that treats reliability as a commissioning activity, to be completed after the connection is agreed, may find that the evidence requirement arrives too late to influence the outcome. Risk management guidance such as ISO 31000 [80] provides a common vocabulary for the risk registers and gate criteria described in Section 4.1. Risk assessment techniques are catalogued in a companion standard [81], and quality management in projects is covered separately [82].

3.4 Project Management Approaches to Grid-Constrained Delivery

Conventional project management, as codified in the Project Management Institute's standard, emphasises scope, schedule, cost, quality, resources, communications, risk, procurement, and stakeholder engagement, with the

project's purpose and value as the organising principle [37]. These principles apply to data centre delivery, and the standard provides a sound basis for managing the programme. The standard has been revised over time, from the sixth edition [83] to the seventh [37], and the International Organization for Standardization provides guidance on project management in ISO 21502 [84]. But the standard does not specify how an external network operator's study timeline should enter a critical path, or how a schedule should respond when a milestone controlled by a third party is uncertain. In most practice, grid connection appears as a single long-lead item with an uncertain start date, and it is managed by procurement or by the electrical contractor rather than by the project governance structure.

Scheduling methods offer some resources for this problem. Front-end planning, which defines scope before commitment, is an established practice [85], and the Last Planner System offers a short-interval planning method for coordinating work when inputs are uncertain [86]. Makut and colleagues proposed integrating critical path scheduling with resource optimisation in building construction projects, within a risk-based delivery framework [38]. Their approach treats the schedule as a network of dependencies whose durations and resource demands can be optimised together. The same logic applies to a data centre, where the connection milestone is one dependency among many, and where the cost of delay depends on the resources committed to the other activities. A critical path analysis that includes the connection milestone as a risk-weighted dependency allows the project to see how the connection uncertainty propagates through the schedule.

Makut and colleagues later extended this work to lifecycle reliability and sustainability in building infrastructure, combining building information modelling with reliability assessment [87]. The integration of information models with reliability data is relevant to data centres because a facility's electrical and mechanical systems are often modelled in detail during design, and the model can be linked to the schedule and to the equipment register. When the connection date changes, the model can show which systems are affected and what their status is. This allows a project to respond to schedule changes with information rather than with estimates. For the information side of this integration, ISO 19650-1 sets out concepts and principles for information management with building information modelling [88].

Capital project delivery models for high-risk infrastructure have also been studied. Integrated project delivery has been examined as a way of transforming how parties share risk and reward [89], and the American Institute of Architects [90] set out the approach in a practice guide. Aminu-Ibrahim and colleagues examined capital project delivery models for high-risk healthcare infrastructure in developing national health systems [39]. Healthcare infrastructure shares with data centres a high consequence of failure, a dependence on reliable utility supply, and a need for phased commissioning. The delivery model they analysed is relevant because it considers how risk should be allocated between the parties involved in a complex project. The same question arises in data centre delivery, where the developer, the utility, the equipment supplier, and the contractor each hold a share of the grid risk. Megaproject research adds that cost and schedule estimates for large public works are often optimistic, which makes early gates and contingency commitments more important [91, 92]. It also argues that the governance of large engineering projects depends on institutions and risk allocation as much as on technical planning [93].

Program management models for coordinated multi-site projects were examined by Aminu-Ibrahim and colleagues [40]. Their work concerns the coordination of several sites under a common programme, which is relevant to developers that build multiple facilities in the same region or on the same network. A programme that shares learning across sites, and that coordinates its connection requests, may be able to reduce the duplication of studies and to present the utility with a consistent load profile. The programme perspective also helps to address the speculative request problem described in Section 3.1, because a developer with a coherent programme can demonstrate its commitment across sites.

Cost control and financial accountability in national programmes were examined by Aminu-Ibrahim and colleagues [94]. Their framework emphasises the link between cost control and the accountability structures that govern large programmes. For data centres, the relevant question is how the cost of delay is recorded and attributed. Where a connection delay causes idle equipment, extended leases, or lost revenue, the project should be able to attribute these costs to their cause. This supports better decisions about whether to accept a later connection date, whether to invest in alternative supply, or whether to renegotiate the commercial terms with the utility or the supplier.

