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HELICS
Simulations Are Better Together

Hierarchical Engine for Large-Scale Infrastructure Co-Simulation

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Dec. 10, 2024

NREL Transforming ENERGY
Pacific Northwest NATIONAL LABORATORY
Lawrence Livermore National Laboratory

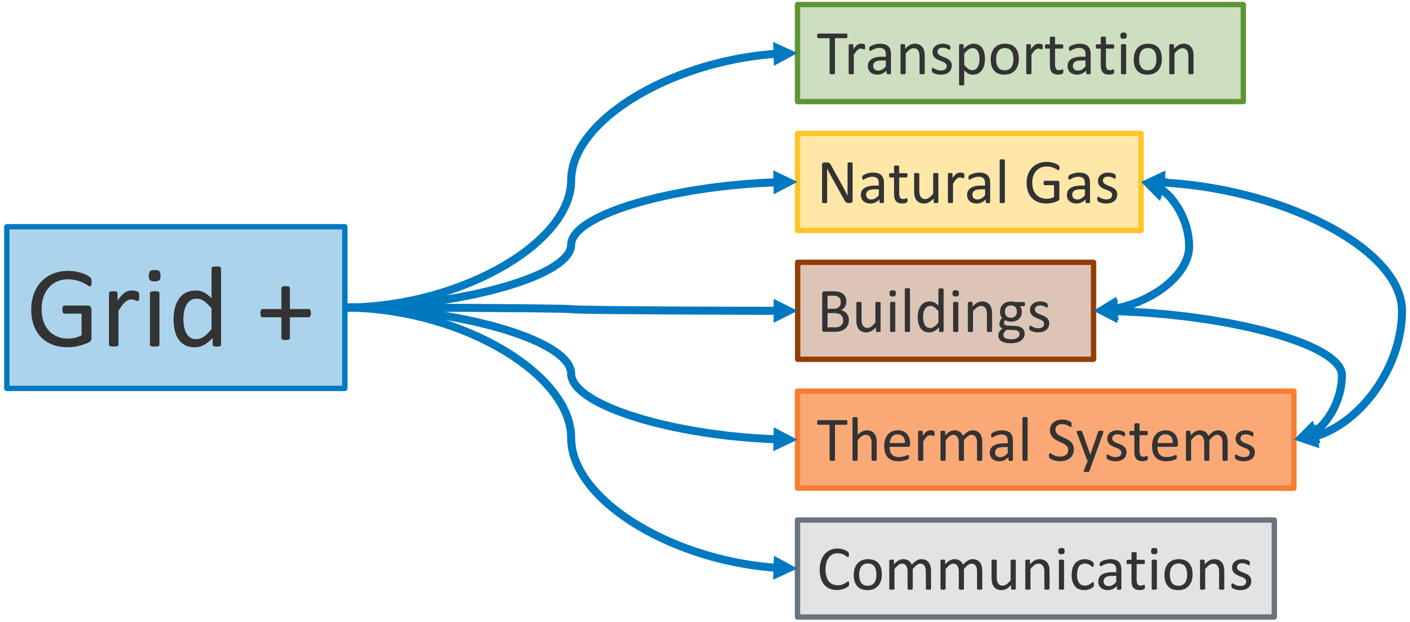
Electrification, digitization, DERs, and other trends increasingly bring together historically separate domains

DERs: Distributed energy resources

Prompting a range of questions

- How do DERs interact with bulk operations? Wholesale markets?
- How do DERs and distribution behave during faults?
- How does the distribution system impact dynamic response to bulk contingencies?
- Where should storage be sited to support local and system-wide stability?
- How can controls reduce or defer upgrade needs?
- How can we best coordinate gas-grid operations?
- Does the distribution system limit DER dispatch for system-wide needs?
- How do building, transportation, or customer needs limit or enhance flexibility?
- What is the impact of communication delays? Poor connections?

And requiring connections to other energy domains



...and many other possibilities*

**For example, HELICS has been used to design supercomputers and data centers.*

Photo by NREL

Simulating these interactions requires capturing cross-domain phenomena

There are many well-trusted tools to simulate each domain

Transmission

GridPACK™ GridDyn PSS®E

Distribution

Gridlab-D OpenDSS CYMDIST

Control & Communications

ns-3 OPNET FMI

Transportation, Water, Gas, etc.

BEAM Riverware SAInt Opal-RT

But they all exist in “silos of excellence”

HELICS brings together two or more existing tools, exchanging data as time advances

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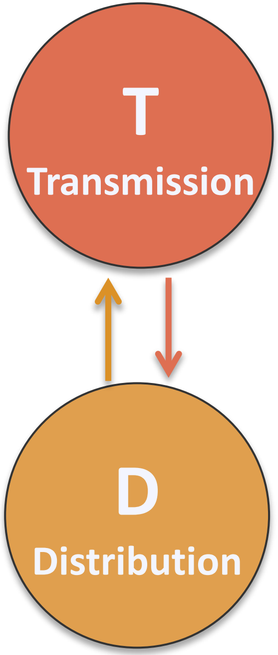
HELICS

to form a tightly integrated **co-simulation.**

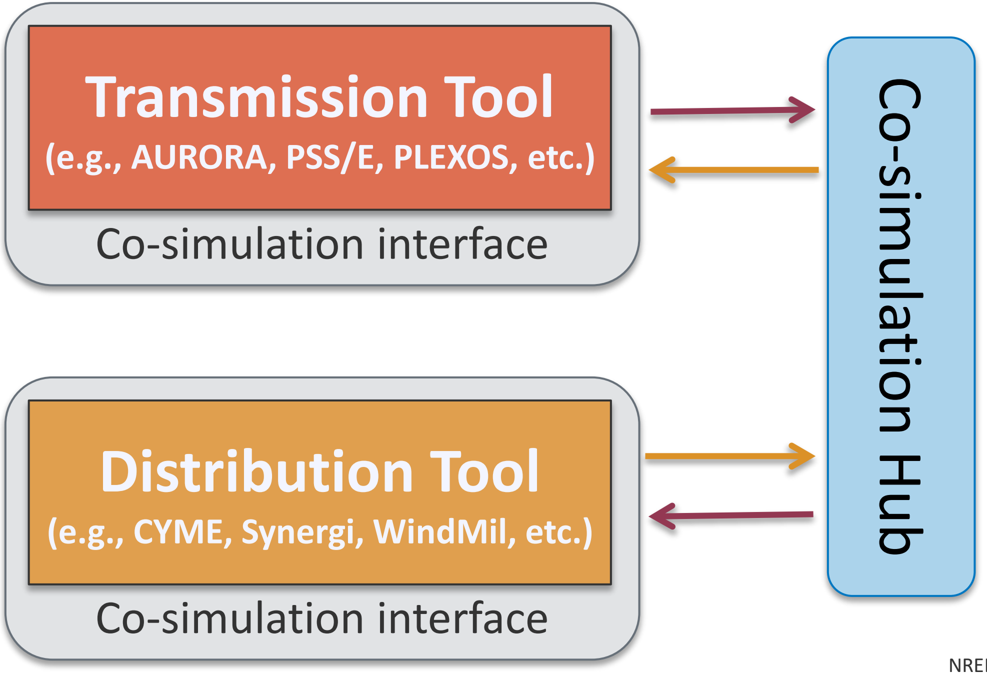
How Co-simulation Works

1. Wrap each tool with a "thin" software interface.
2. Connect to a co-simulation hub to manage data exchange and timing.

