TE-SAT: Transactive Energy Simulation and Analysis Toolsuite

Authors: Himanshu Neema, Janos Sztipanovits, David J. Hess, Dasom Lee

Presented By:
Dr. Himanshu Neema
Research Assistant Professor
Vanderbilt University
Email: himanshu.neema@vanderbilt.edu

Acknowledgements:

- National Science Foundation (NSF)
- National Security Agency (NSA)
- National Institute of Standards and Technology (NIST)

VANDERBILT UNIVERSITY

What is Transactive Energy (TE)?

- **Transactive Energy Systems (TESs) involve "smart devices that communicate with the energy market to make decisions on behalf of the consumer whether to pay higher energy costs during times when power use peaks or delay energy use to pay less and alleviate strain on the power grid" (Pacific Northwest National Laboratory 2020).**
  - Generally includes both real-time pricing and load management
  - Grid reliability and demand management
  - Integration of renewable and distributed energy sources
  - Environmental benefits such as reduced greenhouse gas emissions
  - Lower energy bills
  - Reduce the need for investment in costly and often politically contentious high voltage power lines

Operational Challenges with TE

- **Sometimes TESs were not ready**
  - Hot water heater risk
  - Vendor failures
  - Security issues
- **User readiness**
  - Need for education and greater customer service
  - Recruitment difficulties
  - Participation drop out rates
- **Economic feasibility**
  - Time of use pricing may be better for smaller residential consumers
  - Minimal reduction of residential consumption

Why Modeling and Simulation of Transactive Energy Systems (TES) in the Smart-Grid is challenging?

- **Transactive Energy presents a highly complex *"Cyber-Physical-Human-Economical Problem"*:**
  - multi-users (e.g., individual users, industries, power station operators, power market agents),
  - multi-domain (e.g. analog transmissions & control, digital control, transients, thermal,…),
  - multi-time-scales (e.g., long/medium/short term power generation planning Vs household consumption model),
  - multi-time-resolution (e.g., fault-propagation and dynamics modeling Vs power market operations)
  - multi-tier grid control & synchronization (e.g., local/edge control, sub-station level, micro-grid level, sub-station level),
  - multi-pricing-methods (e.g., time-of-use pricing, local marginal pricing, incentives)

- **Huge challenges for comprehensive modeling and simulation of TES:**
  - It is a multi-provider system with highly dynamic capacity – even consumers can be producers
  - Demand is highly dynamic, providers have diff. views – can lead to "instability or chaotic behavior"
  - Highly complex interdependent network – driven by highly unpredictable elements – weather, humans (users, policies, security, trust, irrationality, politics,..), malicious agents & cyber attacks, ..

Three Design Studios for TE modeling & simulation

What is a Design Studio?

- Meta-programmable integration platforms
- Domain-specific modeling and experimentation
- Supports collaborative modeling (in real-time)
- Web-accessible
- Provide a library of reusable tools and services
- Supports cloud execution of variations of experiments

Note: All design studios require password and are hosted on CPS-VO (http://cps-vo.org)

1. **Cyber-Physical Systems Wind Tunnel for Transactive Energy (CPSWTTE)**
   - http://cps-vo.org/group/cpswtte
2. **GridLAB-D Modeling and Simulation (GDSIM)**
   - http://cps-vo.org/group/gridlabd
3. **Testbed for Simulation-Based Evaluation of Resilience (TeSER)**
   - http://lablet.webgme.org

Design Studio #1:
Cyber-Physical Systems Wind Tunnel for Transactive Energy (CPSWTTE)

Could we use a system-of-systems design for analyzing TES as a whole by integrating many simulations that model diff. TE concerns?

Power Grid Modeling Concerns:

Generation, Transmission, & Distribution	Distributed Energy Resources (DERs)	Distributed Sensors and Controllers	Multi-Physical Domains & Multi-Rate Dynamics

Environmental Effects Modeling Concerns:

Seasons and Weather	Recovery & Management for Natural Disasters	Env. Hazards and Safety	Special Events w/ Demand Surges

Cyber Communication Network Modeling Concerns:

Cyber Network b/n sensors & controllers	Cybersecurity	Large-scale Data Flows & Real-Time Data Delivery	Distributed Data Processing

Operational Modeling Concerns:

Power markets and pricing	Regulations and Policies (Local and Federal)	Consumer and Business Models	Short-Term to Long-Term Planning

Fundamental issues to address:

- Stakeholder confidence in TE approaches only via comprehensive grid-scale "multi-faceted" modeling and simulation
- Integrated power-grid and comm. network (real/simulated/emulated)
- "Integrated analysis" with multiple facets, e.g. analyzing dynamic impacts of supply and demand with transients and cascading faults
- Variation in one facet usually leads to cascading (event disastrous) failures

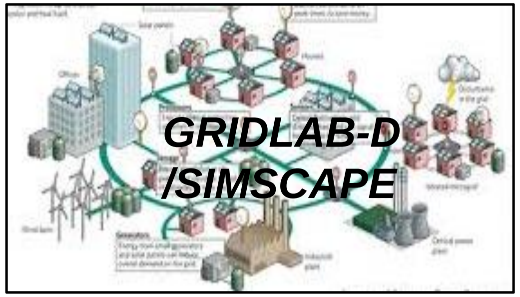
Fundamental system design questions to answer:

How to:

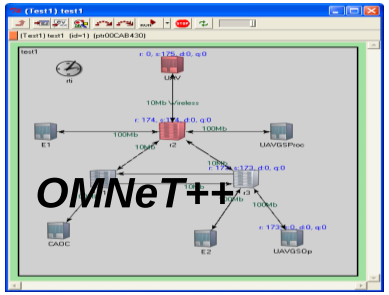
- Address the heterogeneity of TE issues and participating players?
- Address different operational policies and requirements?
- Ensure reliability and security of the grid?
- Generate insights into the behavior of TE approaches and gain confidence in control mechanisms for smart-grids?
- Design policies, standards, & controls for max. resource utilization?
- Provide resilience against cyber vulnerabilities?

Integrating Heterogeneous Simulations

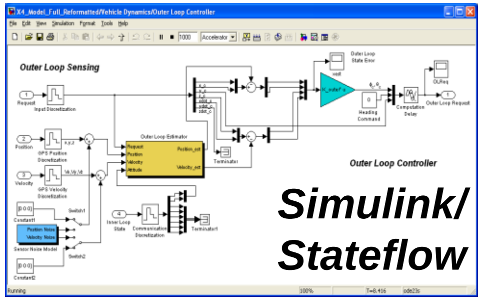
Smart Grid



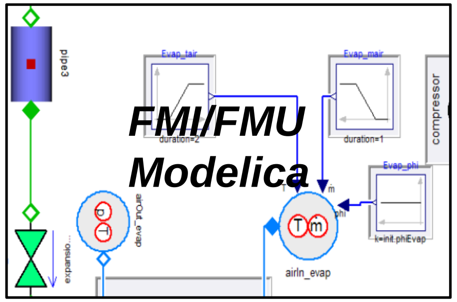
Communication Network



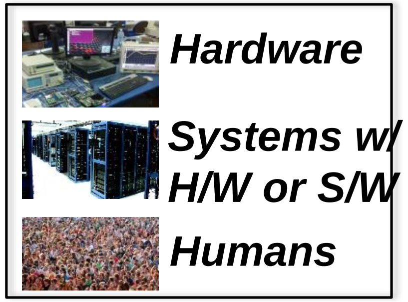
Controller & Dynamics



Acausal model libraries, DAEs



Real-time Components



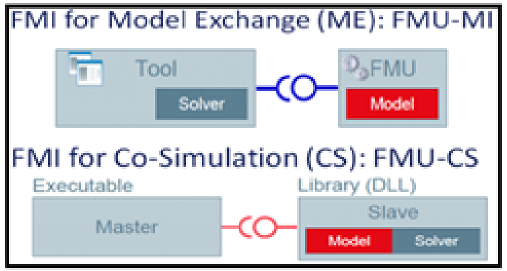
- Modeling languages are different
- Semantics is different for continuous time, discrete time, and discrete event
- Simulated systems are interacting but modeling languages do not have constructs to express them
- No support for specifying experiments

