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A Conceptual Framework for Flexibility-Aware Smart-Grid Operation Linking Smart-Meter Analytics, DER Availability, and Distribution-Level Decision Support

Mateo Alvarez^{1*}, Diego Cruz¹, Sofia Herrera²

Abstract

Distribution networks increasingly host distributed energy resources whose flexibility, if properly harnessed, can support grid operation. Smart-meter data provides a basis for estimating this flexibility by revealing consumption, generation, and behind-the-meter behavioural patterns. The lack of an integrated framework linking smart-meter analytics, DER availability, and operational decision-making hinders the realization of flexibility-aware smart grids. Existing approaches often treat data analytics, flexibility modelling, and distribution-level operation as separate domains. This article develops a conceptual framework that links smart-meter analytics, DER availability estimation, flexibility estimation, and decision support into a coherent system for distribution-level operation. The aim is to clarify how information can flow from metering data to actionable DSO decisions. A conceptual synthesis of literature on smart-meter analytics, DER modelling, flexibility estimation, aggregation, and DSO decision-support architectures is performed. No empirical data, simulations, experiments, or quantitative analyses are used. The framework comprises three interrelated layers: smart-meter analytics, DER availability estimation, and decision support, connected through a flexibility estimation layer. Propositions regarding data granularity, flexibility accuracy, uncertainty handling, and operational benefit are articulated. Two tables summarize DER availability indicators and framework architecture. The framework provides a foundation for future empirical testing and can guide DSOs in building flexibility-aware operational capabilities. It also clarifies how data, flexibility, and decision processes should be conceptualized as linked components of smart-grid operation.

Keywords Smart-meter analytics, DER flexibility, Distribution grid, Decision support, Conceptual framework, Flexibility estimation

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Introduction

Distribution system operators are increasingly required to operate networks in which demand, generation, storage, and controllable load are no longer passive or predictable. Smart-meter analytics can reveal detailed consumption and generation patterns, and recent reviews argue that these data streams are becoming central to reliable, robust, and secure grid operation [1]. At the same time, the proliferation of rooftop photovoltaic systems, batteries, electric vehicles, and heat pumps changes distribution grids from one-directional delivery systems into dynamic flexibility ecosystems. The framework proposed in this article therefore starts from the premise that distribution operation should be conceptualized as an information-mediated process rather than only an asset-management task.

The operational significance of smart-meter data lies not only in measuring consumption, but also in identifying behavioural, technological, and temporal patterns that shape local flexibility. Smart-meter analytics has been used to support load profiling, customer segmentation, non-intrusive load monitoring, and behind-the-meter resource detection, suggesting that metering data can provide a bridge between end-user behaviour and network operation [2]. However, this bridge remains incomplete when analytics outputs are not translated into estimates of DER availability and actionable flexibility. The article therefore proposes that smart-meter analytics should be interpreted as the first layer of a broader flexibility-aware operating logic.

DER flexibility is not simply the theoretical capacity of a device to modify power exchange with the grid. It depends on device state, user behaviour, weather exposure, network location, communication capability, and the decision context in which flexibility is requested, as studies of aggregate DER modelling and flexibility characterization have emphasized [3]. Consequently, a conceptual framework is needed to link device-level availability with feeder-level constraints and DSO decision needs. The contribution of this article is to articulate such a layered framework without presenting empirical results, thereby generating a theory-informed basis for future testing.

The article develops a conceptual architecture that links smart-meter analytics, DER availability estimation, flexibility estimation, and decision support for congestion and voltage management. It draws on literature on smart-meter analytics, non-intrusive load monitoring, DER aggregation, flexibility envelopes, local flexibility markets, and distribution decision-support systems [4]. The framework is intended for distribution-level operation, where operational value depends on converting uncertain, granular, and privacy-sensitive data into interpretable flexibility products. It also advances testable propositions concerning the relationships among data granularity, availability knowledge, uncertainty treatment, and DSO operational confidence.

Figure 1 illustrates the proposed flexibility-aware smart-grid operating logic, showing how smart-meter analytics, DER availability estimation, flexibility estimation, and DSO decision support form an integrated information pathway.

