

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

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Tom Springer is an **Associate Professor at Chapman University** with extensive industry and research experience in embedded systems, cyber-physical systems, and distributed computing.

His research interests include digital twins, real-time systems, trustworthy autonomous systems, IoT, and scalable coordination frameworks for distributed energy and embedded platforms.

Motivation

- Growing Challenges in Modern Energy Systems
 - Increasing deployment of:
 - Distributed Energy Resources (DERs)
 - Microgrids and nanogrids
 - Renewable and intermittent energy sources
 - Future distributed energy systems require:
 - Autonomous coordination
 - Reliable energy sharing
 - Adaptive decision-making across multiple participants
 - Existing approaches primarily focus on:
 - Optimization and control
 - Security and resilience
 - Energy market mechanisms
 - Limited work addresses:
 - Trust-aware coordination
 - Contract compliance under physical constraints
 - Scalable digital twin-based evaluation

How can we evaluate trust-aware energy contracts while accounting for real physical constraints and distributed coordination behavior

FED-MGDT: Digital Twin Platform Overview

- HELICS (Coordination / Interaction Layer)
 - HELICS is a co-simulation framework that allows multiple models to interact.
 - It connects different components (microgrids, controllers, contract logic).
 - It ensures:
 - synchronized time progression
 - consistent data exchange between components
- GridLAB-D (Physical System Model)
 - GridLAB-D is a simulation tool that models how electricity flows through a power system.
 - It represents:
 - Loads (demand)
 - Generation (e.g., solar)
 - Storage (batteries)
 - It captures real physical constraints, such as:
 - power limits
 - energy capacity
 - time-varying demand

GridLAB-D models the physical behavior. HELICS provides interaction and coordinated information exchange

HELICS™: Hierarchical Engine for Large-scale Infrastructure Co-Simulation

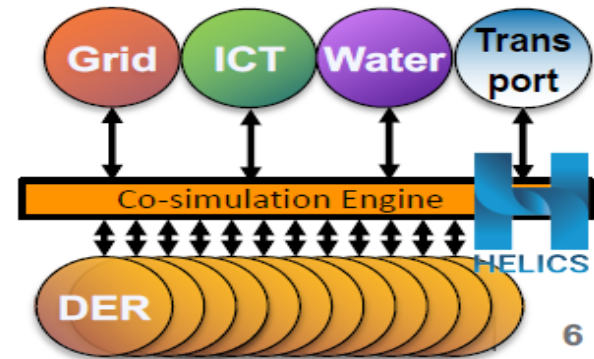
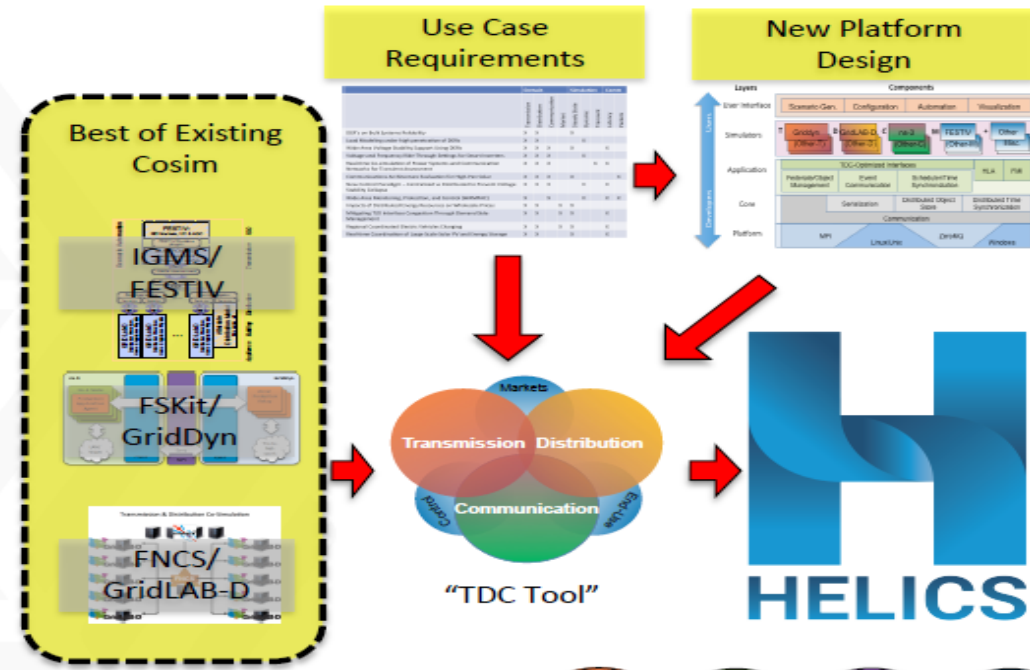
Scalable, High-performance co-simulation to combine best-in-class tools for breakthrough grid modernization simulation and analysis

