# FED-MGDT: A Federated Digital Twin Framework for Autonomous Trust-Aware Microgrid Coordination

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*Abstract* — **The increasing growth of distributed energy resources and prosumer-driven energy systems introduces new challenges for decentralized microgrid coordination and policy enforcement. This paper presents the Federated Microgrid Digital Twin (FED-MGDT), a scalable co-simulation framework for evaluating contract-based DER coordination in microgrid environments. FED-MGDT integrates physics-based GridLAB-D models and a HELICS co-simulation framework, combined with a contract coordinator federate that monitors power exchange, enforces import power limits, and provides cumulative violation energy and trust metrics. By coupling physical microgrid dynamics with contract compliance and trust evaluation, FED-MGDT establishes a scalable experimental platform for investigating autonomous, trust-aware DER coordination mechanisms in future microgrid, nanogrid, and grid-integrated energy systems.**

***Keywords: Digital Twin; Federated Co-Simulation; Microgrid; Contract-Based Coordination; Cyber-Physical Systems***

## I. INTRODUCTION

The electric grid is undergoing fundamental changes primarily driven by decarbonization goals, the adoption of renewable energy, the transition to electric-powered transportation, and advances in distributed computing and sensing technologies [1] [2]. Traditional centralized power generation and delivery models are being replaced by more decentralized energy systems based on Distributed Energy Resources (DERs) [3]. DERs include small-scale power generation and storage technologies such as solar photovoltaic (PV) systems, battery storage systems, and other renewables, which are deployed closer to consumers [4]. Consequently, these resources facilitate more localized energy production and consumption, reducing dependence on a centralized infrastructure.

A primary building block for this distributed architecture is the microgrid. This small-scale, local power grid produces, stores, and manages electricity for a specific area (e.g., a residential neighborhood) and can operate either in coordination with the main power grid or in an autonomous islanded mode. Microgrids offer several benefits over a centralized infrastructure, including improved reliability, renewable energy integration, and a stable energy source in areas where centralized infrastructure is impractical or vulnerable to disruptions [5][6]. As the deployment of networked microgrids increases, grid resilience, efficient energy management systems, and data-driven control strategies become critical for success [7][8]. Additionally, as renewable energy sources further penetrate the market, microgrids are becoming essential for addressing the availability of renewable power generation while maintaining stable grid operations [9].

The push for decentralized energy production is also driving a shift in energy consumption. Historically, users operated only as passive consumers within power company-controlled infrastructures. As the costs of renewable energy decrease, along with regulatory incentives and advancements in energy management technologies, consumers are increasingly becoming energy producers, storage providers, and active market participants [10]-[12]. These "prosumers" can generate, store, and trade locally produced energy while simultaneously interacting with utilities and neighboring energy systems. These emerging prosumer communities can then enable the balancing of generation and consumption through decentralized energy-sharing models that improve system flexibility, cost efficiency, and sustainability.

Additionally, as the adoption of DERs and prosumer energy models increases, interest in even smaller-scale energy systems, known as nanogrids, will grow. A nanogrid represents the smallest operational unit of a distributed energy network operating at the building, facility, or device-level power system. These localized systems integrate DERs and storage systems to support autonomous operation while enabling interoperability with other microgrids and larger grid infrastructures. Nanogrids extend the concept of distributed energy coordination and are expected to play a significant role in enabling personalized energy delivery in future power infrastructure systems [13][14].

However, these new technical and operational challenges position distributed energy coordination as a Cyber-Physical Systems (CPS) problem, requiring tight integration of physical grid dynamics and distributed control logic. In future distributed energy systems, consumers and prosumers will need to negotiate, exchange, and enforce energy services through autonomous coordination mechanisms. These systems require trustworthy, scalable coordination that can verify contractual agreements, monitor compliance, and support distributed decision-making across heterogeneous energy assets.

Digital Twin (DT) technology offers promising solutions to address challenges associated with DER coordination. A DT is a virtualized high-fidelity representation of a physical system. DT technology has already been applied to improve

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energy planning, operational efficiency, and predictive maintenance of microgrids and smart grid infrastructures [15][16]. However, the potential of digital twins as an experimental platform for studying decentralized DER coordination, autonomous service negotiation, and trusted contract-based energy exchanges remains unexplored.