- Simulators have different timing models
- Execution needs to be coordinated
- Data needs to be shared
- Different time-scale and resolution
- Logical time vs. real time
- Different simulation engines

- ***How can we integrate the simulated heterogeneous systems (system domains and components)?***
- ***How can we integrate the heterogeneous simulation engines (software applications)?***
- ***How can we simulation in-the-loop the real-time hardware, systems, and humans?***
- ***How can we rapidly synthesize and deploy integrated simulations?***
- ***How can we analyze operations at the System-of-Systems (SoS) level?***

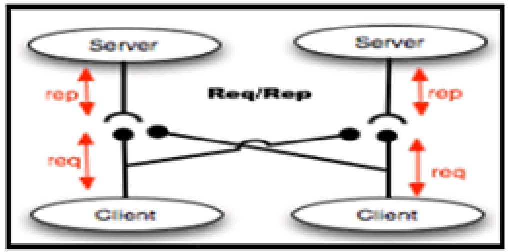
Traditional Approaches Vs IEEE HLA Standard

FMI-Based Co-Simulations



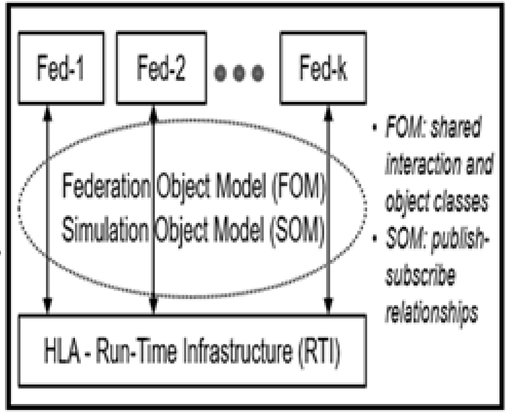
- Standardizes dynamical model to solver int. by defining a set of 'C' functions
- Focusses on re-use with IP-protection
- Leaves it to system designer: (a) "Master Algorithm" implementation for co-ordination and control of FMUs (b) Distribution Object Mgmt. (c) Time Mgmt.

Distributed Messaging Oriented Approaches



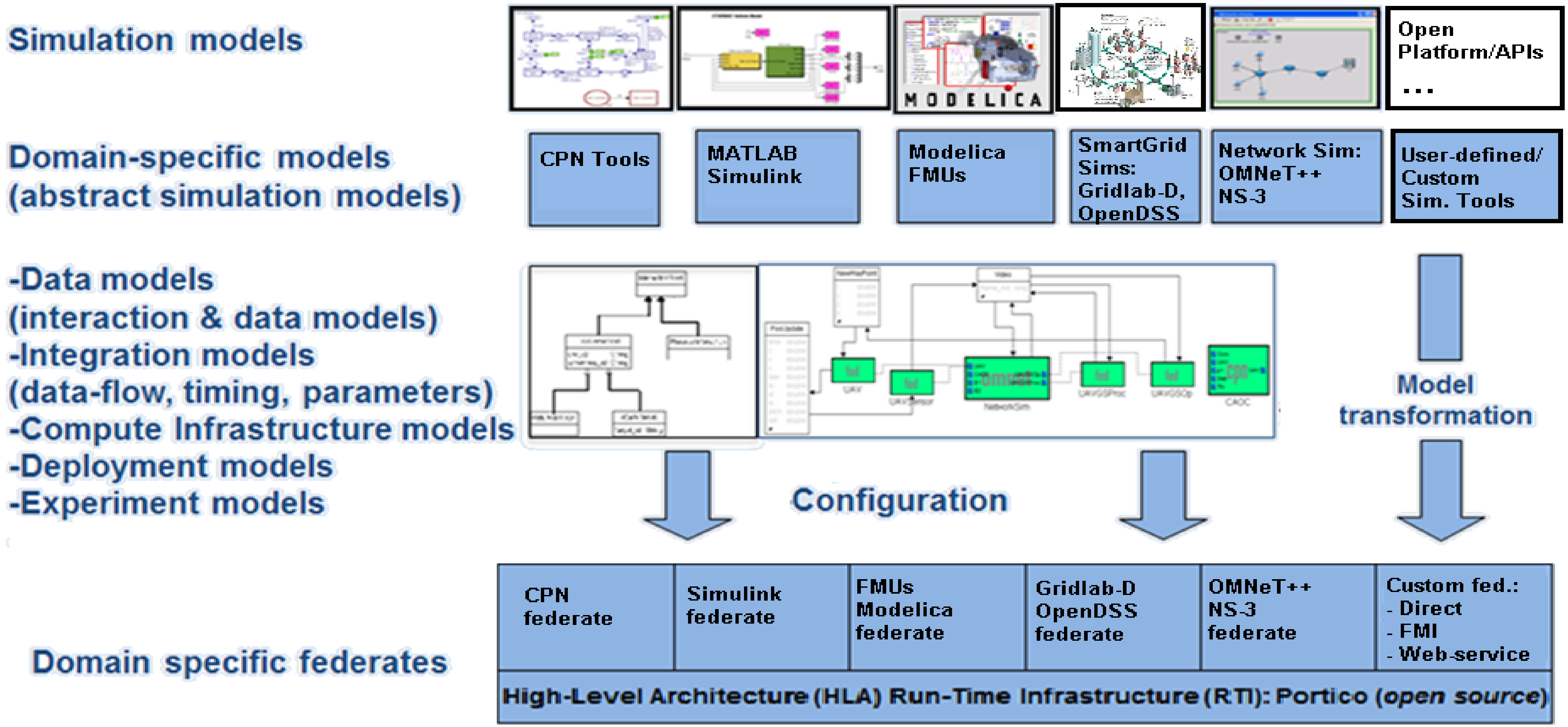
- Mainly use sockets/IPC for comm. & coord. b/n agents (e.g. ICE, ZeroMQ, Mosaik, …)
- Time sync. is adhoc; Limited persistence + QoS support
- Brokered Arch.: Single point of failure + Performance bottlenecks
- Brokerless Arch.: Inflexible for dynamic joins/resigns