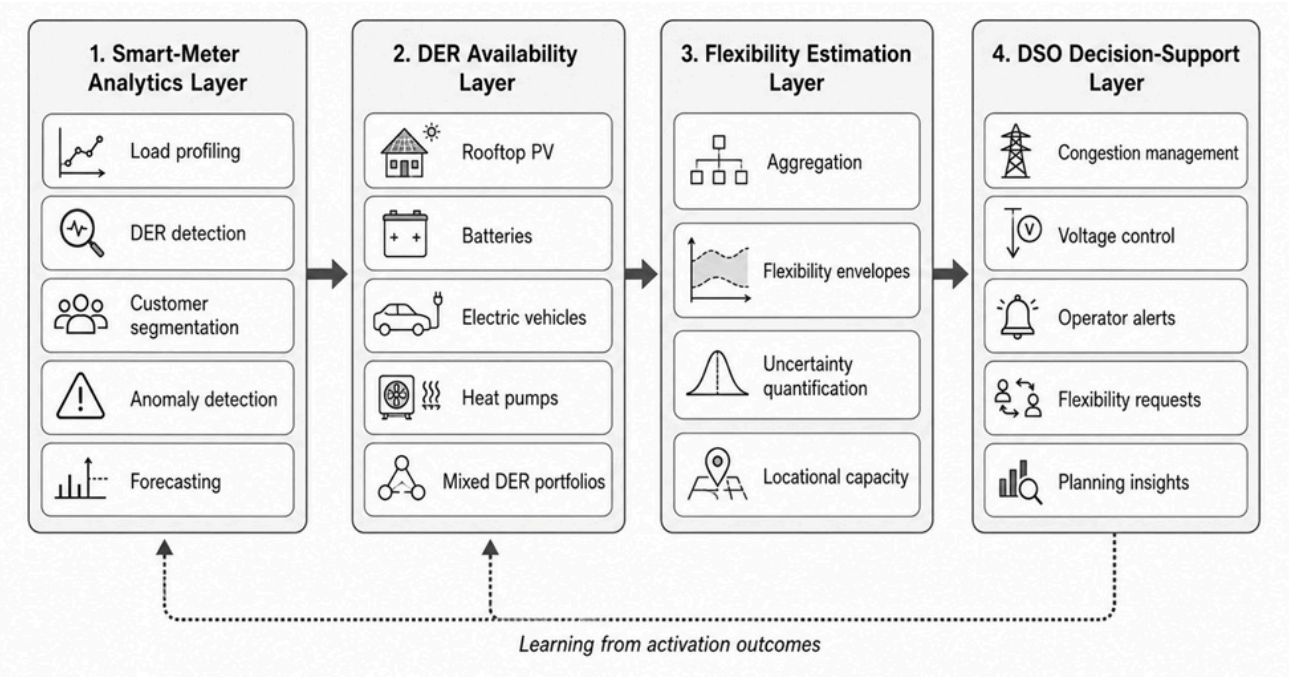


Figure 1. Layered conceptual framework for flexibility-aware smart-grid operation

Conceptual Problem

The flexibility gap in distribution grids

The central conceptual problem is the flexibility gap between the growing technical potential of DERs and the limited operational ability of DSOs to use that potential in real time or near-real time. DERs may provide capacity for demand shifting, export reduction, voltage support, and congestion relief, yet these capabilities are often latent because their availability is uncertain and distributed across many small resources [5]. This gap should be understood as both a measurement problem and an institutional problem: DSOs need credible estimates of where, when, and how flexibility can be used. The framework therefore posits that flexibility becomes operationally meaningful only when it is visible, locationally contextualized, and linked to specific network decisions.

Disconnect between data, estimation, and action

A second problem is the disconnect between smart-meter data, flexibility estimation, and operational action. Smart-meter datasets can support detection of behind-the-meter PV and other technologies, as shown in work on PV disaggregation and solar exemplar methods [6]. Yet such detection does not automatically produce flexibility products that can be incorporated into DSO workflows. The framework proposed here treats analytics, estimation, and decision support as sequentially connected but mutually dependent layers rather than as isolated technical modules.