This work aims to address this research gap by presenting a federated microgrid digital twin (FED-MGDT) architecture that provides an experimental platform for investigating distributed energy coordination among consumers, prosumers, and DERs. The framework integrates GridLAB-D [17], a power distribution system simulation that models smart grid technologies, with HELICS [18], a co-simulation framework that supports scalable, modular federation of heterogeneous microgrids.

The remainder of this paper is organized as follows. Section II presents the FED-MGDT architecture and federated digital twin framework. Section III describes the contract model, and experimental configuration. Section IV presents the simulation results. Section V discusses related work in digital twins and microgrid coordination. Finally, Section VI concludes the paper and outlines directions for future work.

## II. MICROGRID DIGITAL TWIN SYSTEM ARCHITECTURE

### A. *Architectural Overview*

The FED-MGDT framework integrates high-fidelity power system simulations with distributed co-simulation capabilities to model interconnected energy systems and coordination services. Figure 1 depicts an example of a small-scale federation containing three microgrids. The detailed descriptions of the architectural components are provided in the subsequent subsections.

### B. *Microgrid Digital Twin Design*

Each digital twin is implemented as an independent GridLAB-D simulation federate within the HELICS federation. The model includes power generation, energy storage systems, controllable and non-controllable loads, as well as feeders and service transformers. Energy exchange between connected microgrid domains is represented through Points of Common Coupling (PCCs), which serve as interfaces between microgrids or external grid participants. PCC interfaces publish power flow measurements and receive coordination signals via HELICS communication channels.

### C. *HELICS-Based Federation and Scalability*

The HELICS co-simulation framework enables the synchronization of the microgrid digital twins and service coordination. Each microgrid operates as an independent HELICS federate that publishes PCC data, DER generation levels, energy storage state, and load demand. Coordination services subscribe to the relevant system data and publish control or contract policy as needed.

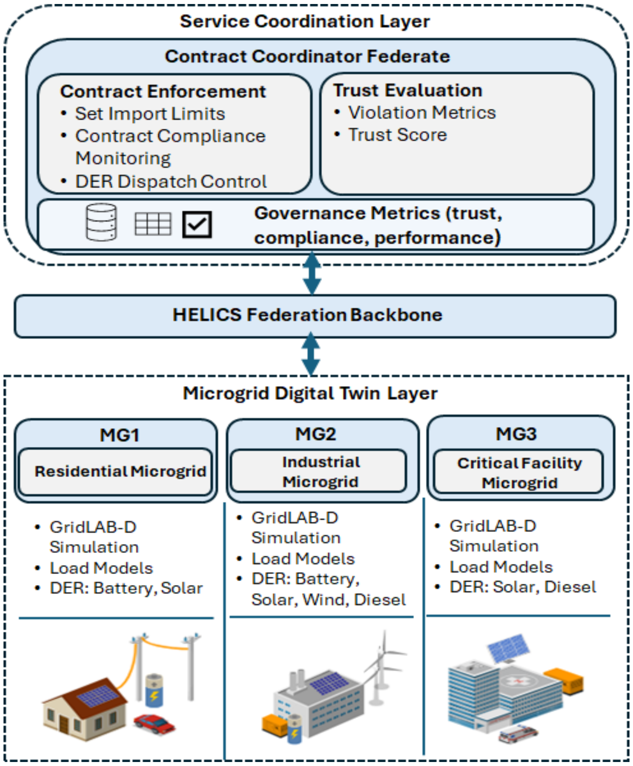

Figure 1: Scalable Federated Microgrid Digital Twin (FED-MGDT) Architecture

### D. *Service Coordination Layer*

The service coordination layer is responsible for providing high-level management and broker service. This layer consists of the Contract Coordinator Federate (CCF), which is responsible for policy evaluation, contract monitoring, and coordination logic. The CCF interacts with microgrid models through HELICS publisher-subscriber channels. While initially this federate was designed as a centralized service abstraction, the architecture does not dictate any specific enforcement mechanisms. Therefore, the coordination logic could be implemented as a decentralized service that supports bilateral negotiation schemes, third-party arbitration, or cryptographic smart contract mechanisms.