HLA-Based Federated Co-Simulations

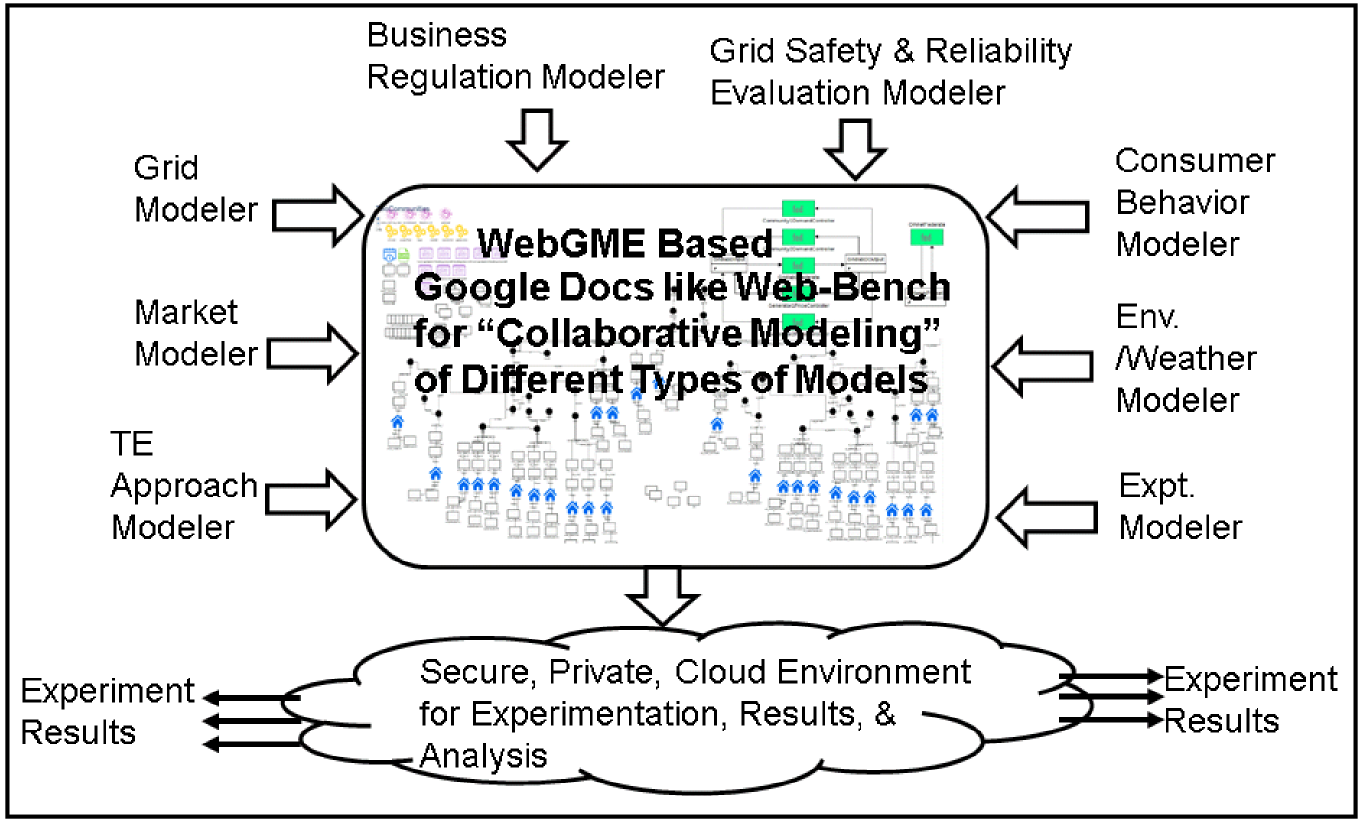


- Flexible data model supporting all different types of simulations (e.g., time-synchronized, real-time, hardware/human in the loop, etc.)
- Well-defined rules, interfaces, APIs with clear semantics
- Flexible architecture for customization and extensibility
- Standardized way supporting the ***essential co-simulation building blocks***:
  - Time Management: Coordinated time-advancement/-synchronization, Diff. time-resolutions/time-scales,..
  - Distributed Object Management: Shared data types/methods, Data delivery/dispatch/security,..
  - Distributed Simulation Management: Coord.& control of distributed co-simulation (systematic orchestration)
  - Real-Time Components Integration: Real-world entities plugged into System-of-Systems simulation

Cyber-Physical Systems Wind Tunnel (CPSWT): A Model-based System and Tool Integration Approach