Need for an integrative framework

An integrative framework is needed because existing strands of research often emphasize either analytics, device modelling, aggregation, markets, or control architecture without fully specifying their conceptual interdependence. Local flexibility market studies show how DERs can be coordinated to meet DSO requests [7], while DER management system literature highlights architectural requirements for coordinating distributed resources [8]. However, the operational value of these approaches depends on whether data-derived availability estimates can be trusted and converted into decision-relevant flexibility representations. This article therefore conceptualizes flexibility-aware operation as a layered information system linking measurement, interpretation, aggregation, and action.

Smart-Meter Analytics Background

Smart-meter data capabilities

Smart-meter data can support operational intelligence by revealing temporal load patterns, consumption diversity, export behaviour, and possible signatures of behind-the-meter technologies. Data-driven studies of residential electricity consumption show that high-resolution profiles can reveal dynamic household patterns that are not visible in aggregate feeder measurements [9]. For the proposed framework, these capabilities are important because flexibility estimation requires more than knowing total load; it requires inferring which portion of load or generation may be controllable, shiftable, or uncertain. Smart-meter analytics should therefore be conceptualized as a pattern-recognition layer that makes latent flexibility conditions observable.

Key analytics for operational intelligence

Key analytics for operational intelligence include load profiling, customer segmentation, non-intrusive load monitoring, DER detection, anomaly detection, and short-term pattern forecasting. Non-intrusive load monitoring has been reviewed as a mechanism for identifying appliance-level consumption and enabling energy management applications [10], while additive factorial hidden Markov models illustrate how active and reactive power may be used to infer end-use behaviour [11]. In a flexibility-aware framework, these analytics do not merely describe customers; they help estimate whether flexible loads, PV exports, or storage behaviours are likely to be available at a given time. Operational intelligence thus emerges when smart-meter analytics is explicitly tied to flexibility categories relevant to the DSO.

Limitations and data privacy considerations

Smart-meter analytics also raises limitations related to missing data, measurement resolution, interoperability, privacy, cybersecurity, and communication reliability. Internet-of-Things-enabled smart-grid architectures highlight the importance of communication technologies and data infrastructures, but they also expose operational systems to risks associated with latency, reliability, and cyber vulnerability [12]. Artificial intelligence and blockchain-oriented smart-grid reviews further emphasize the need for secure and trustworthy automation when data are used in power distribution processes [13]. The framework therefore treats privacy, data quality, and communication requirements not as peripheral constraints, but as boundary conditions shaping what kinds of flexibility estimates can responsibly be used.

DER Availability Layer

Characterizing DER types and their flexibility potential

The DER availability layer translates data-derived observations into conceptual indicators of whether specific resources can provide usable operational flexibility. Rooftop PV may offer flexibility through curtailment or export forecasting, batteries through charge and discharge scheduling, electric vehicles through managed charging, and heat pumps through thermal load shifting, with EV-grid integration studies showing the importance of charging infrastructure and grid impact assessment [14]. Each DER type has a different relationship between physical capability, customer behaviour, and network usefulness. The framework therefore posits that DER availability should be characterized as a conditional state rather than a fixed resource attribute.

Availability indicators from smart-meter data

Availability indicators are inferred signals that suggest whether a DER can contribute flexibility in a given operational context. Behind-the-meter PV detection methods show that smart-meter data can be used to infer generation patterns that are otherwise invisible to the DSO [15], while detection of EVs and PV systems from smart-meter data demonstrates the possibility of identifying flexible technologies without direct device telemetry [16]. For batteries and thermal loads, availability indicators may require indirect inference from net-load shapes, time-of-use behaviour, or recurring consumption patterns. The framework therefore proposes that DER availability should be estimated through a combination of direct measurement, inferred signatures, and contextual assumptions.

Figure 2 shows how smart-meter-derived indicators can be translated into DER-specific availability states before being converted into usable flexibility estimates.