## III. CONTRACT COORDINATION AND MONITORING

### A. *Contract-Based DER Coordination Model*

The FED-MGDT architecture uses a contract-based coordination approach, enabling each microgrid operator or prosumer community to control energy generation and consumption independently.

Coordination between microgrids is handled through service-level contracts that define the conditions for energy exchange across PCCs. These contracts specify various constraints such as energy transfer limits, time-based exchange conditions, or reserve capacity requirements. Microgrids publish measurements while the CCF subscribes

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to these measurements and then evaluates contract compliance during simulation execution.

### B. Contract Representation

Contracts within the framework are parameterized objects that define relationships among participating microgrids and specify constraints on energy exchange behavior. Each contract is defined by a set of attributes that describe each consumer or prosumer, their operational conditions, and evaluation criteria. A contract $C$ between participating microgrids can be represented by the equation:

$$C = \{P_i, P_j, T, \Phi\} \tag{1}$$

where: $P_i$ and $P_j$ represent participating microgrids, $T$ defines the time interval for contract enforcement, and Φ represents contractual constraints. These constraints could include upper bounds, lower bounds, or range-based limits.

### C. Contract Monitoring and Enforcement

Contract compliance is monitored by CCF operating as a separate HELICS federate. This federate subscribes to published measurements including PCC power measurements, DER generation, storage state levels, and load demands. At each simulation time step, the federate evaluates contract conditions using subscribed measurements and computes compliance status based on defined policy constraints.

For example, if $P_{PCC}(t)$ represents measured power exchange of a PCC at time $t$, and $P_{cap}$ defines the max PPC import power then compliance with an exchange limit contract is evaluated by the equation below:

$$V(t) = \max(0, P_{PCC}(t) - P_{cap}) \tag{2}$$

where $V(t)$ represents the violation magnitude. A violation occurs when the measured exchange exceeds contract-defined thresholds. The CCF records violation events and compliance metrics during simulation execution.

### D. Compliance Metrics and Performance Evaluation

The evaluation of coordination performance for FED-MGDT defines several metrics based on PCC monitoring data. These metrics provide insight into coordination effectiveness and support comparative evaluation of the DER coordination strategies. The cumulative violation energy over a contract interval is computed by the equation:

$$E_{viol} = \sum_{k=1}^{N} V(t_k)\Delta t \tag{3}$$

where Δt represents the HELICS time step and $V(t_k)$ defines the violation at step $k$. The compliance rate measures how well microgrids adhere to contract-defined energy exchange constraints and is defined as:

$$R_{comp} = 1 - \frac{E_{viol}}{E_{total}} \tag{4}$$

$E_{viol}$ represents the violation over the contract time interval and $E_{total}$ represents the total monitored energy exchange over the same time interval. $R_{comp}$ ranges between 0 and 1 where $R_{comp} = 1$ indicates full compliance, $0 < R_{comp} < 1$ indicates a partial compliance and $R_{comp} \approx 0$ indicates persistent or severe violations.

## IV. EXPERIMENTAL SETUP AND SIMULATION CONFIGURATION

### A. Federated Microgrids Configuration

The FED-MGDT framework was evaluated using a configuration consisting of three interconnected microgrids. The simulation models included a representative residential microgrid (MG1), a commercial/industrial microgrid (MG2), and a critical infrastructure microgrid (MG3). Each microgrid was executed as an independent GridLAB-D federate within the HELICS co-simulation, along with the Python-based CCF for contract compliance. In the current experimental setup, the three microgrid digital twin federates and the CCF were executed on a single Ubuntu 22.04 host via ZMQ-based communication (multiple hosts are supported). The HELICS co-simulation time step was set to 60 seconds, and the total simulation duration was 24 hours.

### B. Microgrid Models and DER Configuration

The MG1 microgrid included a controllable battery resource used for contract-based coordination. Grids MG2 and MG3 operated in monitor-only mode and did not receive commands during the experiments. All microgrids published measurement data, including net power, PCC power measurements, phase voltages, and aggregate load metrics. The CCF subscribed to these measurements for contract compliance evaluation.

### C. Contract Configuration

To evaluate coordination performance, four experiments were conducted with varying MG1 import power limits during the defined peak enforcement window (17:00-20:00).