CPSWTTE Design Studio for Collaborative TE Modeling and Simulation

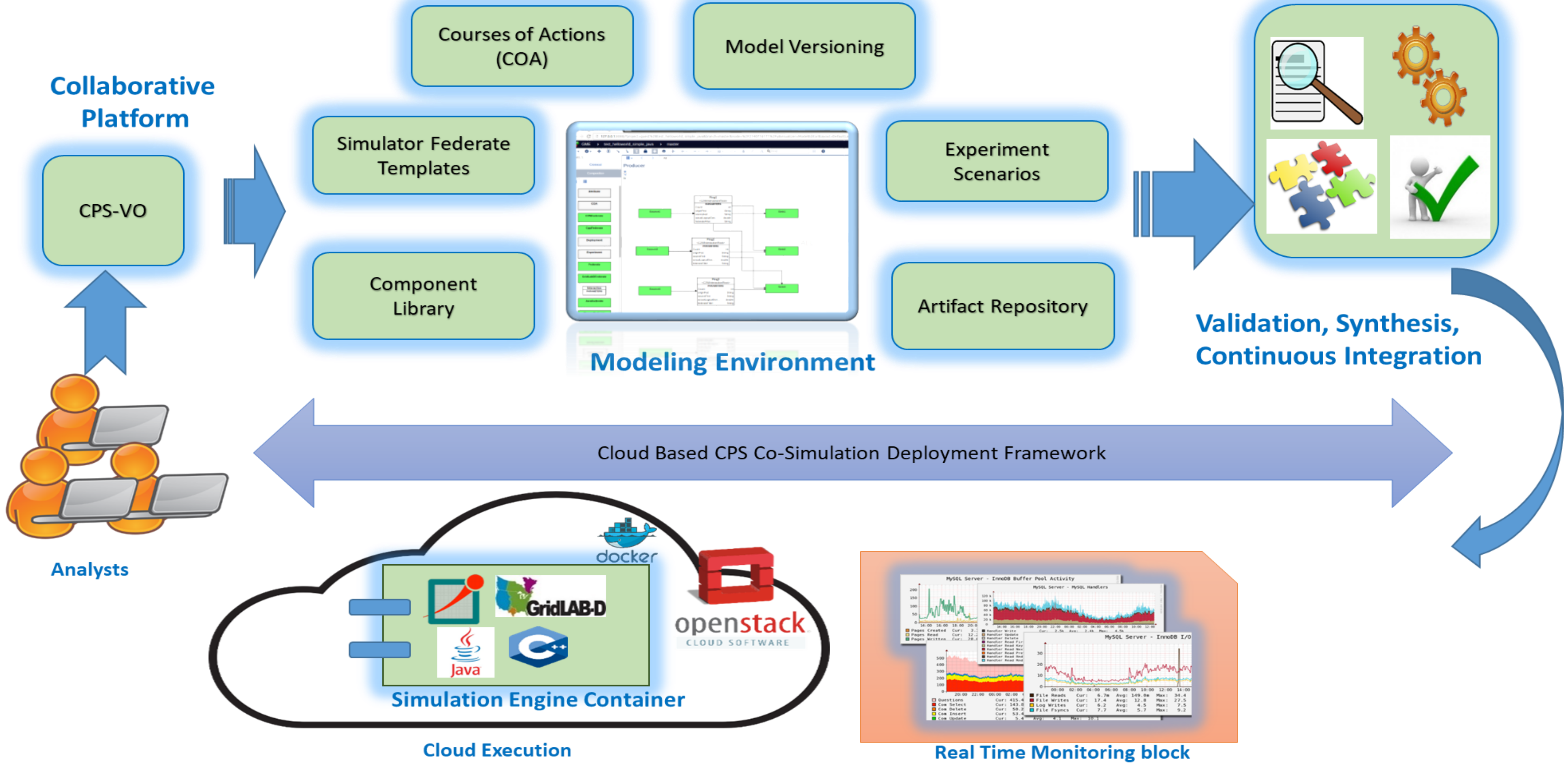


Power exchange among micro-grids?
Business models & market structures?

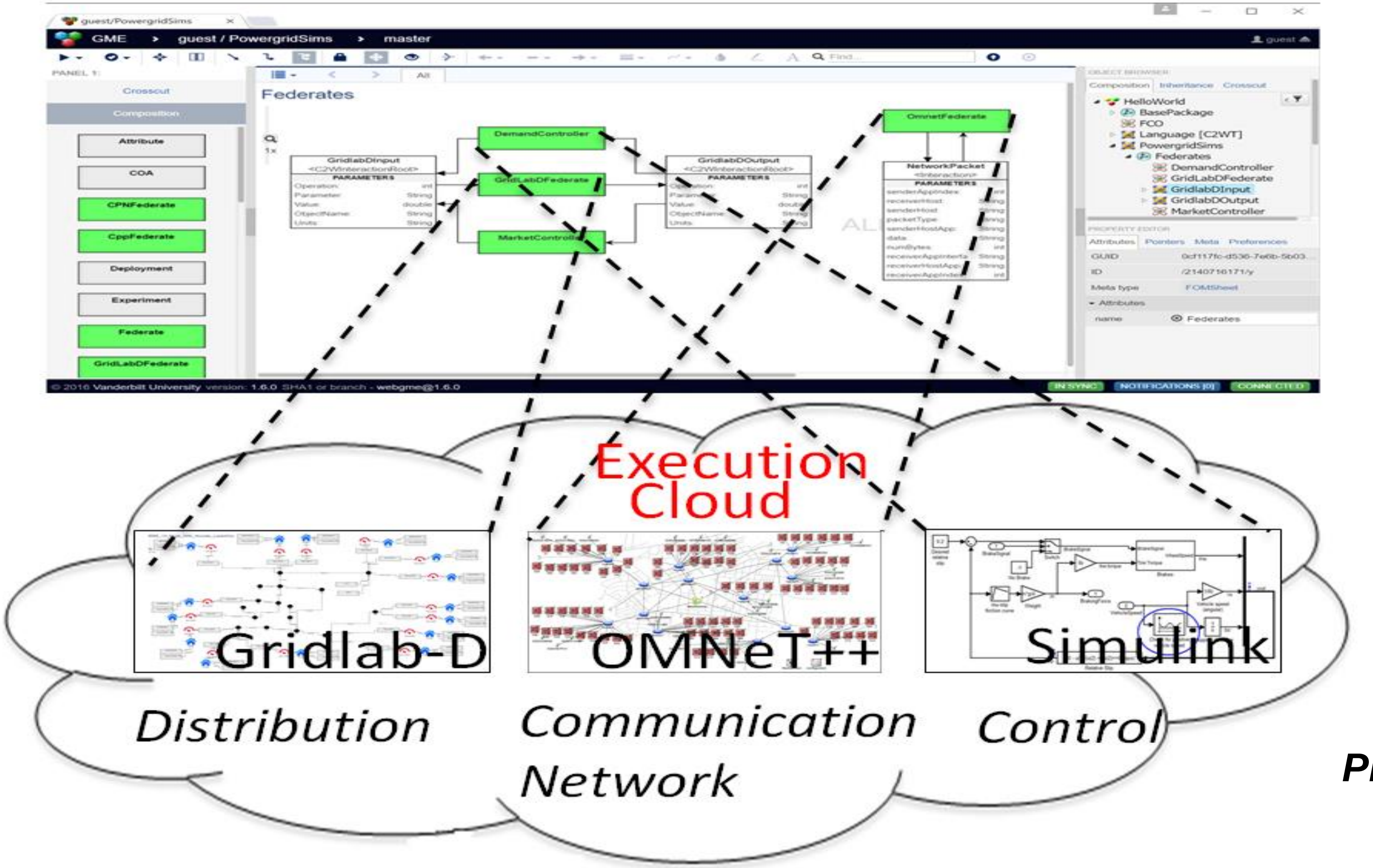
Pricing models?
Market clearing methods?

- Analysis of TE systems require collaborative modeling and experimentation environments because TE design and implementation involves a large number of stakeholders!
- **CPSWTTE Features:**
  - ❑ Multi-Model Simulation Integration
  - ❑ Model-Based Rapid Synthesis of Heterogeneous Simulations
  - ❑ HLA-Based Synchronization, Communication, and Coordination
  - ❑ Web-Based Tools for Modeling and Simulation as a Service
  - ❑ Collaborative Modeling and Experiment Design
  - ❑ Experiments Management and Control
  - ❑ Web-Accessible, Secure, Private, Cloud-Hosted Experimentation Environment

CPSWT-TE Platform Architecture



Design Studio Example: A Multi-Model Integrated Simulation



CPSWT-TE Platform Tools & Methods:

- Build system
- Repositories
- Change tracking
- Authentication
- Analysis tools
- Error handling
- Experiment tools
- Monitoring & control
- Cloud deployment

Platform URL:

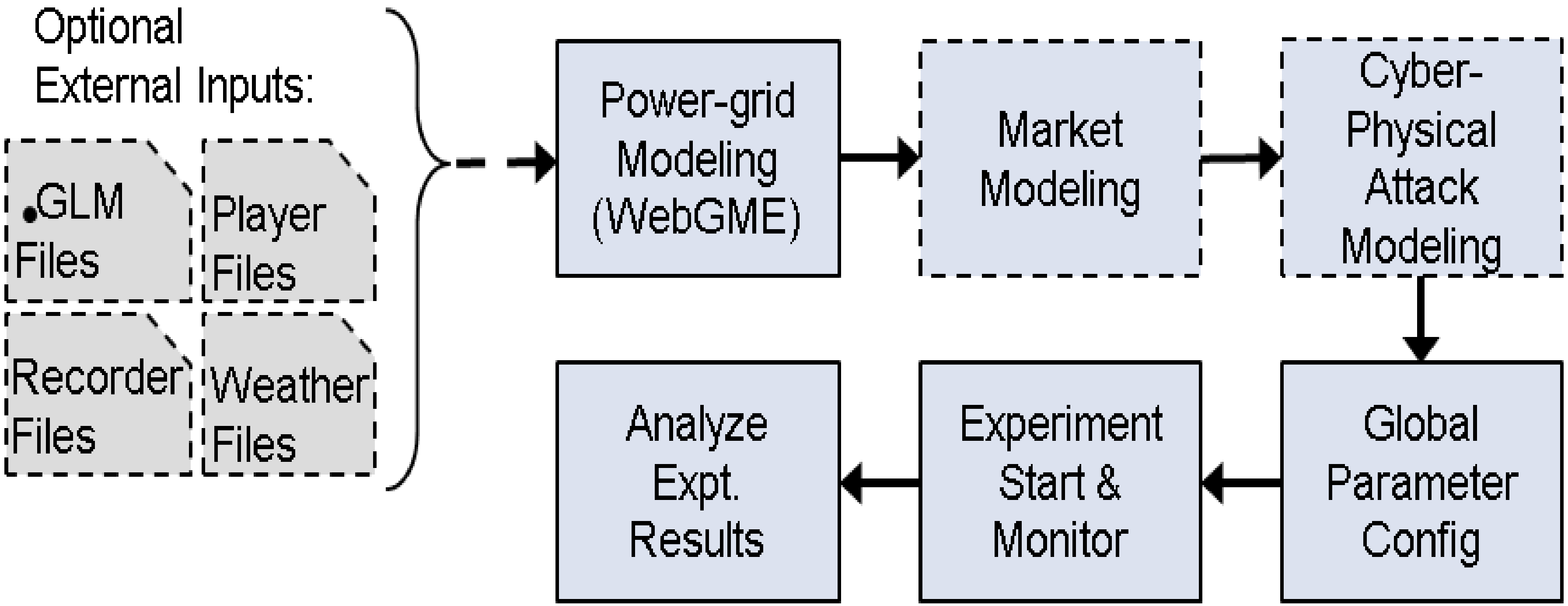
https://cps-vo.org/group/CPSWTTE

Design Studio #2:
GDSim: GridLAB-D Modeling & Simulation for Transactive Energy

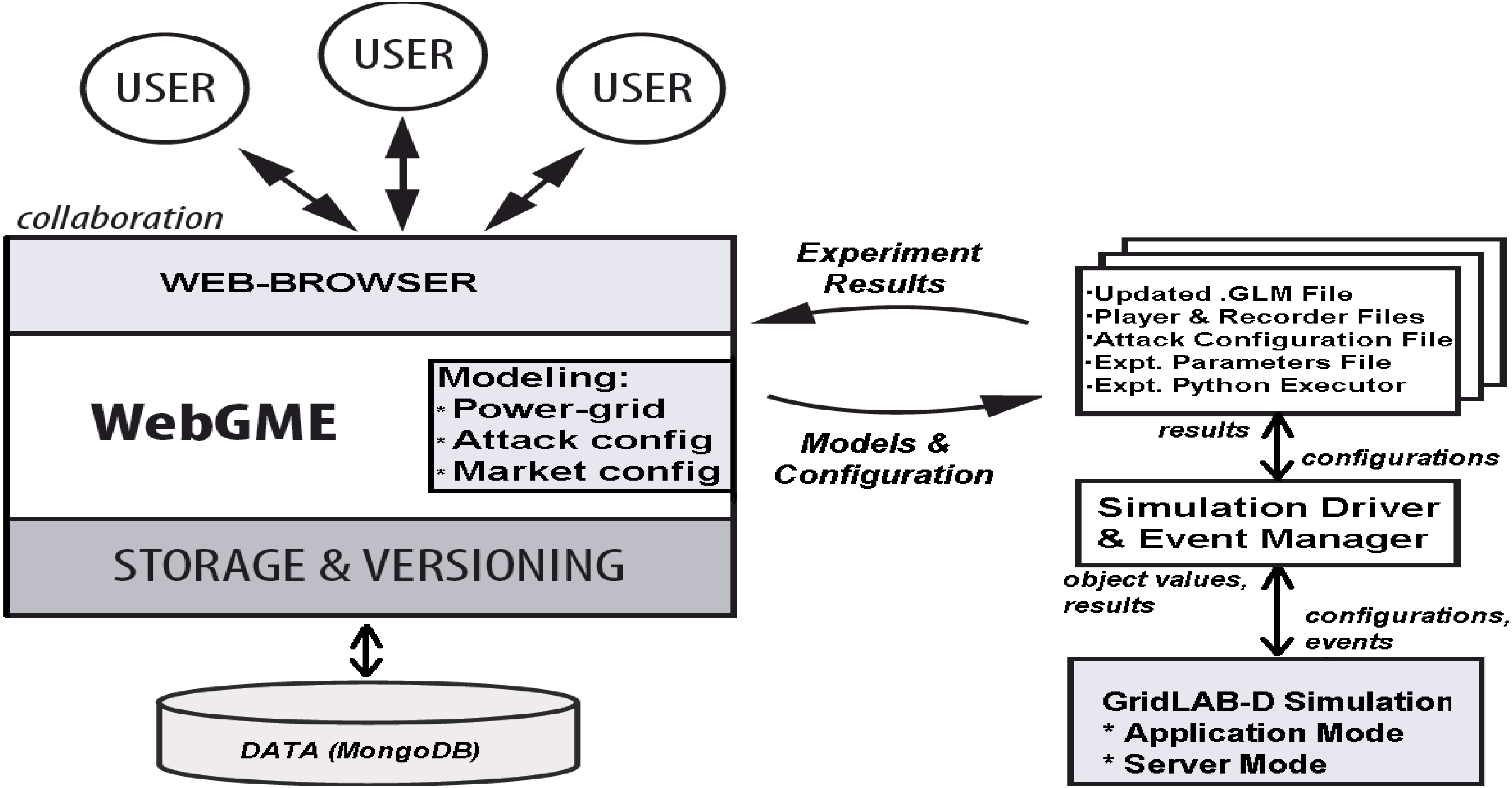
GDSim

- Pure GridLAB-D simulation (no integration with other simulators)
- Power-grid distribution system simulation + Attacks on markets
- Supports market attacks for analyzing TE approaches
- Multi-user real-time collaboration over models and experiments
- Available at: https://cps-vo.org/group/gridlabd