The reviewed literature identifies three shortcomings of conventional arrangements. First, grid milestones are often not represented in the same schedule as construction milestones, so the two can drift apart without warning. Second, risk registers record grid delay as a generic external risk rather than as a set of identifiable study outcomes, which limits the response options available. Third, the commercial terms between developer, utility, and supplier often assign grid risk to the party least able to influence it. Table 4 sets out these shortcomings alongside the responses the literature suggests.

Approaches that address these shortcomings share

several features in the sources reviewed. They integrate utility study stages into the master schedule as gated milestones. They define the information each gate requires, including load profile, flexibility commitment, and phasing. They hold regular joint reviews with the network operator. They attribute the cost of delay to its cause, so that the consequences of a late gate are visible to decision-makers. Where the literature reports outcomes, these approaches are associated with earlier identification of capacity limits and with more realistic phasing of facility energisation. The evidence is mostly from case reports, industry guidance, and the programme management literature rather than from controlled comparison, so the claim should be read as a reasoned expectation supported by limited empirical evidence.

The gated approach has a further advantage. It makes the uncertainty of the connection visible to the people who make commitments. A gate that has not been passed is an open question, and the project can treat commitments that depend on it as conditional. This is a discipline that conventional scheduling does not always enforce, because a schedule that shows an assumed connection date appears to be a plan, even when the date is unsupported. A gated schedule shows the dependency and the condition, which makes it harder for the commitment to be made without the information. The approach also draws on lean construction research on production control [95, 96]. Megaproject studies report that forecasts of cost and demand are often optimistic, which supports staging commitments against evidence [97, 98]. Recent work on hyperscale data-centre construction uses historical schedule performance to predict delays [99].

Finally, the question of stakeholder engagement deserves emphasis. The Project Management Institute standard treats stakeholder engagement as a continuing activity [37], and this is especially important for grid-constrained projects, where the network operator is a stakeholder whose decisions cannot be controlled by the project. Regular engagement with the operator, including the sharing of load profiles and phasing plans and the discussion of study progress, builds the trust and the information flow on which a shared schedule depends. Engagement that is limited to formal correspondence at the start and end of the study is unlikely to achieve this.

3.5 Governance, Procurement, and Supply Chain Arrangements

Table 4: Shortcomings of conventional project management for grid-constrained delivery and responses proposed or implied in the literature

Shortcoming	*Effect on delivery*	*Response proposed or implied in the literature*
Grid milestones kept outside the master schedule	Construction and connection drift apart unnoticed	Integrate utility study stages as gated milestones in the master schedule [38, 87]
Grid delay recorded as a generic external risk	Response options are limited and late	Decompose the connection into identifiable study outcomes with owners and triggers [35]
Grid risk allocated to the least influential party	Risk is priced poorly and disputed late	Allocate grid risk to the party able to manage the relevant study or reinforcement [39]
Connection treated as a single long-lead item	Equipment and leases committed against an unknown date	Phase commitments against gate outcomes rather than assumed dates [37]
Load specification treated as a by-product of design	Repeated studies and changing assumptions	Treat the load specification as a controlled deliverable with quality criteria (synthesis in Section 4.1)

Source: synthesis of the reviewed literature. The responses combine recommendations in the cited sources with the synthesis in Sections 3.4 to 3.5 and the framework in Section 4.1. They have not been tested as a set in controlled comparison.

The governance of a data centre project determines who makes decisions about the connection, who bears the consequences of delay, and how the parties share information. The reviewed literature on energy infrastructure governance is limited, but the supply chain and governance studies that exist are relevant. Ogunwole and colleagues proposed a supply chain resilience framework for critical infrastructure and gas processing plants [41]. Their central argument is that resilience depends on the ability to identify critical suppliers, to assess their dependence, and to build alternatives before disruption occurs. For data centres, the critical suppliers include transformer and switchgear manufacturers, generator suppliers, battery suppliers, and the contractors responsible for connection works. Each of these supply chains has lead times that interact with the grid timeline. Studies of major projects have long described the gap between what is planned and what is delivered [100]. Case studies of multinational infrastructure governance describe how decision rights are assigned across organisations [101].