TABLE I: MG1 CONTRACT IMPORT POWER CONFIGURATIONS

| *Exp ID* | *MG1 Import Power Limit (kW)* |
|---|---|
| E1 | 4 kW |
| E2 | 6 kW |
| E3 | 8 kW |
| E4 | 10 kW |

TABLE II: EXPERIMENTAL & ENFORCEMENT SIMULATION PARAMETERS

| *Category* | *Parameter* | *Value* |
|---|---|---|
| Simulation | Simulation duration | 24 hours |
| Simulation | Simulation Time Step (Δt) | 60 secs |
| Enforcement | Peak Enforcement Window | 17:00-20:00 |
| Physical System | MG1 Max Battery Discharge | 6 kW |
| Trust Model | Penalty Weight (λ) | 1.0 |
| Trust Model | Trust Sensitivity Parameter (β) | 0.5 |
| Federation | Controlled Microgrid | MG1 only |
| Federation | Monitoring Microgrids | MG2, MG3 |

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The import power limits in Table I represent four different import power limits for the same contract. This variation provides analysis of how contractual constraint values affect violation energy, battery dispatch behavior, compliance rate, and trust evolution. In all experiments, MG1 was actively controlled by the contract coordinator, while MG2 and MG3 were operated in monitor-only mode. This initial study isolates single-microgrid contract enforcement to characterize feasibility dynamics prior to multi-party contract interactions.

Table II summarizes the configuration and enforcement parameters applied to all experiments. The parameters define simulation timing, physical system constraints, trust-computation constants, and the federation scope, rather than distinct contract terms.

### D. *Contract Monitoring and Compliance Evaluation*

The CCF subscribed to PCC and DER measurements, then evaluated compliance at 60-second intervals. Contract violations were computed when MG1's PCC import exceeded the contractual cap during the peak interval period. Cumulative violation energy was also computed using discrete-time integration based on equation (3). The coordinator logged the following metrics at each timestep: instantaneous violation (kW), cumulative violation energy (kWh), cumulative penalty, trust score, and compliance per timestep. Scenario simulation metrics were recorded in a CSV output file for post-simulation analysis.

## V. RESULTS AND PERFORMANCE EVALUATION

### A. *Baseline Federated Operation*

A baseline simulation scenario was used as an initial test to verify the contract enforcement capability and that contract-based coordination did not destabilize the underlying power simulation. The coordinator federate was configured to enforce a time-bound PPC import contract for MG1 during the peak window from 17:00 to 20:00.

The contract imposed an upper bound on MG1's grid import power. The contractual import limit was set to relaxed values (8-kW and 10-kW), where microgrid MG1 rarely exceeded the import threshold during peak hours. Battery dispatch was minimal or moderate, and PCC interchange remained within acceptable limits during the peak window. Voltage deviations across MG1, MG2, and MG3 remained within nominal limits.

### B. *Contract Enforcement Behavior*

A time-based analysis was performed to verify contract enforcement for a 6-kW import power cap experiment. During peak enforcement, the CCF continuously monitors MG1 PCC import power and compares it against the 6-kW threshold. When the power import exceeds this limit, the CCF computes the required discharge power and issues a battery dispatch command through HELICS. In this proof-of-concept implementation, the CCF determines dispatch actions, while battery control execution remains with the local MG1 controller.