Conceptual:



Software Implementation:



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

Get v3.5.x and details at:

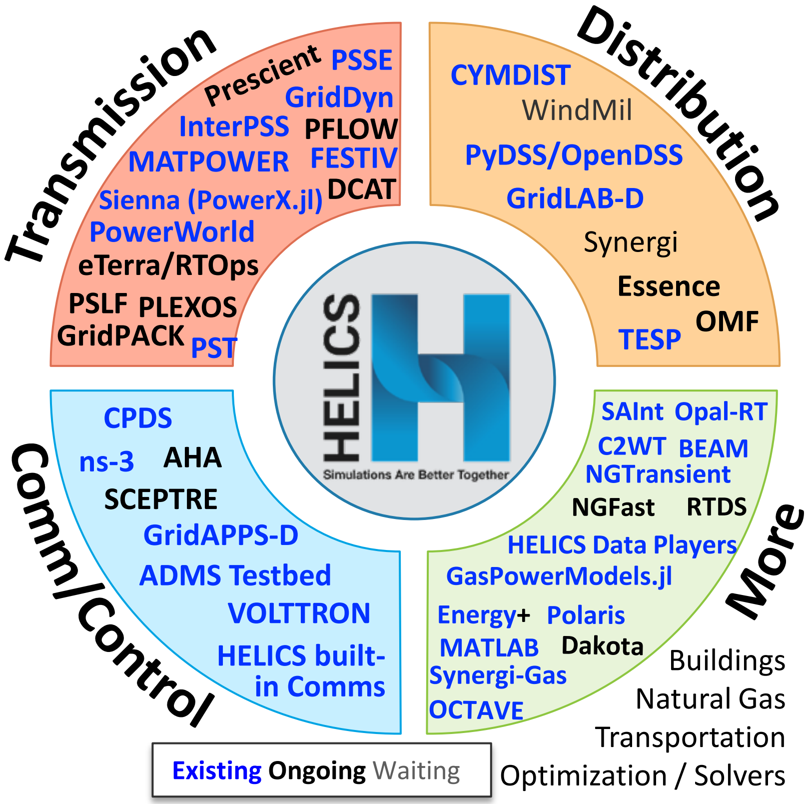
- https://helics.org/introduction/
- https://github.com/GMLC-TDC/HELICS/releases
- or via `pip install helics`

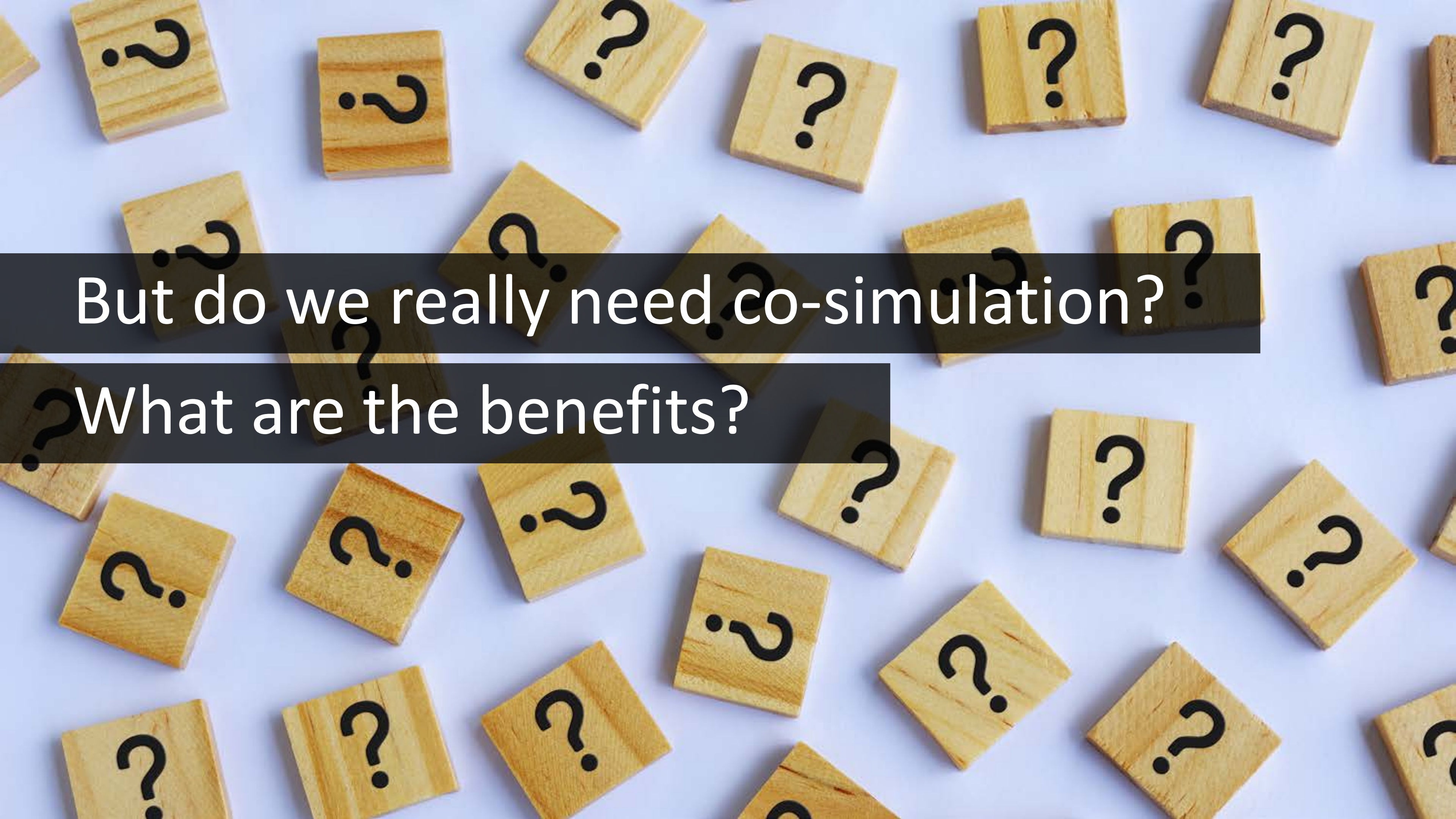
High-performance co-simulation to combine best-in-class tools for breakthrough integrated energy analysis

Capabilities:

- **Scalable:** 2–10,000,000+ Federates
- **Open Source:** BSD 3-clause
- **Unique Features:**
  - Physical Data (Values) vs. Market/Controller Data (Messages)
  - Multiple hierarchical “brokers” for multi-site, large-scale, high-performance co-simulation
- **Cross-platform:** HPC (Linux), Cloud, Windows, OSX
- **Modular:** Mix and match tools
- **APIs:** Python, C++, Julia, FMI, etc.

There are many commercial and open-source tools that have been used with HELICS





But do we really need co-simulation?

What are the benefits?

Benefit #1: HELICS leverages existing tools

- Standing on the "shoulders of giants"
- Lots of effort has gone into (sub) domain-specific tools
  - Trusted by stakeholders
  - Continue to improve.
- Allows focus on the "glue-ware"
- Encourages modularity
  - Swap/add models as needed.

Graphic by Getty Images

B. Palmintier, et al., "Experiences … with the Integrated Grid Modeling System (IGMS)," in Power Systems Computation Conference (PSCC'16), Genoa, Italy, 2016.