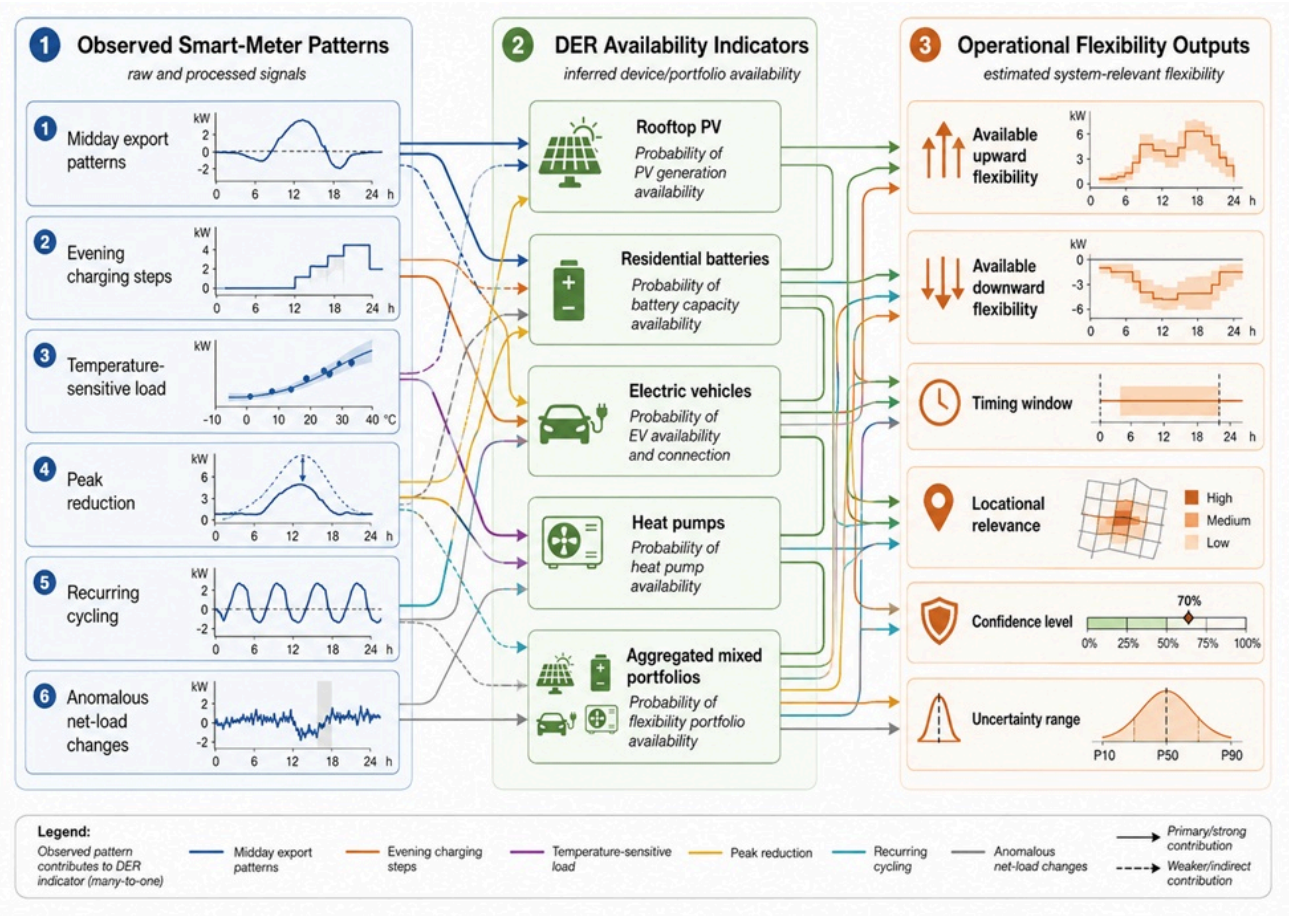


Figure 2. Translation of smart-meter indicators into DER availability and flexibility estimates

Temporal and spatial granularity challenges

Temporal and spatial granularity determine whether DER availability can be useful for congestion and voltage management. Aggregate feasible-region approaches show that distributed resources can be represented through approximate operational regions, but these representations remain sensitive to network location, device constraints, and temporal coupling [17]. Fine-grained smart-meter data may improve availability inference, yet it can increase privacy exposure and communication burdens, creating a trade-off between operational precision and governance acceptability. **Table 1** summarizes how the proposed framework links DER types, availability indicators, and data requirements immediately after this discussion.