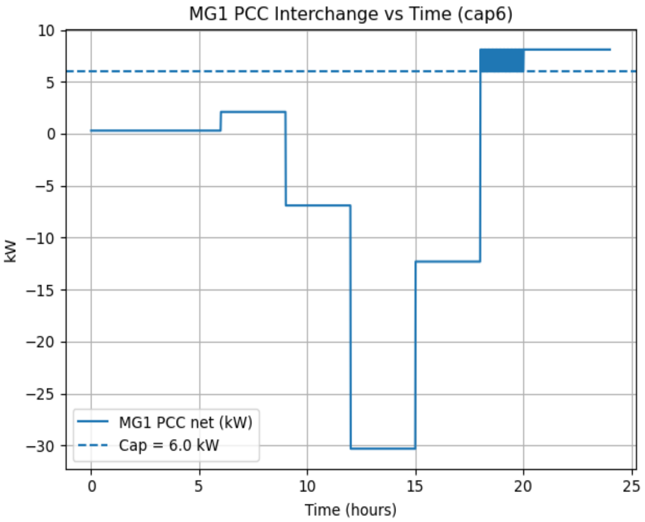

Figure 2:MG1 PCC Interchange Under a 6-kW Contract Cap

As shown in Figure 2, PCC import power exceeds the 6-kW threshold during the peak window. The shaded region above the 6-kW limit represents the violation magnitude. When violations occur, the CCF computes the additional battery discharge needed to offset the excess import. However, because the MG1 battery's maximum discharge capacity is 6 kW, it is not always possible to bring the import down to meet the contractual limit. Positive PCC values indicate net power import into MG1, while negative values represent net export due to local DER generation or battery discharge.

### C. *Contract Sensitivity and Trust Analysis*

To evaluate the influence of contract-based compliance on coordination performance, a sensitivity analysis was conducted by varying the MG1 allowable import power to 4 kW, 6 kW, 8 kW, and 10 kW. For each scenario, cumulative violation energy and the resulting trust score were computed over the peak enforcement interval. Trust is defined by the equation below:

$$trust = e^{-\beta E_{viol}} \tag{5}$$

Figure 3 presents the final trust score as a function of the contracted import power limit. Under the 4-kW restrictive limit, cumulative violation energy increases rapidly, resulting in significant trust degradation. At 6-kW, trust improves slightly but remains reduced due to sustained violation periods when peak demand exceeds the contracted limit and available battery discharge. A distinct transition occurs between the 6-kW and 8-kW scenarios, indicating a capacity-bounded feasibility threshold governed by the 6-kW battery discharge constraint. Beyond this point (i.e., 10 kW scenario), violations are minimal, and trust remains effectively constant.

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Additionally, the trust score outlined in Figure 3 identifies a feasibility threshold of DER flexibility constraints. The MG1 battery has a maximum discharge capability of 6-kW, but when the contracted import limit is set below the peak import cap, complete compliance becomes infeasible. In contrast, when the import limit exceeds this threshold, the battery can compensate for peak demand, enabling full compliance.

This feasibility behavior reflects the interaction between contractual policy and available energy storage resources. Contractual limits that exceed the capabilities of DER assets result in violations, regardless of the control strategy. Conversely, when contract parameters align with the system's capacity, compliance improves dramatically. As a result, contract design in distributed energy systems must account for underlying DER flexibility limits.

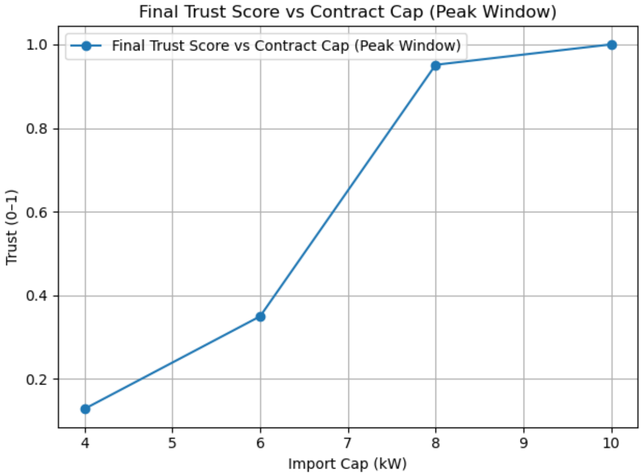

Figure 4:Trust Score as a Function of PCC Contract Limit

## D. *Violation Energy Analysis*

To further interpret the contract sensitivity results, cumulative violation energy is analyzed as a function of the contractual import power limit. Cumulative violation energy represents the total excess energy (kWh) imported above the contractual power limit during the peak enforcement interval. It is computed by integrating the violation magnitude over time.

Figure 4 presents energy violations as a function of the MG1 microgrid import power limit. Energy violations decrease as the limit is relaxed, while contract-violation energy is highest at the 4-kW limit. Increasing the cap to 6-kW reduces violation energy, but violations still occur when peak demand exceeds the battery's capacity. At 8-kW and above, violation energy drops sharply, reflecting near-complete compliance. Since trust is an exponential function of cumulative violation energy as defined in (5), slight changes in violation energy result in exponential changes in trust, highlighting a feasibility boundary constrained by DER flexibility limits. Because the MG1 battery has a maximum discharge capability of 6-kW, when the import power limit is set below the peak import minus the battery capacity, violation energy cannot be eliminated solely through control action.