Okonkwo and colleagues [42] proposed a conceptual framework for digital supply chain governance in energy and infrastructure sectors. Their framework emphasises the use of digital records to track commitments, deliveries, and performance across the supply chain. For a data centre

project, the value of such records is that they allow the project to know, at any time, which equipment is committed, which is delivered, and which depends on the connection date. This information is essential when the connection date changes, because it determines which commitments can be deferred and which must be honoured. A project without this information may find that it cannot respond to a change without incurring avoidable costs.

Okonkwo and colleagues [43] proposed a framework for secure and scalable supply chain systems supporting national energy reliability. The emphasis on security is relevant because the digital systems used to manage supply chains, and the operational technology used to control facilities, are increasingly connected. A data centre that exchanges load and schedule information with a network operator must consider the security of that exchange, and the governance framework should specify who is responsible for it. This is not only a technical matter. It affects the terms on which information is shared and the confidence each party has in the other.

The commercial arrangements between developer, utility, and supplier are central to governance. The reviewed sources suggest that these arrangements often assign grid risk to the party least able to influence it, and that the assignment is made early and rarely revisited. A developer may accept a fixed connection date, or a penalty for delay, without the means to influence the study or reinforcement that determines the date. A utility may commit to a date without control over the reinforcement schedule of a third party, such as a transmission operator. And a supplier may commit to a delivery date that depends on the developer's connection, creating a chain of dependencies that is not visible in any single contract.

A better allocation starts from the question of who can influence each element of the connection timeline. The developer can influence the quality and timing of the load specification, the choice of flexibility, the phasing of commitments, and the coordination with the utility. The utility can influence the study schedule, the design of reinforcement, and the sequencing of connection requests. The supplier can influence the delivery schedule and the availability of equipment. The contract should assign each risk to the party that can most effectively manage it, and should provide mechanisms for sharing risks that no single party can manage. This principle is consistent with the broader project management view of risk, which emphasises that responses should be proportionate to the party's ability to act [37].

Procurement decisions interact with the grid timeline in ways that are often overlooked. A developer that orders long-lead equipment before the connection is confirmed takes a financial risk, and the decision to order is typically made on the basis of the construction programme. A developer that waits for confirmation risks delay to the rest of the project. The reviewed sources do not offer a single answer to this trade-off, but they suggest that the decision should be made explicitly, with reference to the gate structure, and that the cost of the options should be assessed. Some equipment can be ordered with cancellation or deferral provisions. Some can be ordered in phases that match the connection stages. Each option has a cost, and the choice should reflect the project's risk appetite. Lead-time quotation under contingency has been studied as an online decision problem [102], and a later study addresses order quotation with a bottleneck resource and delayed feedback [103].

Supply chain resilience also depends on the wider energy system. Equipment for the grid, including transformers and cables, is subject to global supply constraints, and the demand from data centres may compete with demand from other sectors. A developer that depends on a single supplier may be exposed to delays that are unrelated to the grid, and a developer that has not considered the wider market may underestimate its own lead times. The governance of procurement should therefore include a view of the market, not only of the project.

The governance of equity and of the distribution of benefits is also relevant. Komi and Ganiu [53] raised questions of lifecycle equity in the deployment of grid-connected battery storage, and the same question of who benefits arises for investment in network capacity. Where a data centre's connection requires reinforcement that benefits other users, the question of who pays for the reinforcement is contested. The governance framework should address this question explicitly, because an unresolved allocation can delay the connection as effectively as a technical constraint. The reviewed literature does not provide a generally accepted allocation, and this is one of the research gaps identified in Section 4.2. In the United States, the Federal Energy Regulatory Commission has set out regional transmission planning and cost allocation requirements in Order No. 1920 [104], with later amendments in Order No. 1920-A [105] and Order No. 1920-B [106]. The Department of Energy's national transmission needs and planning studies [107, 108] identify the scale of transmission expansion required, which bears directly on how reinforcement costs are shared. Interconnection procedures for generators were reformed separately in Order No. 2023 [109].