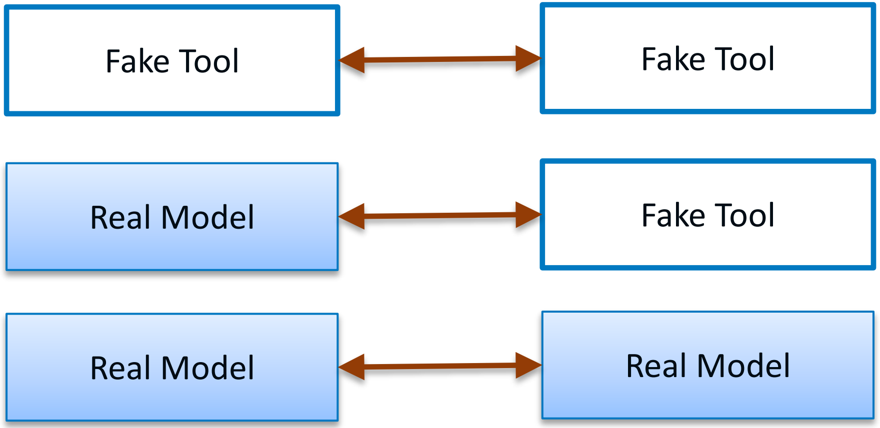
Benefit #2: Co-simulation eases integration, both now and in the future

- **Two main goals for co-simulation:**
  - Keeping all simulations running at the same time
  - Delivering data to the right places.
- ~~"But I'll just make a custom Tool A – Tool B link"~~
  - The two co-simulation goals are hard to get right.
- Thinking ahead:
  - A framework makes reusing components possible.
  - A framework makes it easier to add/remove things.

Note: A co-simulation framework doesn't actually model anything on its own. Model behavior comes from the tools you connect.

Benefit #3: Modular development and debugging

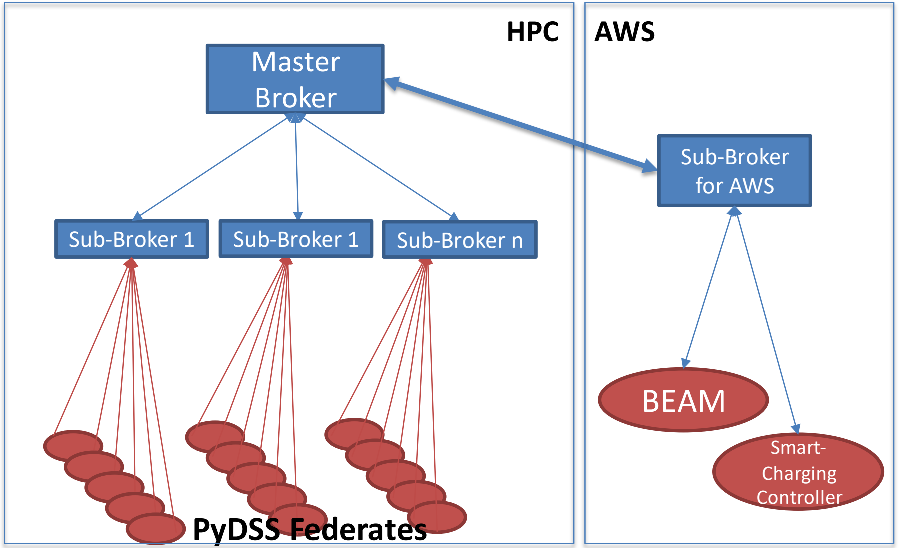
- Co-simulation enables model swapping.
- Well-defined API advantages:
  - Multiple developers simultaneously
    - Easier merging in version control (You are using software version control, right? Git is great.)
  - Refine components separately.
- And… *TESTING*
  - Asynchronous development
  - Isolate problems.



B. Palmintier, et al., "Experiences … With the Integrated Grid Modeling System (IGMS)," in Power Systems Computation Conference (PSCC'16), Genoa, Italy, 2016.

Benefit #4: Performance and scalability

- Hierarchical brokers
- Inherent parallelization
- Break up smaller problems
  - e.g., Very large power flow
- Enable use of mixed solver types
  - Mixed-integer linear programming
  - Engineering tools
  - Differential-algebraic equation
  - etc.



Benefit #4: Performance and scalability

But don't just take our word for it…

Researchers at Politecnico di Torino found HELICS to **perform and scale best compared to tested co-simulation frameworks**, with "low-complexity" setup.

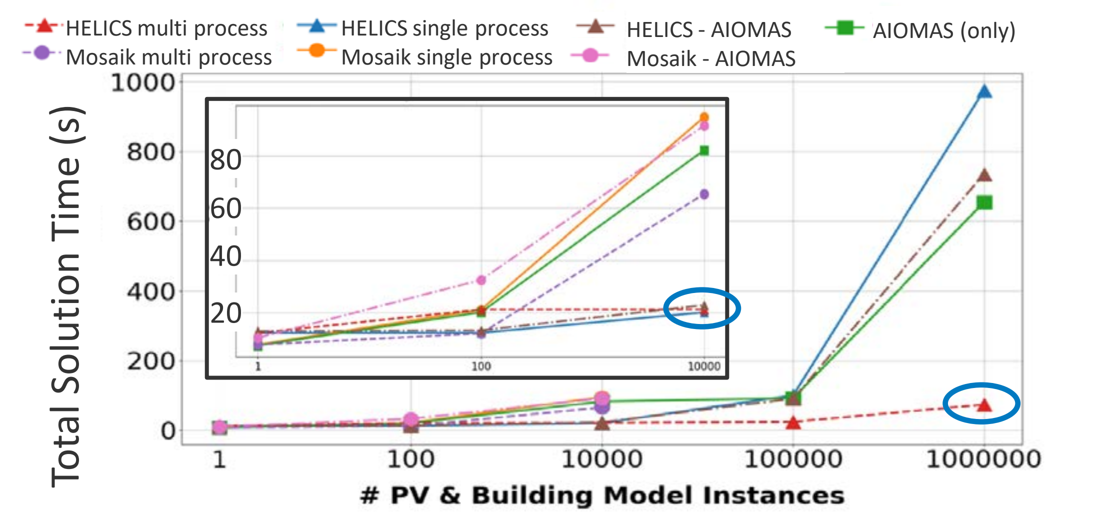
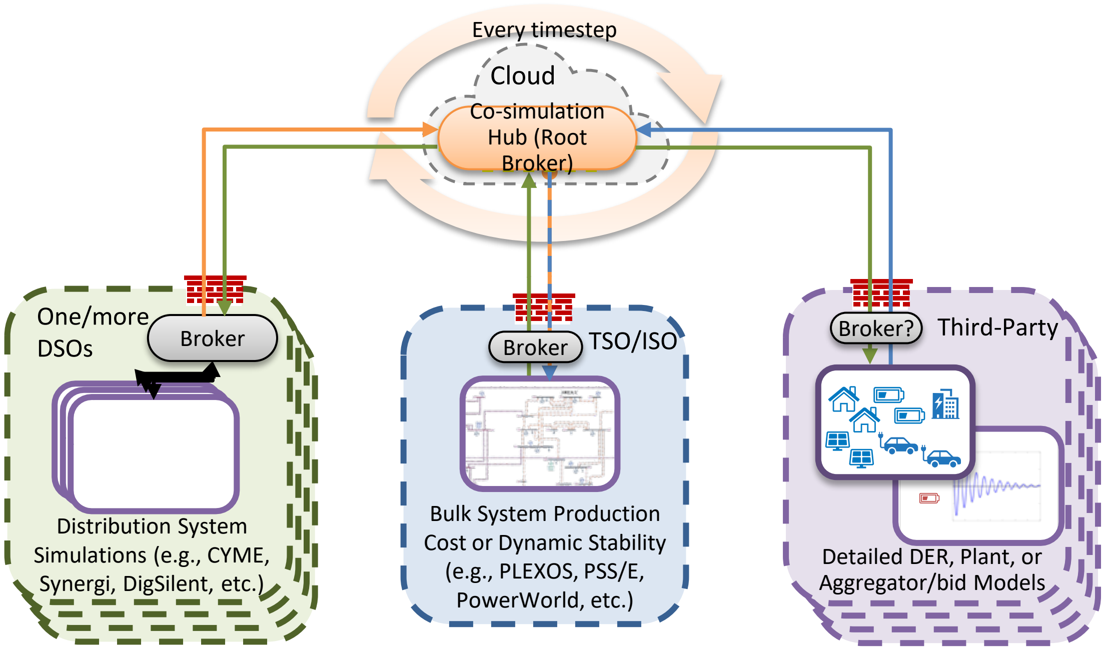