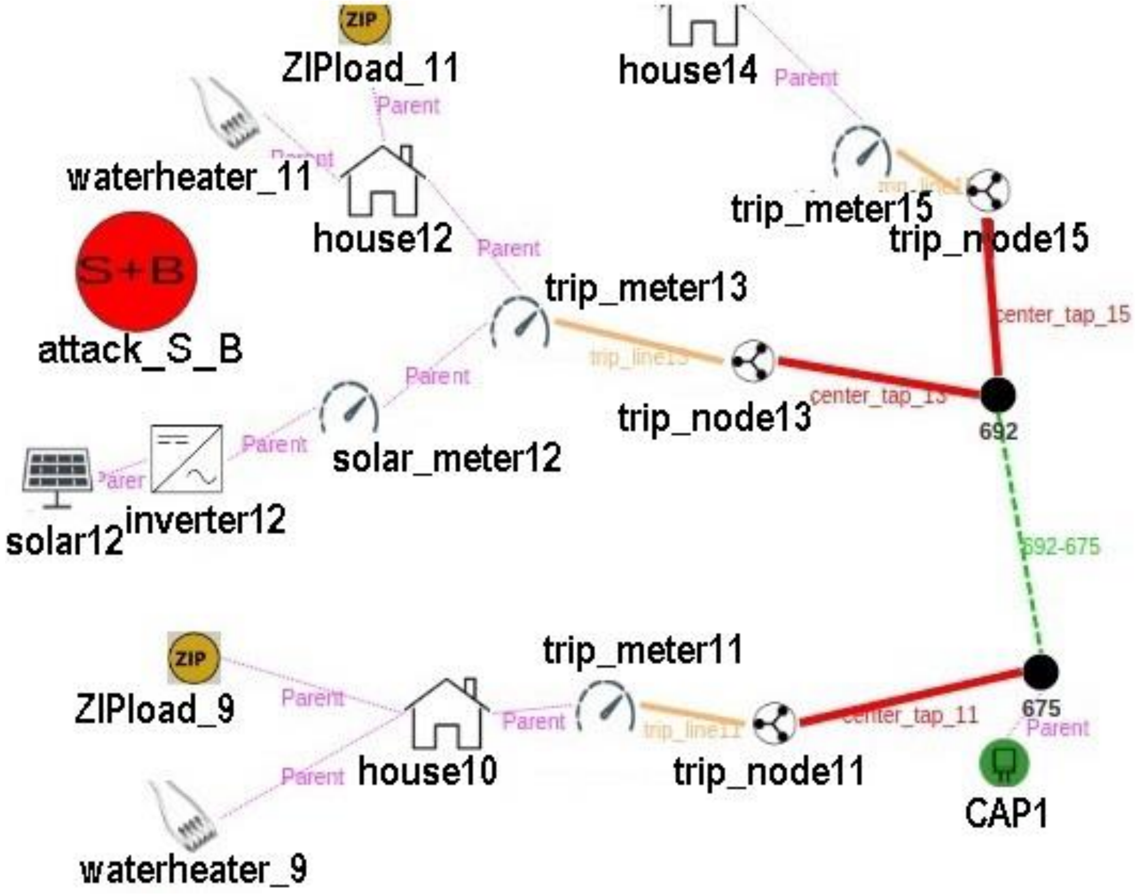
Modeling and Simulation Workflow:

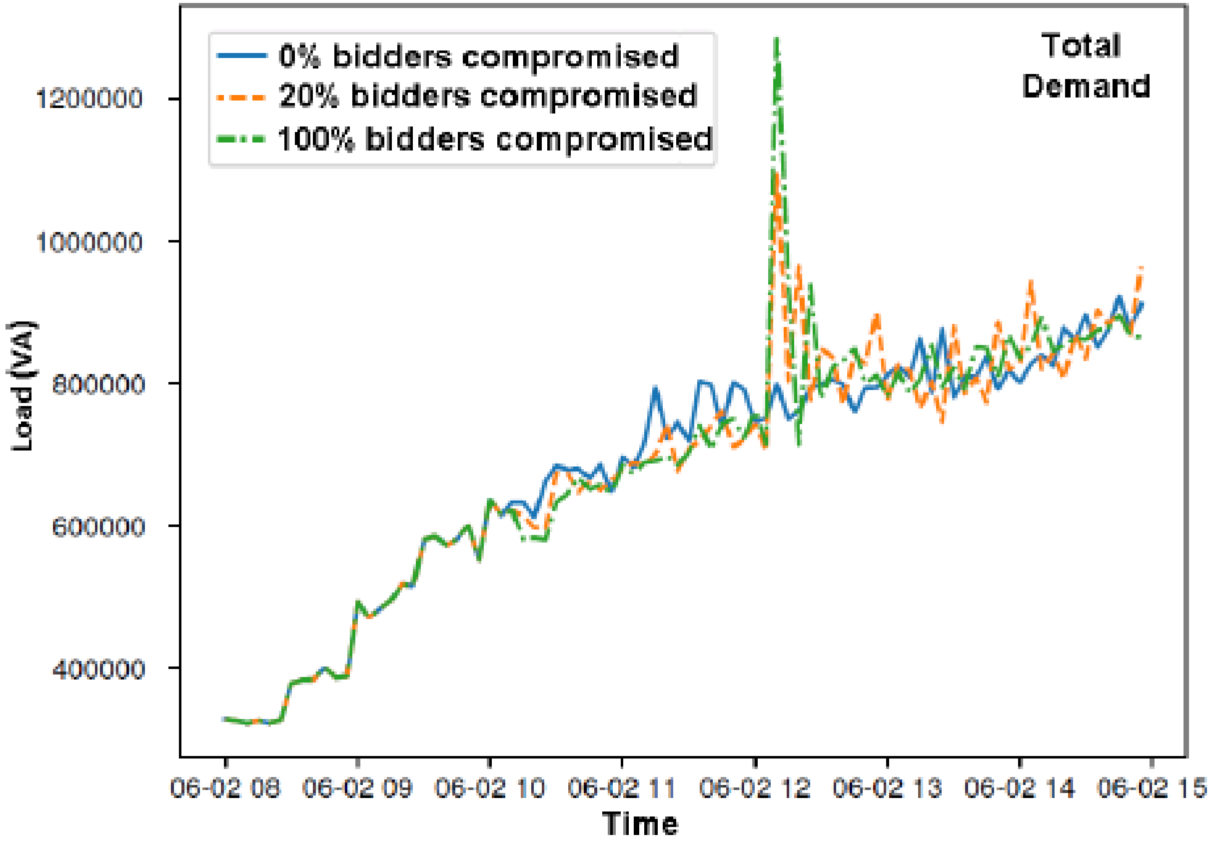


GDSim: Implementation Architecture



Example: Creating Demand Peaks through Market Attacks





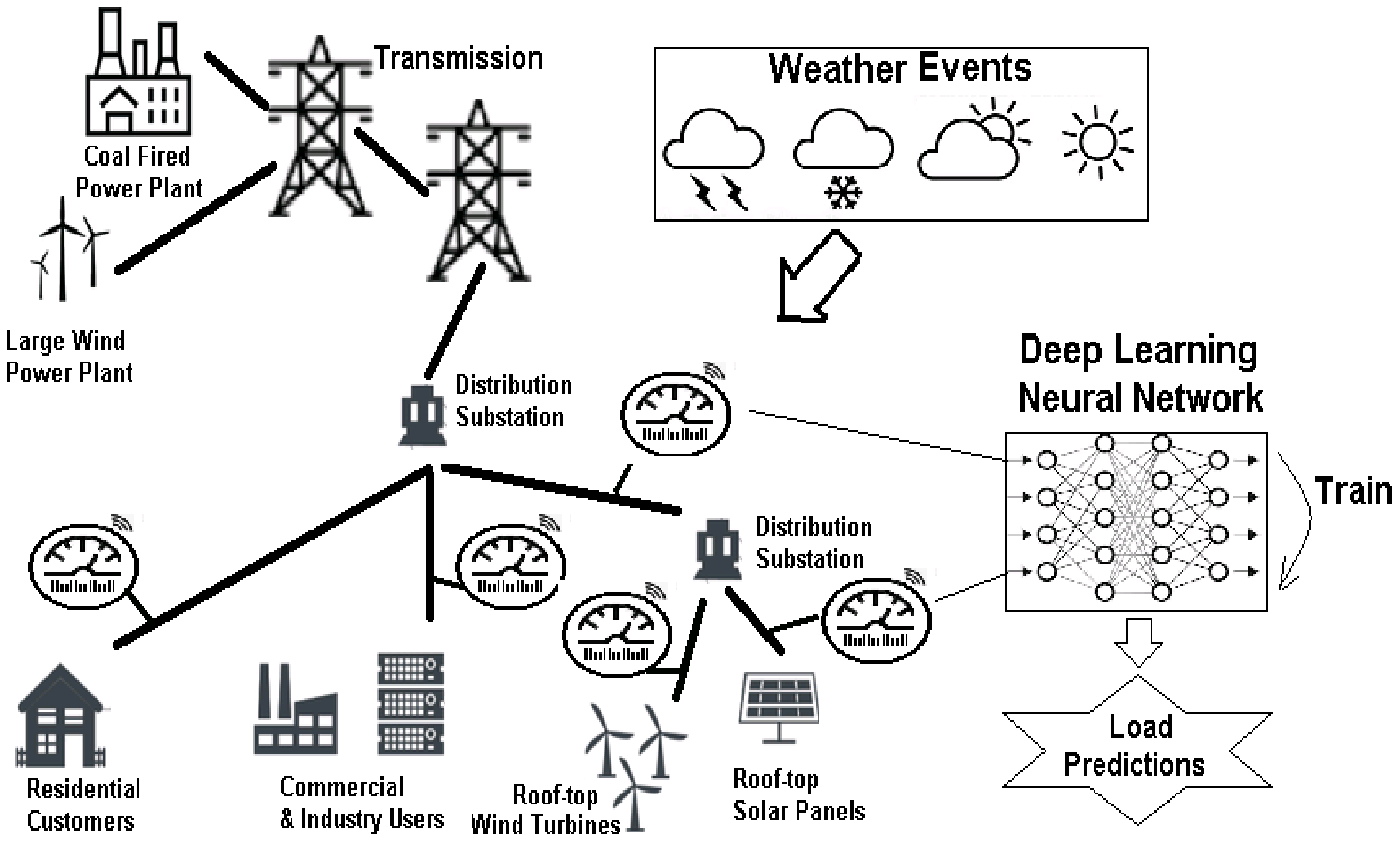
- *Neema, Himanshu, Harsh Vardhan, Carlos Barreto, and Xenofon Koutsoukos. "Web-based platform for evaluation of resilient and transactive smart-grids." In 2019 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), pp. 1-6. IEEE, 2019.*

GDSim Design Studio: Summary

- Power-grids are a complex system involving many different components
- Increased connectivity and DERs have increased grid’s vulnerability to attacks
- A Web-based platform with the following advantages:
  - Web-accessible
  - Graphical modeling environment
  - Real-time collaboration
  - Transactive energy simulations
  - Experimentation with market attacks
  - Several case study models
  - Library of high-level models

Design Studio #3:
TeSER: Testbed for Simulation-Based Evaluation of Resilience

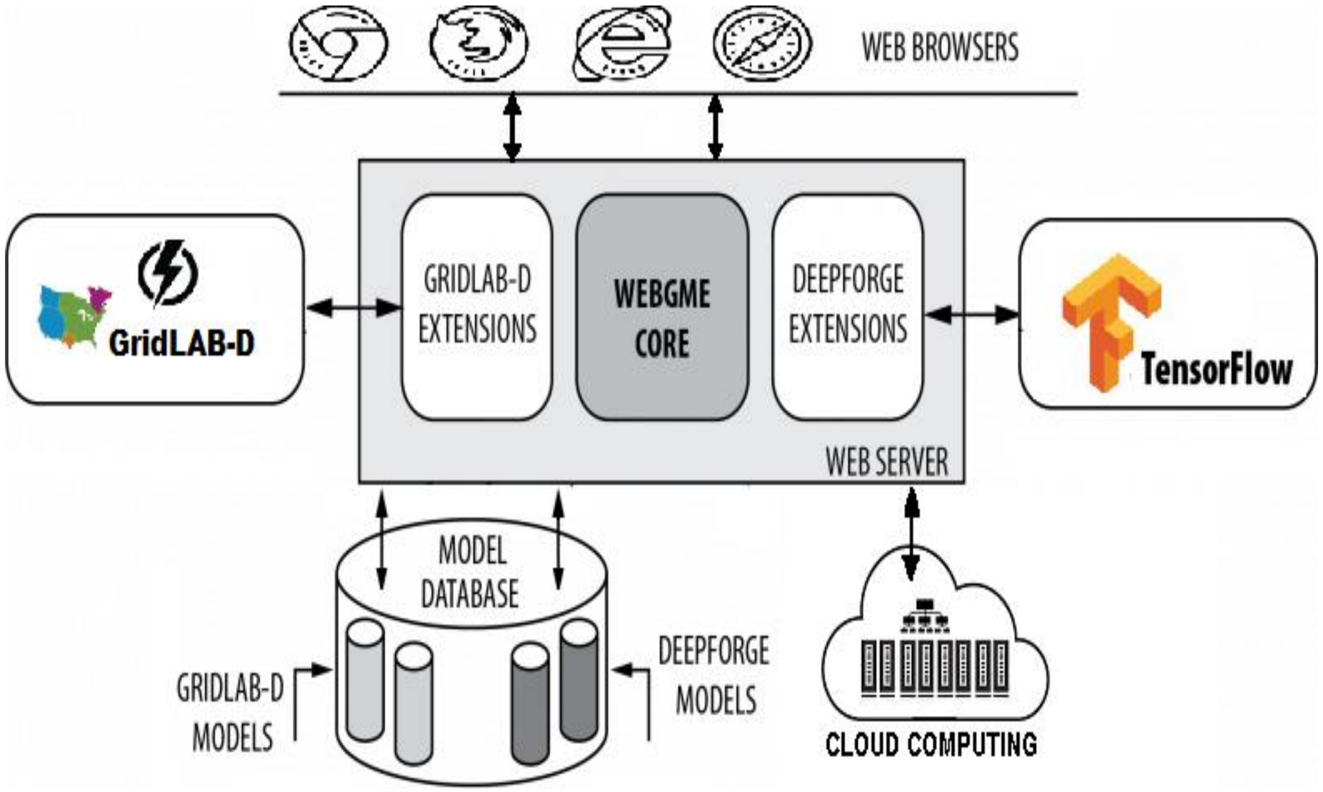
5. TeSER: Testbed for Simulation-based Evaluation of Resilience



- Distributed Energy Resources (DER) integration makes grid controls highly dynamic and distributed
- Prosumers = Producers + Consumers
- Dynamic power pricing adds to complexity
- Traditional load forecasting becomes highly challenging
- Deep-learning based predictors using smart meter data is more manageable

PROBLEM: These neural network based load forecasters are vulnerable to stealthy adversarial attacks!