4. Discussion

4.1 An Integrated Framework for Grid-Constrained Delivery

The review supports an integrated framework with four linked layers, the fourth of which operates across the other

three. The first layer is a demand specification that states the facility's load in phases, with scenario ranges, documented workload assumptions, and flexibility commitments where these are offered. The second layer is a grid readiness gate structure, in which each utility study stage is a named milestone with entry and exit criteria. The third layer is a delivery plan in which construction, procurement, and commissioning activities depend on the gates rather than on assumed connection dates. Under this structure, a late gate triggers a defined re-planning step rather than an unplanned schedule slip. Table 5 sets out the layers, their components, and the outputs each produces.

The first layer converts the uncertainty described in Section 3.1 into a specification that the utility can use. It requires the developer to state the load in phases, to give ranges where the forecast is uncertain, and to document the assumptions behind each workload class. Where flexibility is offered, the specification must state the conditions, the verification method, and the baseline against which reductions will be measured. The specification is a controlled deliverable. Its version history is kept, and changes are reviewed jointly with the operator, so that both parties work from the same information.

The second layer converts the connection process into a set of gates. Each gate is a study stage or an agreement that the network operator completes, and each has an entry criterion, which states what must be true before the stage begins, and an exit criterion, which states what must be delivered for the stage to be complete. For example, a gate might be defined as the completion of a connection study under a specified load profile, with an exit criterion of a signed study report that identifies the reinforcements required and their timing. The gate records its owner, its expected date, and the trigger that will cause re-planning if the date is missed. The gate structure makes the connection process visible within the project.

The third layer links the delivery plan to the gates. Construction, procurement, and commissioning activities are scheduled with dependencies on specific gates. Commitments that depend on an open gate are marked as conditional, and the cost of committing before the gate is passed is estimated. When a gate is missed, the framework triggers a re-planning step, in which the schedule is re-run with the new date, the cost of delay is attributed, and the options for responding are reviewed. This step is defined in advance, so that the response is structured rather than improvised. Makut and colleagues propose integrating scheduling with resource and reliability data [38, 87], and the third layer applies that integration to the connection milestone.

The fourth layer, which can be understood as a cross-cutting element, links the reliability and risk literature to the gates. Hazard and reliability assessments are carried out for the facility's supply infrastructure, and the results inform the gate criteria and the commissioning plan. A condition monitoring plan defines which assets will be monitored, from what point, and with what data. A permit map identifies the approvals required for backup generation, connection works, and other activities, and links each approval to a gate or to a construction milestone. The risk register records the risks associated with each gate, and it is updated when a gate outcome changes. This layer ensures that the reliability evidence required by the network operator is produced in time to inform the connection decision.

The framework is consistent with the sources reviewed, particularly the view that scheduled, network-aware demand measures reduce delay [29] and the governance expectations set out for managed projects [37]. It is also consistent with the risk-based engineering approaches that treat design decisions as informed by structured assessment [35]. Its novelty lies in the combination of these elements in a single structure that is organised around the connection gate. The reviewed literature contains the components but not, to the author's knowledge, a published account that brings them together for data centre delivery.

The framework has several practical implications. It requires an early decision on the level of flexibility to be offered, because the decision affects the load specification, the control architecture, and the verification plan. It requires the developer to agree gate criteria with the operator, which is a negotiation as well as a technical exercise. It requires the project to maintain a conditional commitment register, which records the commitments that depend on each gate and the cost of withdrawing them. And it requires the project to maintain a link between the schedule, the risk register, and the commercial team, so that changes in one are reflected in the others.

The framework also has limits. It is designed for projects where the connection is the binding constraint, and it may add overhead where the connection is straightforward. It depends on the willingness of the network operator to share gate status and study information, and in some jurisdictions this willingness is limited by regulation or by commercial sensitivity. And it does not resolve the allocation of grid costs, which remains a matter for regulation and for negotiation between the parties. These limits are not reasons to reject the framework, but they define the conditions under which it can be expected to add value.

Table 5: Layers of the integrated framework for grid-constrained data centre delivery

Layer	*Components*	*Principal output*	*Link to the literature*
Demand specification	Phased load profile; scenario ranges; workload assumptions; flexibility commitments and verification	Load specification accepted by the network operator	Demand uncertainty [28]
Grid readiness gates	Named study stages; entry and exit criteria; owners; triggers for re-planning	Gate status record reviewed jointly with the operator	Connection and flexibility [29, 30]
Delivery plan	Construction, procurement, and commissioning activities linked to gates; conditional commitments; cost-of-delay attribution	Schedule of conditional commitments and phasing plan	Scheduling and programme governance [38, 94]
Reliability and risk	Hazard and reliability assessment; condition monitoring plan; permit map	Risk register linked to gate outcomes	Reliability and risk [23, 35]

Source: framework developed by the author from the synthesis in Sections 3.1 to 3.5.