Table 1. Summary of Distributed Energy Resource (DER) Types, Smart-Meter-Based Availability Indicators, and Data Requirements for Flexibility Assessment

DER type	Availability indicators derived from smart-meter data	Associated data requirements
Rooftop photovoltaic systems	Midday export patterns, weather-correlated net-load reductions, recurring negative net demand, inferred solar generation profiles, deviation between expected and observed load	Interval smart-meter readings, feeder or customer location, irradiance context, historical net-load profiles, metadata on export limits where available

Residential batteries	Charge and discharge signatures, evening peak reduction, rapid changes in net demand, recurring storage cycling behaviour, possible response to tariffs or control signals	High-resolution interval readings, tariff information, historical daily profiles, customer connection point, optional inverter or state-of-charge telemetry
Electric vehicles	Evening or overnight charging signatures, high-power step changes, weekday or weekend plug-in regularity, charging duration and timing patterns	Interval smart-meter readings, phase and connection information where available, historical charging-like events, tariff and time-of-use context, optional charger telemetry
Heat pumps and thermal loads	Temperature-sensitive consumption, morning or evening heating peaks, load persistence, preheating or setback patterns, weather-correlated demand variation	Interval smart-meter readings, outdoor temperature data, building or customer class, seasonal consumption profiles, optional thermostat or building-energy metadata
Aggregated mixed DER portfolios	Coincident export or demand-shift potential, diversity of availability across customers, locational clustering of flexible capacity, uncertainty-adjusted flexibility envelopes	Customer-level or feeder-level smart-meter aggregation, network topology, resource classification, time synchronization, communication and data-quality indicators

Flexibility Estimation Layer

Bottom-up and top-down estimation methods

The flexibility estimation layer converts DER availability indicators into operationally interpretable estimates of flexible capacity, timing, location, and reliability. Bottom-up methods start from device or customer-level constraints and aggregate them, while top-down methods infer flexibility from measured aggregate behaviour and network response, reflecting the distinction between disaggregated modelling and system-level characterization [18]. In the proposed framework, neither approach is inherently superior because bottom-up models may require unavailable device data, whereas top-down models may obscure resource heterogeneity. Flexibility estimation should therefore be conceptualized as a hybrid inference process that balances observability, tractability, and operational relevance.

Aggregation of individual flexibilities

Aggregation is required because DSOs typically need feeder-level or zone-level flexibility products rather than isolated device capabilities. Research on virtual batteries and aggregate flexibility indicates that many small resources can be represented through simplified operational models, enabling flexible demand and DER portfolios to be used in higher-level decision processes [19]. However, aggregation also introduces conceptual risks because it may hide local voltage constraints, customer rebound effects, and temporal coupling between current actions and future availability. The framework therefore posits that aggregated flexibility should be expressed as a bounded and conditional envelope rather than a guaranteed block of capacity.

Decision-Support Layer

DSO operational needs and decision contexts

The decision-support layer translates estimated flexibility into operational choices for congestion management, voltage control, outage risk mitigation, and operational planning. Distribution system operators require tools that connect locational flexibility to network constraints, because flexibility that is valuable at one node may be irrelevant or even counterproductive elsewhere [20]. The framework therefore posits that decision support should not treat flexibility as a

generic energy commodity, but as a network-conditioned operational resource. This means that the value of flexibility depends on timing, location, controllability, uncertainty, and compatibility with existing protection and planning processes.

Integration of flexibility products into DSO tools

Flexibility products must be represented in forms that can enter DSO tools without requiring operators to interpret raw metering data or device-level signals. Local flexibility market frameworks demonstrate how prosumers and aggregators may participate in flexibility provision, but their operational usefulness depends on whether products are aligned with DSO requests and constraints [21]. Microgrid energy-management research similarly shows that optimization, forecasting, and control functions must be embedded within decision architectures rather than treated as isolated algorithms [22]. The framework therefore conceptualizes flexibility products as standardized, uncertainty-aware information objects that mediate between analytics outputs and operational decisions.