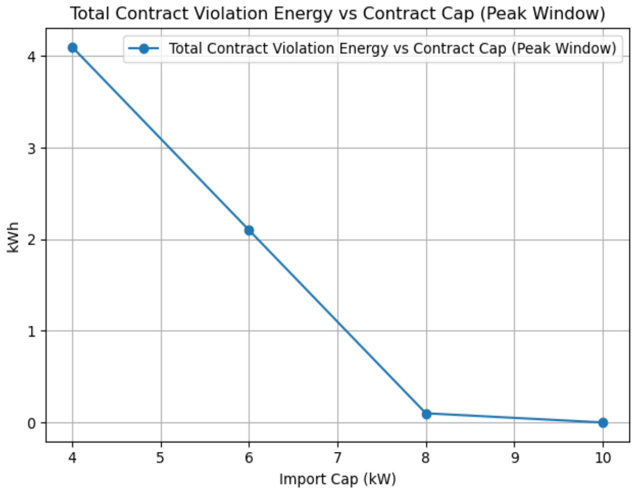

Figure 3:Contract Violation Energy vs PCC Import Cap

## VI. RELATED WORK

Digital twin (DT) technologies have been widely investigated for microgrid modeling, monitoring, and optimization. Recent survey articles, including a review by Kumari et al. [19] examine the role of DTs in enhancing observability, predictive maintenance, renewable integration, and operational efficiency. Similarly, another recent article [20] highlighted the potential of DT frameworks to support improved energy management and system resilience. Together these works among others [21][22] demonstrate that DTs provide high-fidelity virtual representations that support advanced analysis and optimization of grid-connected microgrids.

Digital twins have also been applied to cybersecurity and resilience. For example, the ANGEL framework [23] proposes an intelligent DT architecture for microgrid security, focusing on anomaly detection and cyber-physical threat mitigation. However, these efforts address system monitoring and threat detection rather than decentralized coordination policies or contract-based enforcement mechanisms.

Other co-simulation frameworks such as the Transactive Energy Simulation Platform, or TESP [24], were established to reduce the software development effort for simulation of new transactive systems to study distributed market and coordination mechanisms. This work was used to validate the effectiveness of federated co-simulation for modeling large-scale, multi-domain energy systems. Nevertheless, many transactional or market-based studies assume enforceable agreements without explicitly modeling contract-compliance metrics grounded in system behavior.

Additionally, research on distributed and peer-to-peer energy coordination explored decentralized decision-making among prosumers and microgrids [25]. However, these approaches are often evaluated in market simulations or simplified physical models. While prior digital twin research has focused on optimization and security applications, it has paid little attention to autonomous, trust-aware coordination mechanisms. In contrast, FED-MGDT provides a scalable federated foundation for advancing trust-based energy contracts in distributed microgrid and nanogrid systems.

## VII. CONCLUSION AND FUTURE WORK

FED-MGDT presents a first step toward integrating contract-based coordination mechanisms with high-fidelity physics simulation. While prior research has addressed optimization, security, or market-based coordination in isolation, existing approaches do not evaluate how contractual constraints interact with physical system dynamics. This work demonstrates such interaction through the feasibility boundaries imposed by DER flexibility limits, providing a foundation for investigating trust-aware energy coordination in distributed microgrid and nanogrid systems.

The framework integrates GridLAB-D and HELICS with a contract service federate, enabling assessment of contractual import power limits, cumulative violation energy, compliance rate, and trust metrics within a single simulation environment. As a proof-of-concept, this work verifies that a modular co-simulation architecture can support contract monitoring and compliance evaluation alongside physics-based grid simulation.

Future work will extend FED-MGDT in three directions. First, the trust model will be expanded to incorporate distributed trust mechanisms, including authentication, compliance verification, and reputation. Second, the contract model will be extended to support bilateral agreements, contract negotiation, and multi-party coordination. Third, the federation will be scaled to support hundreds of microgrid participants and nanogrid-scale nodes, enabling evaluation of grid-wide trust-based coordination scenarios

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