Capabilities:

- **Scalable:** 2-100,000+ Federates
- **Cross-platform:** HPC (Linux), Cloud, Workstations, Laptops (Windows/OSX)
- **Modular:** mix and match tools
- **Minimally invasive:** easy to use lab/commercial/open tools
- **Open Source:** BSD-style.
- **Many Simulation Types:**
 - Discrete Event
 - QSTS
 - Dynamics
- **Co-iteration enabled:** “tight coupling”
- **APIs:** C++, . C, Python, Java, Matlab, Julia, FMI

v2.0.0 available now at <https://www.github.com/GMLC-TDC/HELICS-src>

B. Palmintier, et al., “Design of the HELICS High-Performance Transmission-Distribution-Communication-Market Co-Simulation Framework,” Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, Pittsburgh, PA, 2017.



Source: HELICS for Integrated Transmission, Distribution, Communication, & Control (TDC+C) Modeling

GridLAB-D: High-fidelity power system simulation platform

Unifies models of the key elements of a smart grid:

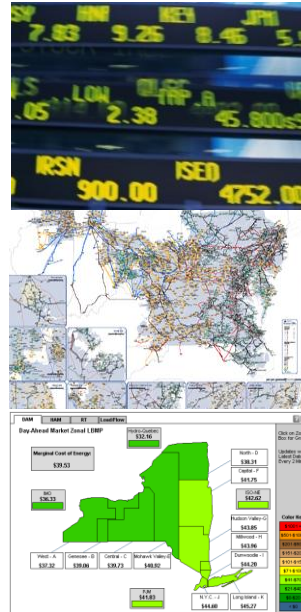
Loads & DERs



Power Systems



DSO Markets



- ✓ Smart grid analyses
 - field projects
 - technologies
 - control strategies
 - cost/benefits
- ✓ Time scale: *ms* to years
- ✓ Open source (BSD-style)
- ✓ Contributions from
 - government
 - industry
 - academia
- ✓ Vendors can add or extract own modules

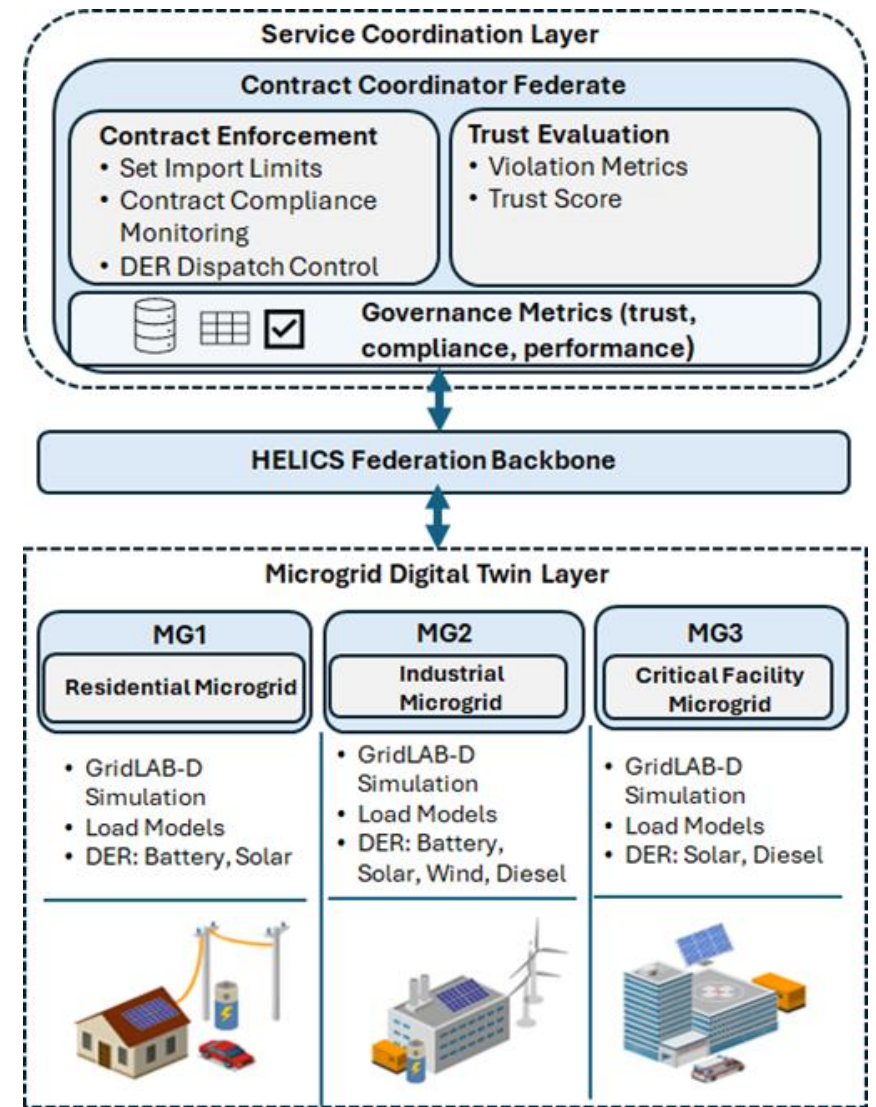
Source: Pacific Northwest National Laboratory | PNNL (.gov)
<https://www.pnnl.gov › external › PNNL-22204>