Framework Logic

Layer interactions and information flow

The framework logic begins with smart-meter analytics, which identifies consumption, generation, and behavioural patterns that may indicate DER presence or controllable demand. Non-intrusive load-monitoring applications show that appliance- and device-level insights can be derived from aggregate metering signals, although the reliability of inference varies by context [23]. These insights flow into the DER availability layer, where they are converted into indicators of whether resources are likely to be technically and behaviourally available. The flexibility estimation layer then aggregates these indicators into network-relevant flexibility envelopes that feed the DSO decision-support layer.

Feedforward and feedback loops

The framework is not a one-way pipeline, because decision outcomes should feed back into analytics and estimation assumptions. Residential energy-flexibility characterization using non-intrusive load monitoring suggests that observed responses can improve the interpretation of flexible loads over time [24]. Similarly, predictive building energy-management approaches show that self-reported or inferred flexibility envelopes can be refined through repeated interaction between estimation and control [25]. The framework therefore posits a learning loop in which flexibility activation, non-delivery, rebound effects, and customer behaviour update future availability estimates.

Figure 3 presents the feedback-based decision cycle through which flexibility activation outcomes refine future availability assumptions and improve DSO operational confidence.

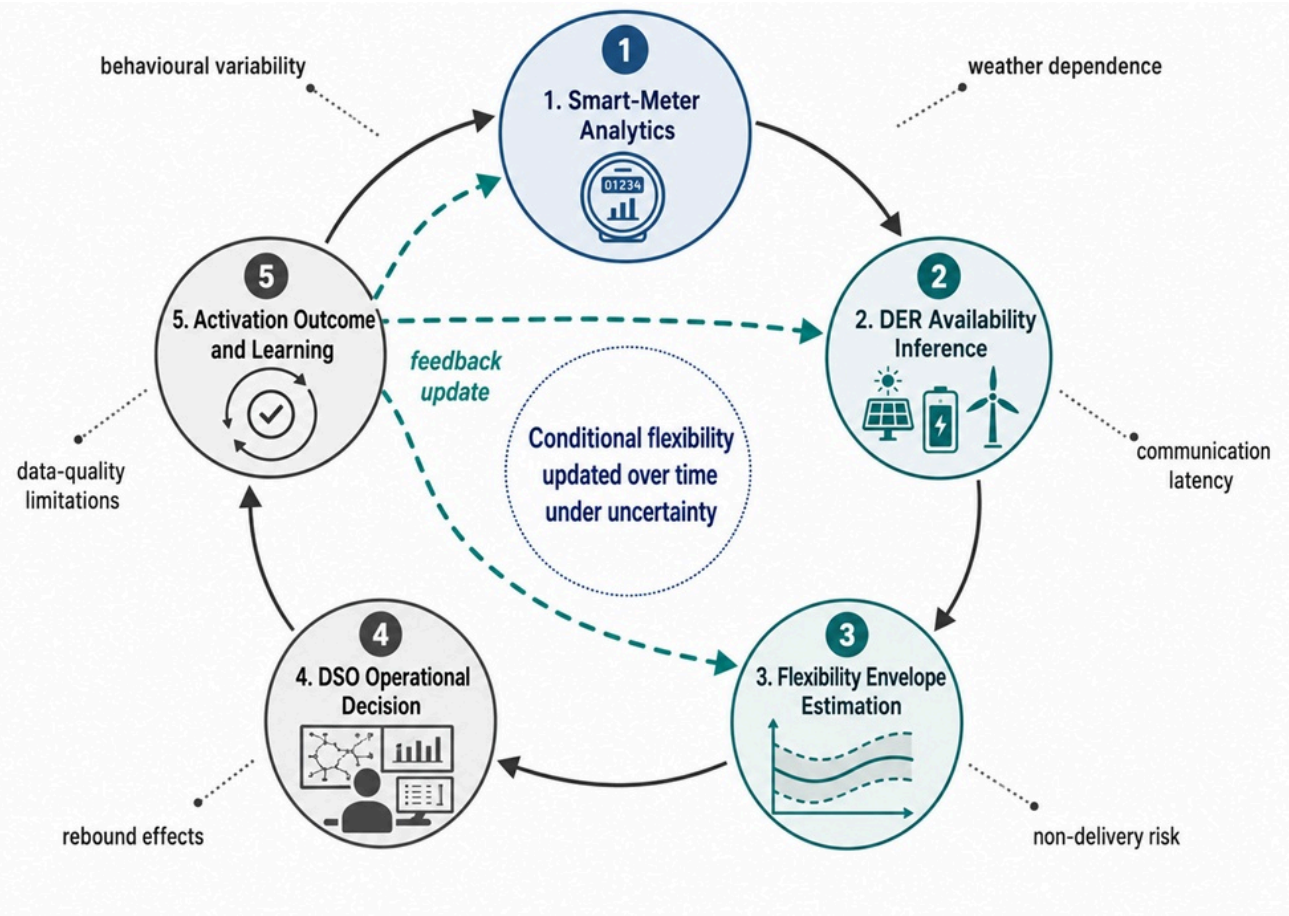


Figure 3. Feedback and learning cycle for uncertainty-aware DSO flexibility decision support

Real-time and planning timescales

The same layered architecture can operate across real-time, day-ahead, seasonal, and planning timescales, although each timescale requires different data granularity and uncertainty treatment. Electric vehicle fleet-management research shows that charging flexibility can support multiple services, but its value depends on plug-in timing, user mobility patterns, and control horizon [26]. Building and microgrid flexibility studies similarly indicate that virtual battery representations can support planning-oriented and operational decisions when temporal constraints are represented coherently [27]. The framework therefore conceptualizes timescale alignment as a critical condition for converting DER availability into useful DSO action.

Assumptions and boundary conditions

The framework assumes that DSOs have access to sufficiently reliable smart-meter data, appropriate privacy safeguards, and communication infrastructures capable of supporting operational or planning use cases. It also assumes that flexibility can be represented through bounded availability and uncertainty rather than perfect controllability, consistent with stochastic modelling of aggregated DER flexibility [28]. Market and prosumer-oriented studies show that user participation and institutional design strongly influence whether flexibility can be mobilized, so the framework should be interpreted as a socio-technical architecture rather than a purely technical model [29]. Table 2 presents the framework architecture, showing how information moves from analytics to decision support.