Figure adapted from L. Barbierato, et al., "A Comparison Study of Co-simulation Frameworks for Multi-energy Systems: The Scalability Problem," *Energy Informatics*, Dec. 2022, https://doi.org/10.1186/s42162-022-00231-6.

Benefit #5: Multi-entity simulation without full data exchange

- Run a combined simulation across multiple sites/organizations
- Only exchange interface data
  - Avoid detailed/sensitive model exchange.



B. Palmintier, T. Hardy, P. Top, A. Latif, and J. Keen, “Keep Your Grid Model to Yourself: Co-simulation for Multi-entity Planning and Simulation Without Needing Detailed Model Exchange,” 2024 Grid of the Future Symposium, Raleigh, NC: CIGRE US National Committee, Nov. 2024.

How has HELICS been used?

General areas for growth:

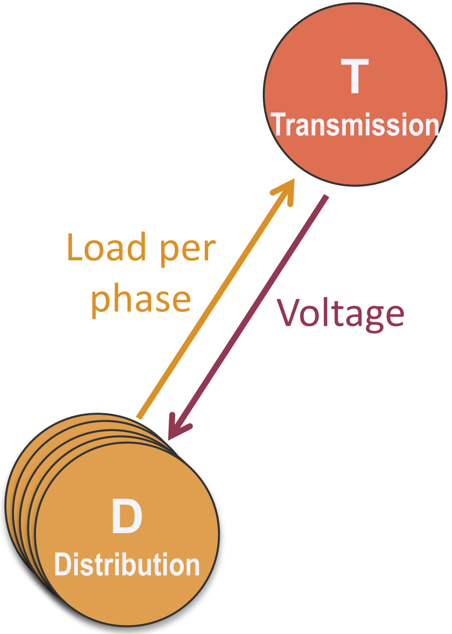
- T+D Impact Modeling
- Transportation + Grid
- New Controls + Grid
- Natural Gas + Grid
- Cybersecurity
- Anomaly Detection
- Techno-economic Analysis
- Hardware-in-the-Loop

HELICS projects/efforts (not exhaustive):

- Autonomous Energy Grids (NREL)
- GridAPPS-D (PNNL, NREL)
- GEMINI-XFC: Large-scale Grid-Transportation Simulation (NREL)
- Transactive Energy Simulation Platform (PNNL)
- Cyber-Physical Dynamic Systems (NREL)
- Inverter Transient Co-simulation (PNNL)
- ISO New England T+D (NEISO)
- ADMS Testbed Power-Hardware-in-the-Loop (NREL)
- Hardware-in-the-Loop Simulation of Cyber Attack and Defense (LLNL)
- Transactive Communities (WSU/PNNL)
- Anomaly Detection (NRECA)
- T+D Co-Convergence (NREL / Eaton)
- Multi-sector Techno-economic Analysis (encoord/NREL)
- Natural Gas-Grid Operation Co-optimization (ANL)
- North American Energy Resilience Model (multi-lab)
- Blockchain for Optimized Security and Energy Management (BLOSEM).

HELICS distinguishes between two classes of data:
1. Physical Values

- Physical Data (Values)
  - Voltage, Frequency, Current.



Example Application:

Bulk dynamic impacts with DERs

Transmission Bus Voltage

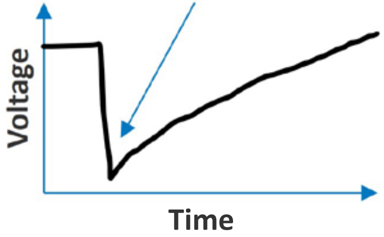
HELICS

Substation Power

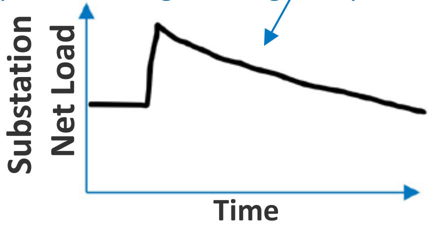
PSSE (Dynamic)

Distribution Simulator
GridLab-D/OpenDSS

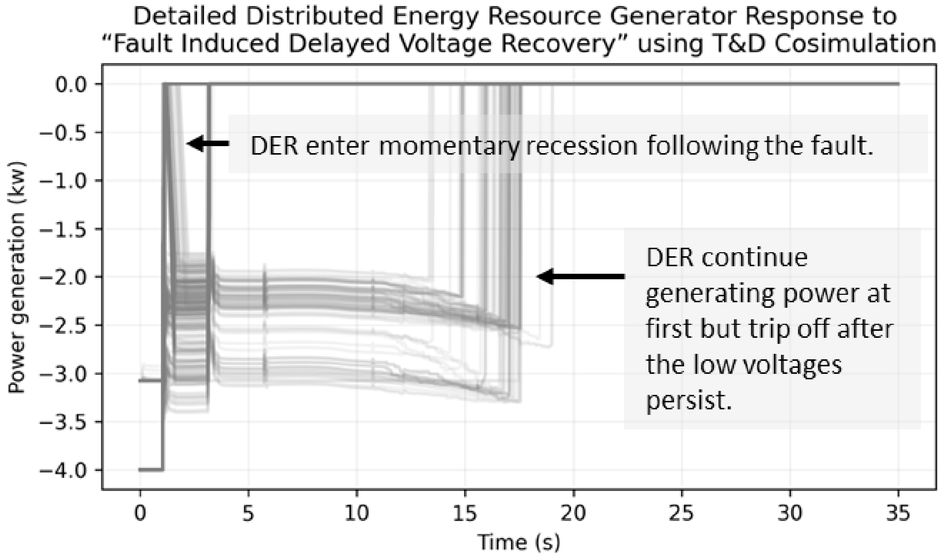
During a fault, transmission models have limited visibility into distribution network voltage heterogeneity.