➤ Open-source, time-series simulation of an operating smart grid, from the substation to individual end-use loads & distributed energy resources. GridLab-D solves:

- 1) power flow
- 2) control systems
- 3) retail markets
- 4) electromechanical dynamics
- 5) load behavior in buildings and devices

FED-MGDT Architecture

- Federated Digital Twin Structure
 - The system models multiple microgrids as independent digital twins
 - Each microgrid operates as a separate federated component
 - The federation enables coordinated simulation of distributed energy systems
- Physical Layer (GridLAB-D Models)
 - Each microgrid is modeled using high-fidelity power system simulation
 - Captures:
 - Load demand
 - Renewable generation (e.g., solar)
 - Battery storage behavior
 - Enforces real physical constraints (power limits, capacity, dynamics)
- Coordination Layer (Contract Coordinator Federate – CCF)
 - A centralized (or logically centralized) contract coordination entity
 - Monitors contract compliance across microgrids
 - Evaluates constraint violations (e.g., import limits)
 - Issues coordination signals (not direct control commands)
- Communication Layer (HELICS Federation)
 - HELICS enables synchronized communication between all components
 - Each federate exchanges data in time-coordinated steps



This architecture lets us study how distributed energy systems coordinate under contracts, while being constrained by real physical limits.

Trust Model

Trust Behavior

- Trust decreases as violations increase
- Repeated violations have cumulative impact
- Larger violations result in faster trust degradation
- Trust reflects contract reliability over time

Purpose of Trust

- Quantifies participant reliability
- Measures long-term contract performance
- Supports future coordination decisions
- Provides feedback for adaptive contract mechanisms

Trust equation:

$$Trust = e^{-\beta E_{viol}}$$

Where:

- E_{viol} - Cumulative contract violation energy
- β - Trust sensitivity parameter

FED-MGDT Analytics for Trust and Contracts

- **Contract Performance Data**
 - Contract compliance rate (% of time constraints satisfied)
 - Magnitude of violations (kW, kWh)
 - Duration of violations
 - Time-of-day violation patterns
 - Contract success/failure outcomes
- **Resource Constraint Data**
 - Available battery capacity over time
 - Maximum feasible discharge limits
 - Load variability profiles
 - Renewable generation uncertainty (PV fluctuations)
 - Flexibility margins
- **Cost and Penalty Signals (Derived – not fully implemented)**
 - Violation energy → can map to penalty cost
 - Battery usage → operational cost (cycling, degradation proxy)
 - Import/export levels → energy cost exposure
 - Missed contract obligations → economic penalties
- **System-Level / Grid-Level Signals (regional grid)**
 - Aggregate demand vs constraints
 - Congestion events
 - System-level violations
 - Interactions between local and global constraints
- **Trust and Reliability Metrics**
 - Trust score evolution over time
 - Relationship between violations and trust decay
 - Sensitivity of trust to contract strictness
 - Stability of trust under volatility

Experimental Configuration

Simulation Environment

- HELICS-based federated co-simulation
- GridLAB-D microgrid models
- Ubuntu 22.04 execution environment

System Configuration

- Three microgrid digital twin federates
 - MG1: controlled microgrid
 - MG2 and MG3: monitoring participants
- Contract Coordinator Federate (CCF)