Table 2. Framework Architecture for DER Flexibility Assessment: From Smart-Meter Analytics to Decision Support and Feedback Learning Loops

Framework component	Primary function	Key inputs	Key outputs	Interaction with other components
Smart-meter analytics layer	Identify load, generation, DER signatures, customer patterns, and data-quality conditions	Interval meter readings, historical profiles, weather context, tariff context, customer or feeder metadata	Load profiles, DER indicators, anomaly flags, consumption and export patterns	Provides inferred operational intelligence to the DER availability layer
DER availability layer	Translate observed patterns into conditional resource availability	Analytics outputs, DER type assumptions, behavioural regularities, environmental context	Availability indicators for PV, batteries, EVs, heat pumps, and mixed portfolios	Converts data-derived signals into resource-specific flexibility potential
Flexibility estimation layer	Aggregate and bound available flexibility across customers and locations	Availability indicators, network topology, temporal constraints, uncertainty assumptions	Flexibility envelopes, virtual battery representations, confidence levels, locational flexibility estimates	Supplies standardized flexibility products to DSO decision support
Decision-support layer	Match flexibility products to operational and planning needs	Flexibility estimates, network constraints, congestion or voltage forecasts, market or control rules	Recommended actions, flexibility requests, operator alerts, planning insights	Uses flexibility products to support congestion management, voltage control, and operational planning
Feedback and learning loop	Update assumptions after flexibility activation or non-delivery	Activation outcomes, customer response, forecast errors, constraint violations, communication failures	Revised availability assumptions, improved confidence estimates, updated operational rules	Connects decision outcomes back to analytics and estimation layers

Propositions

Proposition 1: data granularity and flexibility accuracy

Proposition 1 is that higher temporal and locational granularity in smart-meter data could be expected to improve flexibility-estimation accuracy, but only up to the point where privacy, communication, and data-quality constraints reduce practical usability. Behind-the-meter PV estimation studies illustrate how detailed meter data can reveal otherwise hidden generation patterns, making granularity important for distinguishing load reduction from local generation [30]. However, the framework posits that accuracy is not solely a technical function of more data; it also depends on interpretability, governance, and alignment with DSO decision needs. Future empirical research should therefore test whether additional granularity produces operationally meaningful improvements rather than only better analytical resolution.