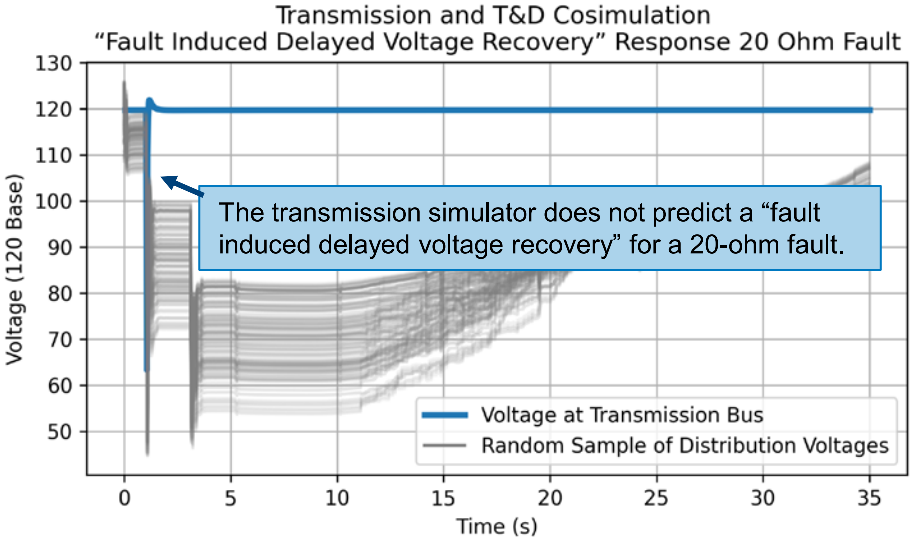


DER tripping depends on location and air conditioners/motors require more power during a voltage drop.



T&D Co-simulation in Puerto Rico: How high DER penetrations can affect transmission stability

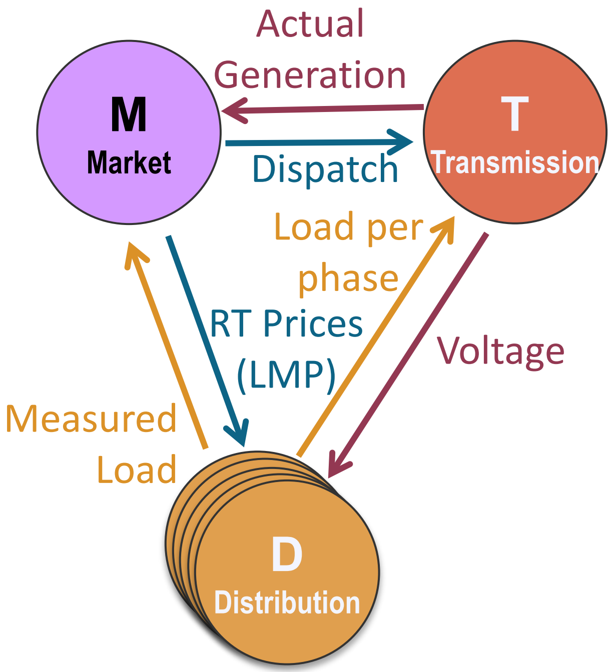




M. Elizondo et al., "Section 10: Bulk System Power Flow, Dynamic, and Resilience Impact Analysis," in *Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study (PR100): Final Report*, Golden, CO: National Renewable Energy Laboratory, 2024. Accessed August 26, 2024. https://www.nrel.gov/docs/fy24osti/88384.pdf.

HELICS distinguishes between two classes of data:
1. Physical Values
2. ICT Messages.

- Physical Data (Values)
  - Voltage, Frequency, Current
- Market Data (Messages)
  - Measured Load, LMPs.

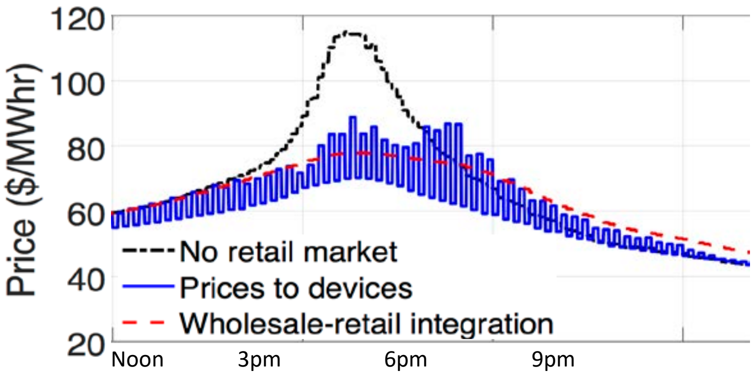


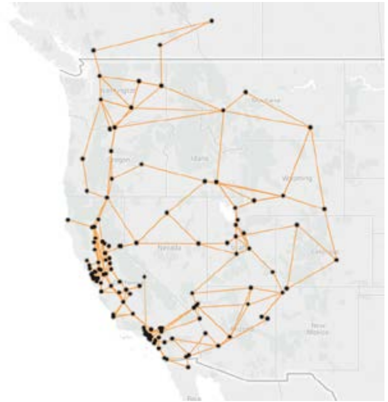
HELICS distinguishes between two classes of data: 2. ICT Messages

For example: Powerflow + Market Operations

Large-scale DER-Market Interactions

- 35k feeders
- WECC-240 trans.
- 25M homes
- Simplified CAISO-style Market.

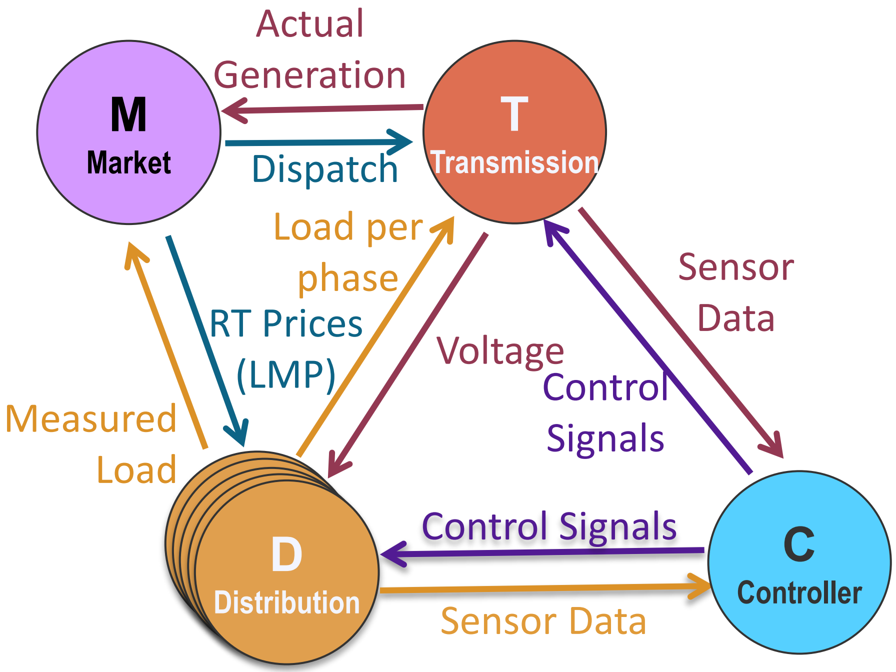




J. Hansen, T. Hardy, and L. Marinovici, "Transactive Energy: Stabilizing Oscillations in Integrated Wholesale-Retail Energy Markets," in 2019 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), Feb. 2019, https://doi.org/10.1109/ISGT.2019.8791658.

This also makes it easy to add separate controllers

- Physical Data (Values)
  - Voltage, Frequency, Current
- Market Data (Messages)
  - Measured Load, LMPs
- Controller Data (Messages)
  - Sensor Readings, Control Signals.