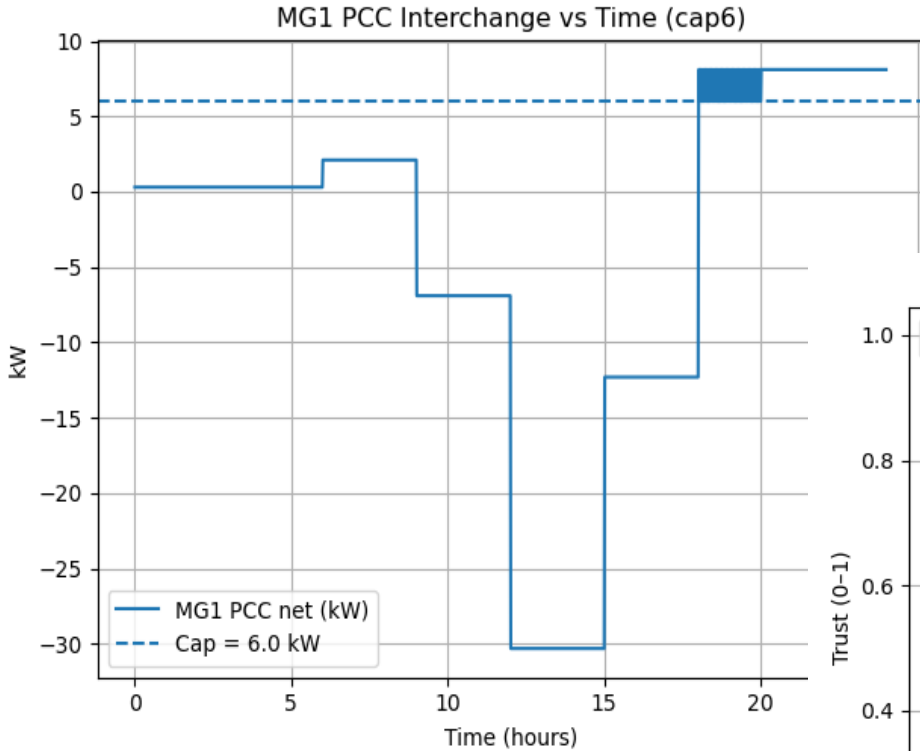
Simulation Parameters

- Simulation duration: **24 hours**
- Simulation timestep: **60 seconds**
- Peak enforcement window: **17:00–20:00**
- MG1 battery maximum discharge: **6 kW**