Proposition 2: DER availability knowledge and operational benefit

Proposition 2 is that richer knowledge of DER availability should increase the operational benefit of flexibility actions for congestion and voltage management. Peer-to-peer and federated power-plant concepts suggest that distributed prosumers can be coordinated into larger operational entities when their flexibility can be identified and mobilized [29]. Electricity market design for the prosumer era further indicates that system value depends on mechanisms that translate

distributed participation into reliable network services [31]. The framework therefore proposes that DER availability knowledge mediates the relationship between smart-meter analytics and DSO operational benefit.

Proposition 3: uncertainty handling and DSO confidence

Proposition 3 is that explicit uncertainty handling should increase DSO confidence in using flexibility as an operational resource. Data-driven flexibility characterization shows that residential flexibility can be inferred from consumption patterns, but such inference remains dependent on behavioural variability and model assumptions [24]. If flexibility products include confidence intervals, validity windows, and assumptions about customer or device response, DSOs could be more willing to integrate them into decision processes. The framework therefore posits that uncertainty transparency is not merely a modelling improvement, but a condition for institutional trust and operational adoption.

Proposition 4: integration level and network performance

Proposition 4 is that stronger integration among smart-meter analytics, DER availability estimation, flexibility estimation, and decision support should improve distribution-level network performance relative to fragmented approaches. Demand response research has long emphasized that flexible demand can contribute to grid operation when coordinated with renewable energy and system needs [32]. However, the framework argues that performance gains depend on integration level, because isolated analytics cannot relieve congestion unless translated into actionable flexibility and embedded in DSO workflows. Future research should therefore test whether integrated architectures produce more reliable voltage control, congestion mitigation, and planning support than siloed analytical systems.

Implications

Implications for DSO operational practice

For DSO operational practice, the framework implies that smart-meter analytics should be embedded in workflows that produce decision-ready flexibility information rather than retrospective descriptive reports. Distribution system flexibility characterization research suggests that network-informed, data-driven methods can connect resource availability to operational constraints [20]. DSOs should therefore develop capabilities for data validation, resource inference, locational aggregation, and uncertainty-aware flexibility visualization. The practical implication is that flexibility-aware operation requires organizational routines as much as analytical tools.

Implications for regulation and market design

For regulation and market design, the framework implies that flexibility products should be defined in ways that reflect locational value, uncertainty, privacy requirements, and customer participation conditions. Local flexibility markets demonstrate one route through which DSOs can procure flexibility from distributed resources, but such markets require clear products, baselines, verification rules, and coordination with network operation [4]. The framework therefore suggests that regulators should avoid treating flexibility only as a wholesale-market resource and should recognize its distribution-specific operational value. Market rules should support transparent availability reporting, privacy-preserving data use, and accountability for non-delivery.

Conclusion

This article has proposed a conceptual framework for flexibility-aware smart-grid operation linking smart-meter analytics, DER availability, flexibility estimation, and distribution-level decision support. The framework treats smart-meter data as the starting point for operational intelligence, but not as sufficient on its own. Its central argument is that flexibility becomes useful only when data-derived insights are translated into resource availability, aggregated into bounded flexibility products, and embedded in DSO decision processes.

The framework contributes a layered logic for understanding how DERs can support congestion management, voltage control, and operational planning. It conceptualizes DER availability as conditional, flexibility estimation as uncertainty-aware, and decision support as both technical and organizational. By doing so, it avoids treating flexibility as a static quantity and instead frames it as a dynamic operational capability.

The four propositions articulate testable relationships among data granularity, DER availability knowledge, uncertainty handling, integration level, and network performance. These propositions can guide future empirical research using field data, simulations, DSO case studies, or comparative institutional analysis. They are intended to support theory development as well as practical experimentation.

The practical value of the framework lies in helping DSOs move from passive data collection toward active flexibility-aware operation. Future studies should test the framework under different regulatory, technological, and network conditions. Such work can help determine how smart-meter analytics and DER coordination can be responsibly transformed into reliable distribution-level decision support.

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