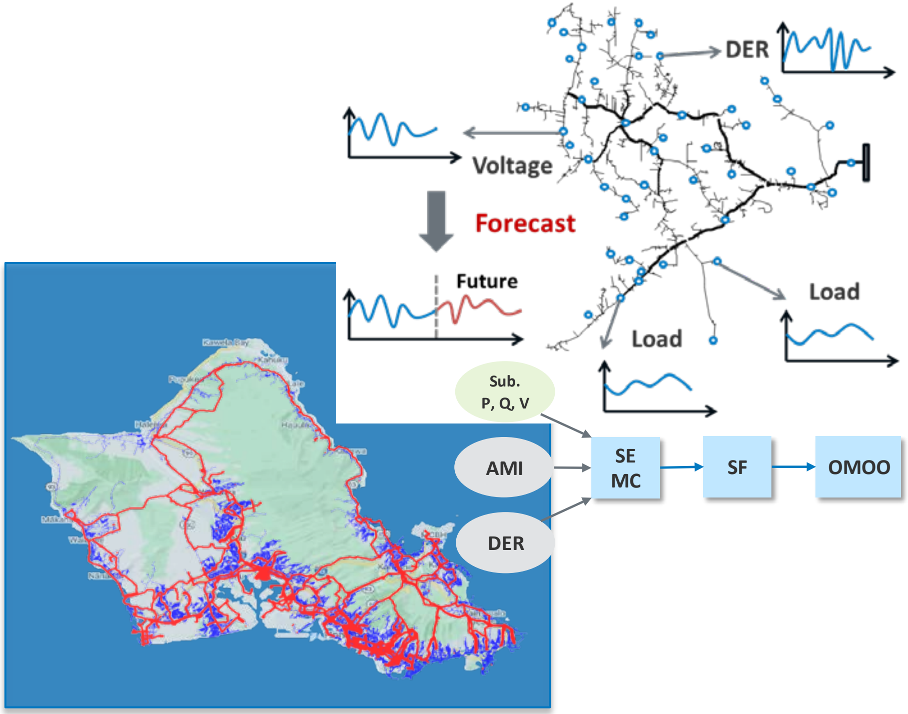
This also makes it easy to add separate controllers
For example: Control Architecture Scaling & Performance

Project: GO-Solar

Novel T&D Control Architecture

<u>*Design:*</u> Predictive State Estimation & Machine Learning Control

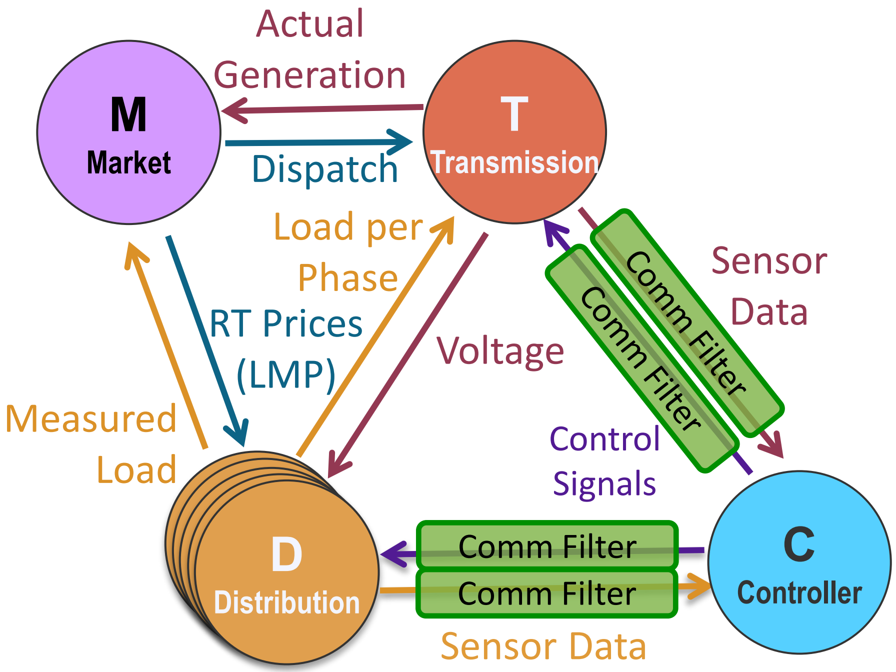
<u>*Grid Sim:*</u> Entire Island of Oahu, HI, with >1 M electric nodes



R. Yang, et al., "Grid Optimization With Solar (GO-Solar)," presented at the ADMS Test Bed Webinar, Feb. 16, 2022. https://www.nrel.gov/docs/fy22osti/82026.pdf.

HELICS also has built-in Simple Communication Simulation.

- Built in "Filters" for
  - Delays
  - Random drops
  - Other message effects (e.g., packetization)
  - And more.
- No changes to domain models.

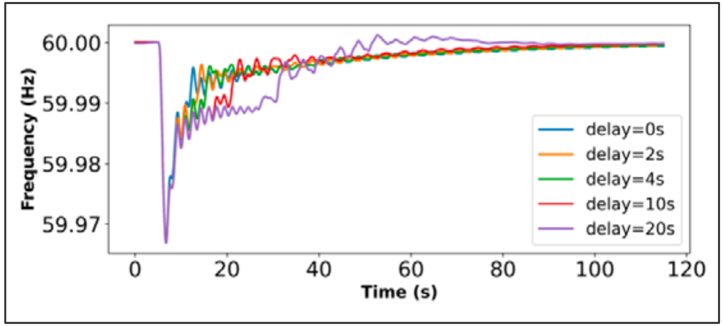


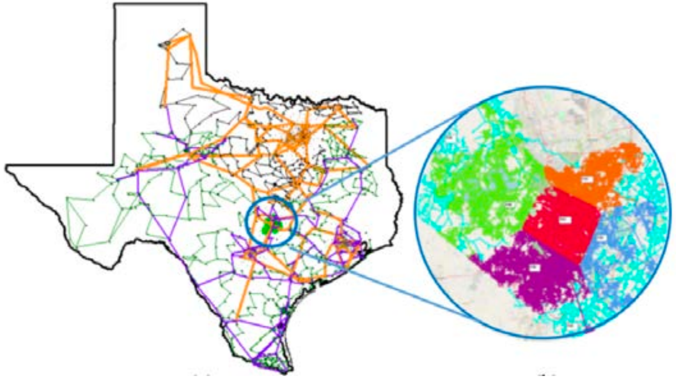
HELICS also has built-in Simple Communication Simulation
For example: Impact of delays on AGC to DERs

Cyber-Physical Dynamic Simulation

Scenario: Freq response during fault with 42k EVs providing frequency reserves (via AGC)

Grid Sim: Synthetic Texas 2000 bus + 243 Distribution Feeders (MV+LV) at full resolution



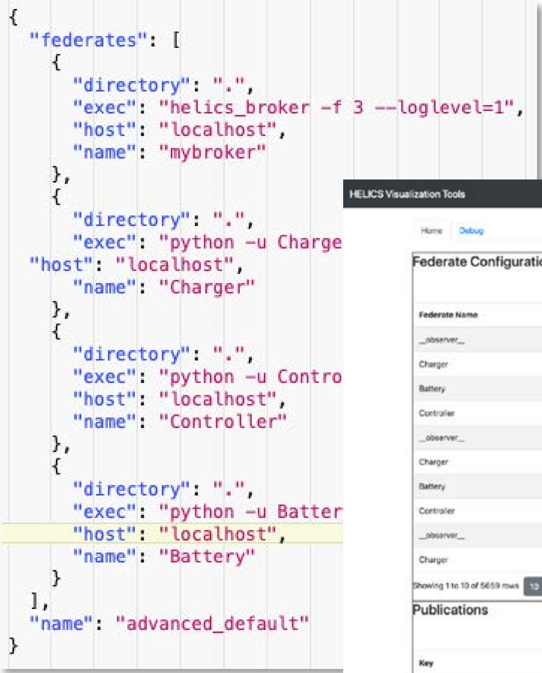


W. Wang, et al., "Impact of Open Communication Networks on Load Frequency Control with Plug-In Electric Vehicles By Cyber-Physical Dynamic Co-simulation," in 2023 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Jan. 2023, https://doi.org/10.1109/ISGT51731.2023.10066380.