Implementation would require a modest set of tools. A scheduling system capable of representing conditional dependencies is needed, together with a register for load specifications, a log of gate status, and a risk register linked to the schedule. The tools do not need to be sophisticated, but they must be used consistently, and the discipline of updating them when a gate changes is essential. The literature on digital supply chain governance suggests that such records are most valuable when they are shared with the parties who depend on them [42], and the framework assumes that the gate status record is shared with the operator.

4.2 Research Gaps and Research Agenda

The review identifies four principal research gaps. Each arises from a point where the reviewed literature makes a claim that the evidence does not fully support, or where a relevant question has not been studied in the data centre context. The gaps are presented here in the order in which they bear on the framework in Section 4.1, and each is accompanied by a suggested research approach.

The first gap is the absence of published, paired data on connection timelines for facilities with and without committed flexibility. The argument that flexibility shortens connection timelines is plausible and is supported by principle, but it has not been tested with data from comparable facilities in the same network. A study would need to identify facilities with similar load profiles, similar connection points, and similar network conditions, and compare their connection timelines according to whether flexibility was offered. Such a study would require cooperation from network operators and developers, and it would need to control for the number of other requests in the queue. The approach would be a matched comparison using administrative data, supplemented by interviews with planners and developers to understand the process.

The second gap is the lack of governance models that allocate the benefits of flexibility between developer, utility, and ratepayers. Where flexibility reduces the need for reinforcement, the benefit accrues to the network as a whole, but the costs of providing flexibility fall on the developer. The allocation of this benefit is a question of regulation and of negotiation, and the reviewed literature does not offer a generally accepted model. A study would need to examine the regulatory arrangements in several jurisdictions, to analyse the incentives they create, and to model the effects of alternative allocations on the willingness to offer flexibility. The approach would combine institutional analysis with economic modelling.

The third gap is the limited evidence on how onsite generation affects permitting and fuel supply timelines in specific jurisdictions. The reviewed sources differ on whether onsite assets reduce connection queues or shift the constraint to permitting, emissions, and fuel. The question is empirical and depends on local rules, and it has not been studied systematically for data centres. A study would need to map the permitting requirements for onsite generation in a set of jurisdictions, to measure the time required to obtain them, and to assess how the time compares with the grid connection timeline. The approach would be a documentary and case-based study, with interviews to validate the timelines.

The fourth gap concerns the transfer of frameworks between markets with different regulatory structures. The reviewed sources come mainly from North America and Europe, and the institutional arrangements in those regions differ from those in other regions where data centre growth is expected. A framework that works in one regulatory structure may not transfer directly to another, and the conditions for transfer have not been identified. A study would need to compare the regulatory structures of several markets, to identify the features that affect the framework's components, and to test the framework in at least two contrasting settings. The approach would be comparative and would require local partners.

5. Conclusion

Grid capacity now governs when many data centres can operate, yet most project management practice still treats grid connection as an external dependency. This review finds that integrating grid study stages into project schedules, specifying demand and flexibility in phased and verifiable terms, and assigning grid risk to the parties able to manage it offers a more reliable basis for delivery. The reliability and risk literature on energy infrastructure supplies tools that can be applied to the connection problem, and the programme management literature supplies methods for coordinating schedules, costs, and commitments across several parties.

The strongest evidence concerns the diagnosis of the problem, which is well documented in institutional reports and in the grid literature. The evidence for specific interventions remains largely case-based and principle-based, and the claim that the integrated framework improves delivery outcomes has not been tested in controlled comparison. Closing that gap requires paired empirical studies of connection outcomes, the governance research needed to make flexibility commercially meaningful, and comparative work across regulatory settings. The framework proposed here is offered as a structure for such work and as a practical basis for projects that must deliver under grid constraints now.

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