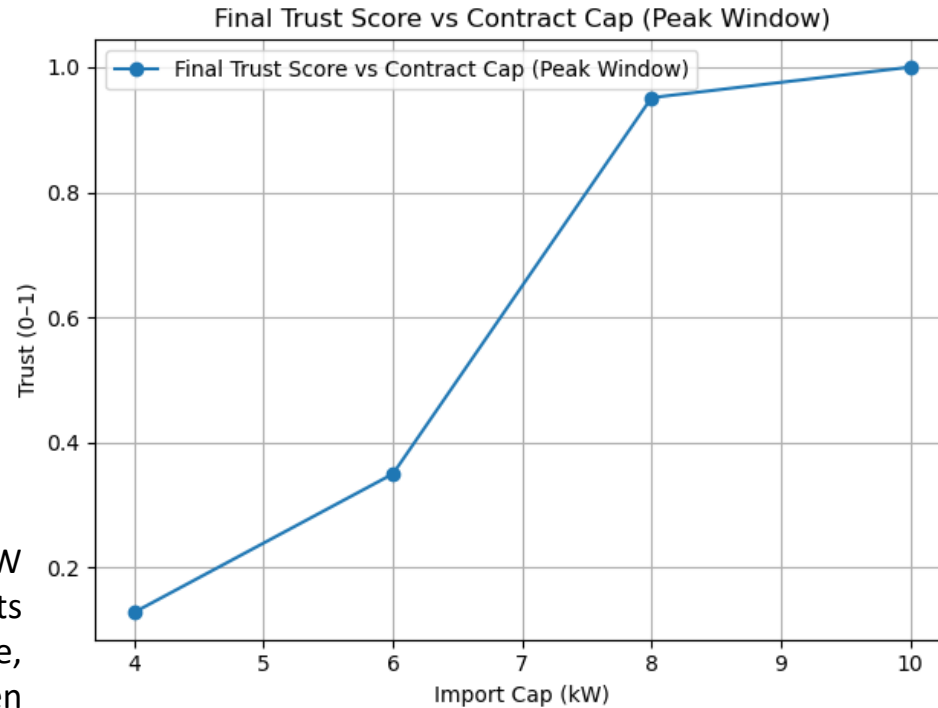
Trust Parameters

- Penalty weight $\lambda = 1.0$
- Trust sensitivity parameter $\beta = 0.5$

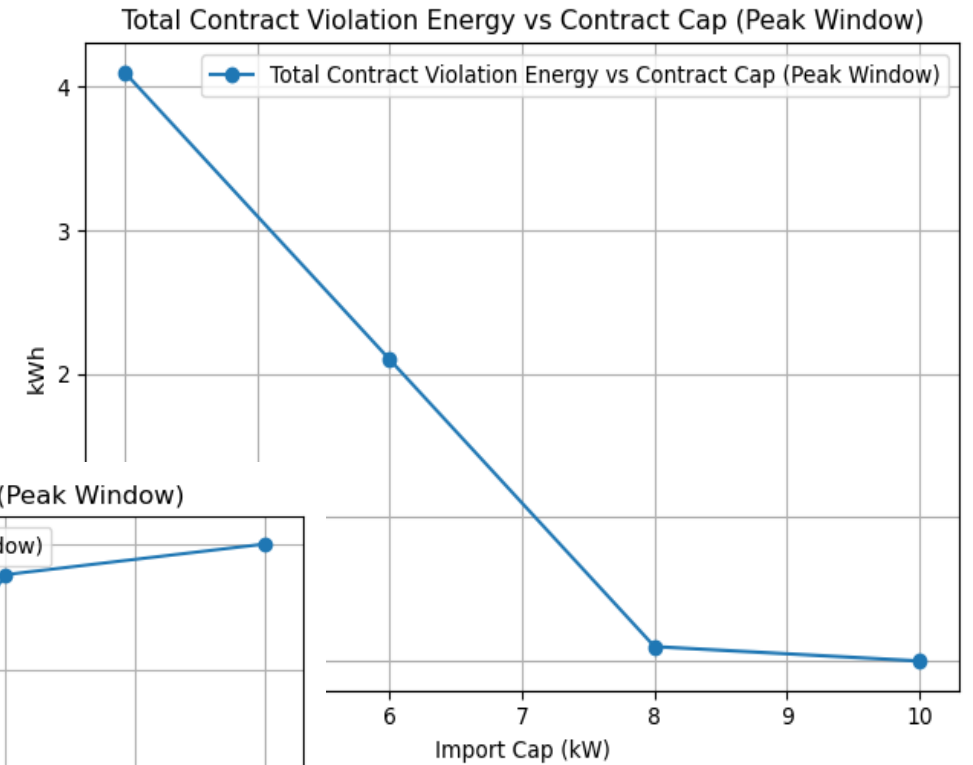
FED-MGDT- Contract Enforcement and Trust Behavior Results



MG1's power import over time relative to a 6-kW contractual limit. During peak periods, imports exceed this limit despite battery response, illustrating that contract compliance can fail when physical resource constraints are binding.



Trust varies as the contract import limit is relaxed. As the limit increases, violations decrease and trust improves, revealing that stricter contracts can lead to lower reliability when physical constraints are binding.



Total contract violation energy changes as the import limit is varied. As the limit is relaxed, violations decrease sharply, indicating a transition from infeasible to feasible contract conditions driven by available system flexibility.

Future Work

Expanded Trust Mechanisms

- Incorporate authentication and compliance verification
- Add reputation-based trust aggregation
- Study long-term trust behavior

Enhanced Contract Models

- Support bilateral energy agreements
- Introduce time-dependent contract clauses
- Add penalty and settlement mechanisms

Architecture Enhancements

- Integrate local controller federates
- Add nanogrid participants
- Improve cyber-physical realism

Conclusions

Major Contributions

- ✓ Developed a federated digital twin framework for microgrid coordination
- ✓ Introduced a contract-based coordination mechanism
- ✓ Integrated a trust model linked to contract performance
- ✓ Demonstrated how physical constraints influence contract feasibility

Key Findings

- Contract compliance is limited by physical resource flexibility
- Stricter constraints do not always improve system behavior
- Trust can degrade rapidly under repeated violations
- Digital twins provide a realistic environment for evaluating coordination strategies

Trust-aware energy contracts must satisfy both cyber-level objectives and physical system constraints.