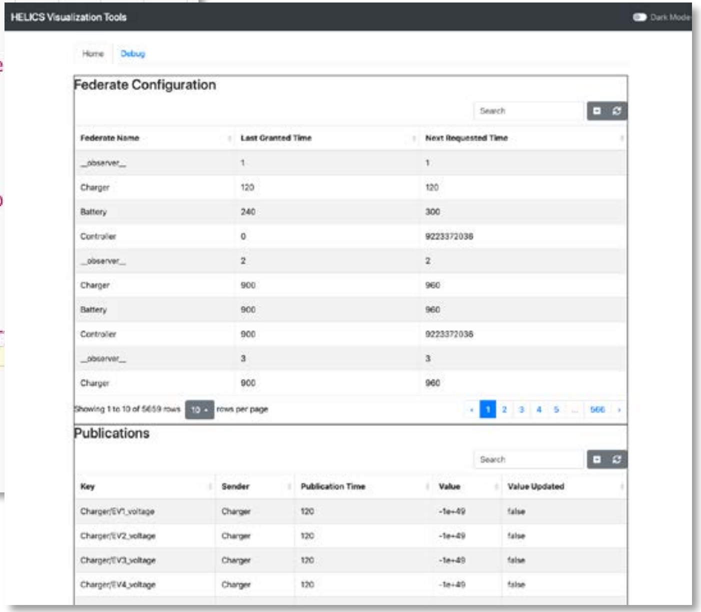
helics_cli

- Managing co-simulations can quickly grow in complexity, both in managing the inputs and processing the outputs.
- `helics_cli` is a HELICS-supplied tool for helping with this.
  - One-command means of launching all federates in a co-simulation
  - Ability to record data exchanges in a database for post-processing
  - Web interface for runtime monitoring of the co-simulation.

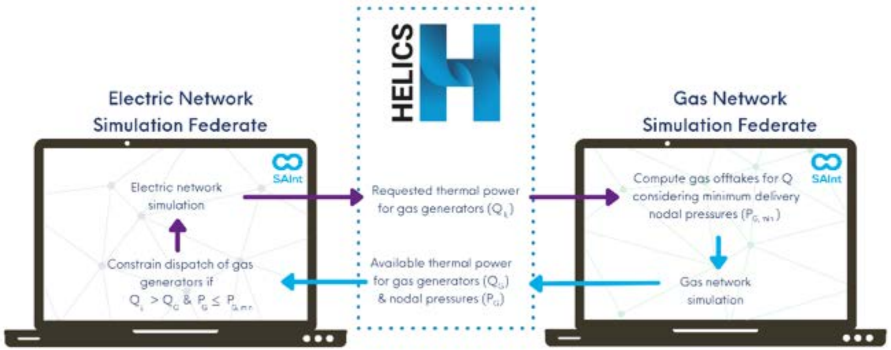
`helics_cli` launcher configuration

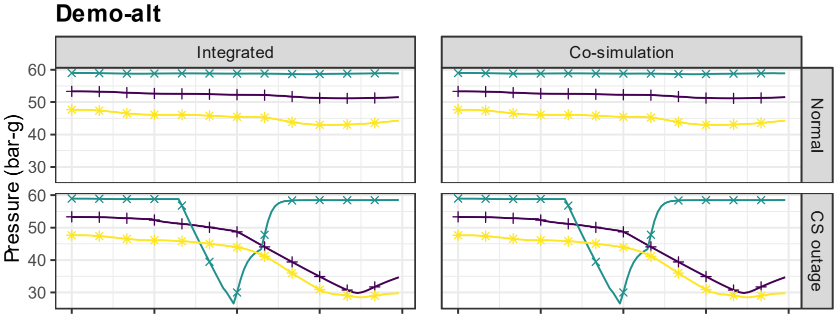


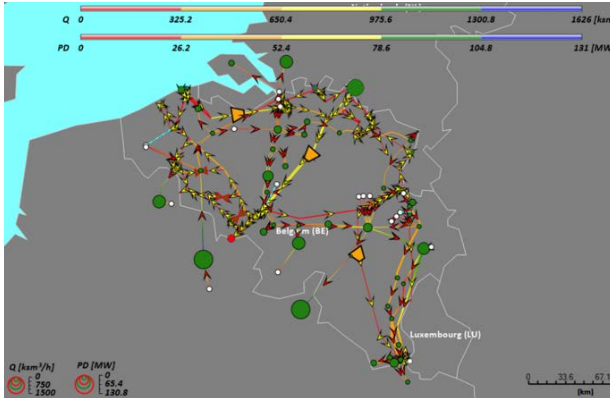
`helics_cli` web interface



Power Grid + Natural Gas Co-simulation



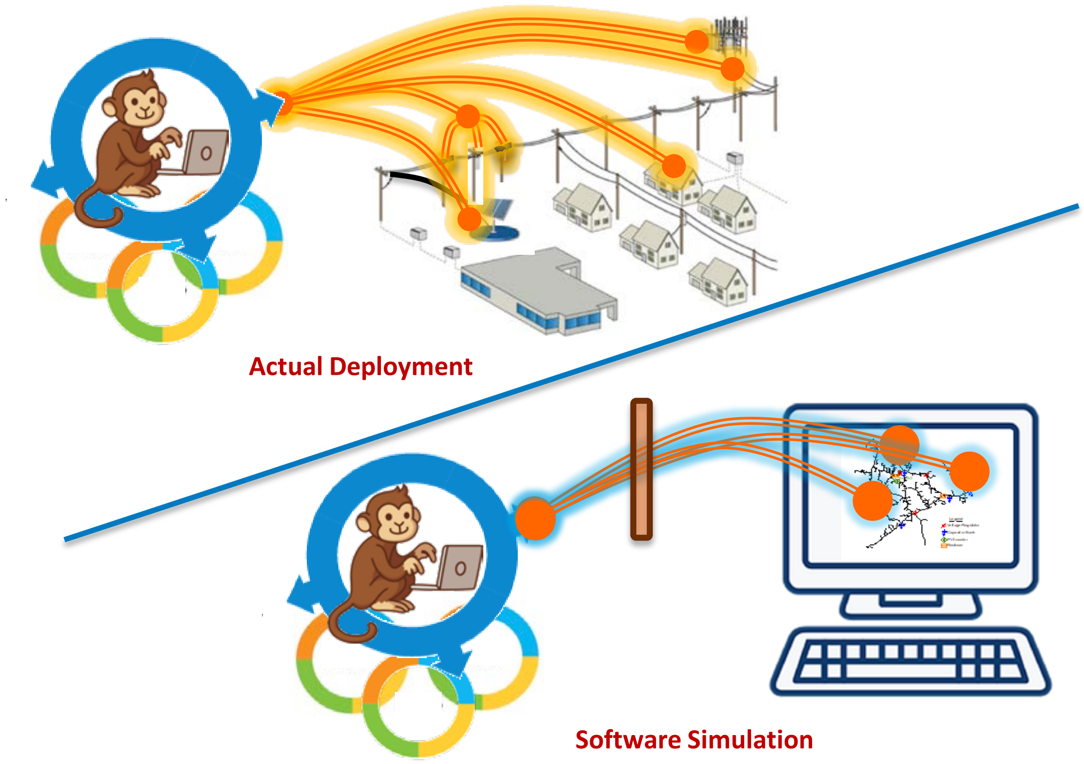




GitHub repository for SAInt-HELICS interface: https://github.com/NREL/SAInt_HELICS_interface
Co-simulation validation paper: https://www.mdpi.com/1996-1073/15/14/5277
Encoord case study website: https://www.encoord.com/resources/case-studies/helics
NREL Technical Report on gas + grid coordination: https://www.nrel.gov/docs/fy20osti/77096.pdf

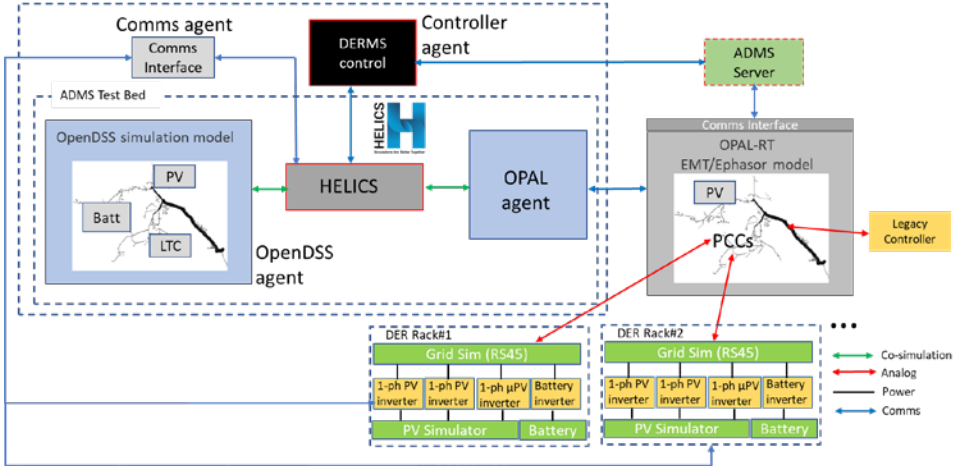
B. Sergi and K. Pambour, "An Evaluation of Co-Simulation for Modeling Coupled Natural Gas and Electricity Networks," *Energies,* vol. 15, no. 14, Art. no. 14, Jan. 2022, https://doi.org/10.3390/en15145277.

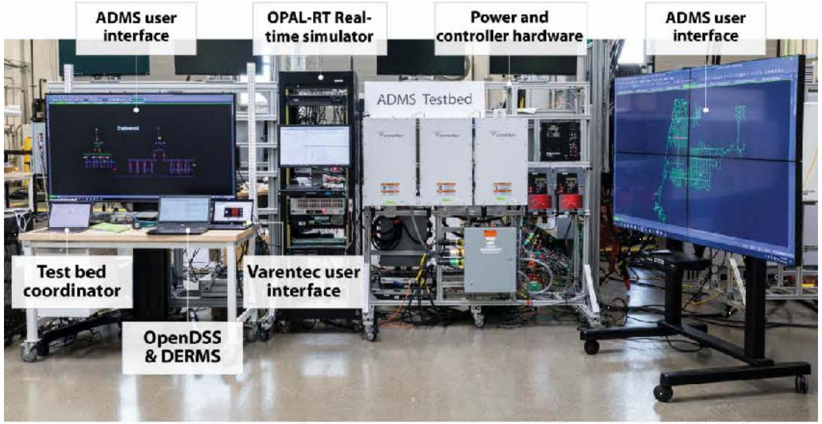
Realistic simulation for controllers… no matter who they are



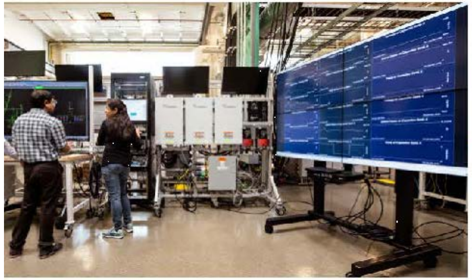
Other HELICS use cases: Hardware-in-the-Loop

- Commercial ADMS, DERMS
- Mixed QSTS, Real-time EMS
- 1–100 Hardware devices.

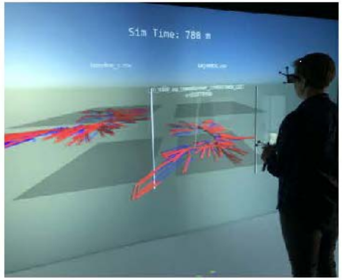




Photos by NREL



2D real-time visualization



3D visualization

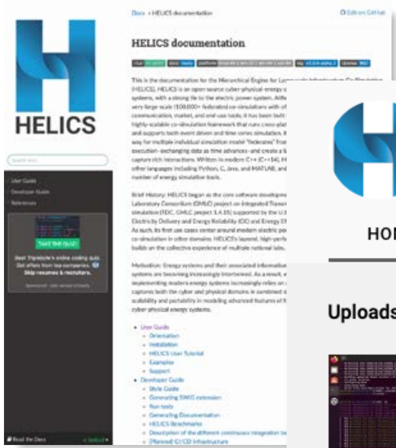
Ready to dive in?

How to access HELICS

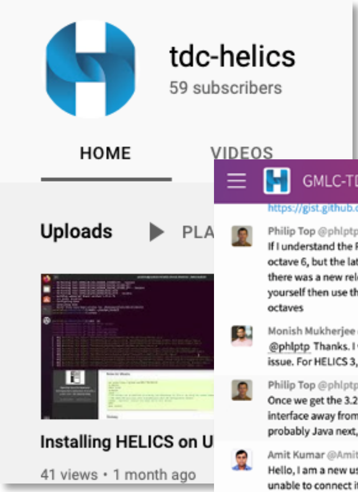
User Support Offerings

- ReadTheDocs
  - User Guide
  - Developer Guide
  - API Reference
  - Configuration Options Reference.
- Examples suite
- YouTube channel
  - Discussion of various HELICS topics
  - Screencasts of HELICS in action.
- Discussion forums on GitHub
- Gitter channel for real-time chat with HELICS team
- Bi-weekly office hours for debugging support with developers.

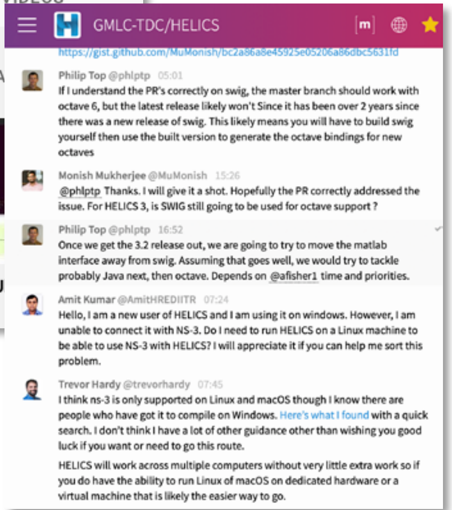
[ReadTheDocs]



[YouTube Channel]



[Gitter]



Discussion? Questions?

Contact

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Documentation and Code:

https://www.helics.org
https://github.com/GMLC-TDC/
pip install helics (among other package managers)

https://helics.readthedocs.io
https://helics.readthedocs.io/en/latest/user-guide/index.html

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Join us Jan. 14, 2025, 10 a.m. MT

Presented by Bethany Frew