TeSER Testbed Architecture



Web-accessible, Collaborative, Cloud-Supported

TeSER Testbed (requires password): https://lablet.webgme.org

Built using four "open-source" technologies:

- **WebGME** (Web-based Generic Modeling Environment): Meta-modeling environment for creating rich domain-specific modeling languages
- **GridLAB-D**: Power grid distribution systems steady-state simulator
- **DeepForge**: Deep Learning Framework
- **MongoDB**: Object-oriented database

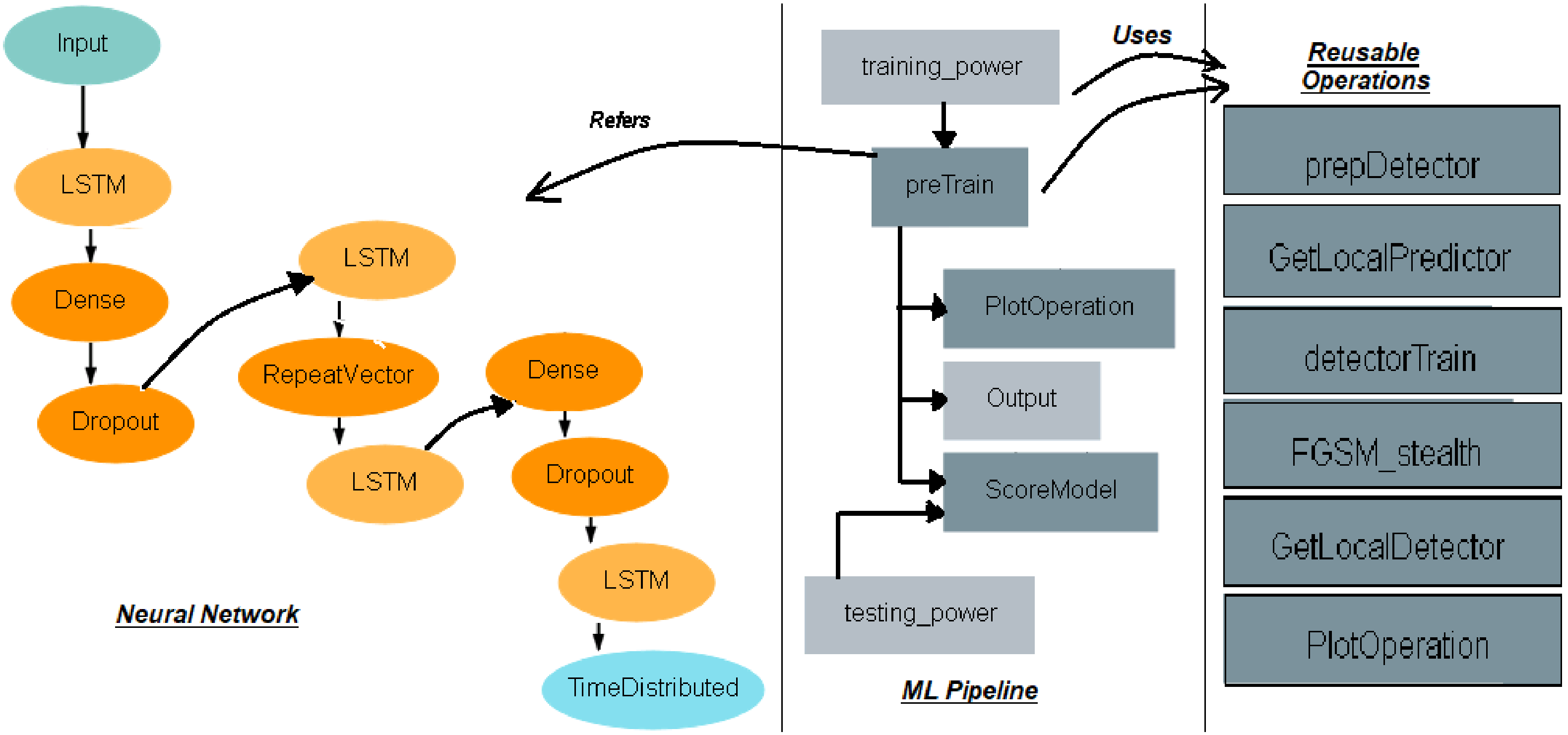
Integrated cloud computation platform for executing large-scale experiments

Integrated support for modeling various Tensorflow/ Keras based machine learning architectures

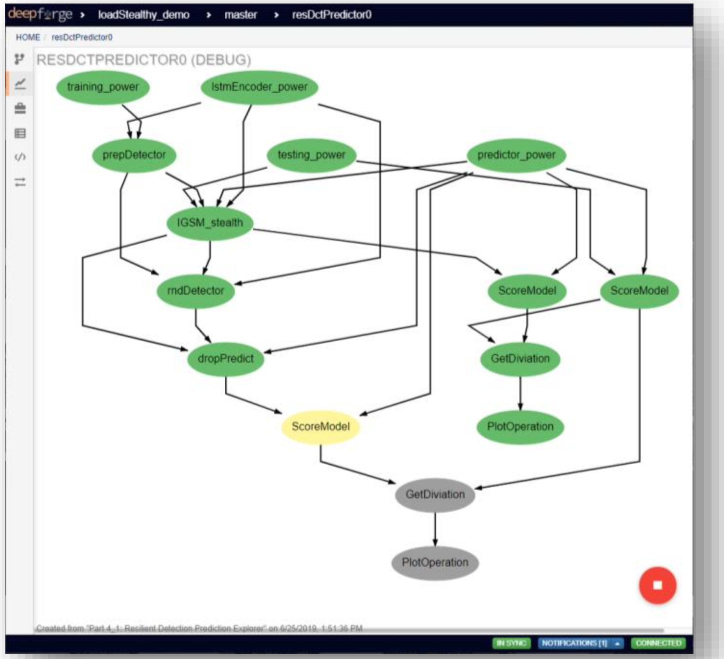
Supports storage of experiment results and presenting as digestible plots

- Full versioning and change-tracking of all models
- Full record of executed ML pipelines: iterations, console logs, etc.

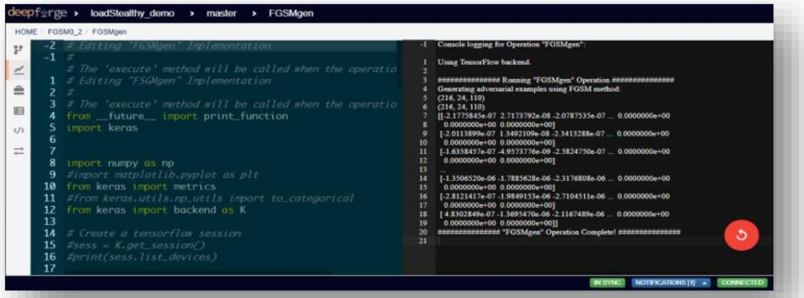
Deep Learning Framework



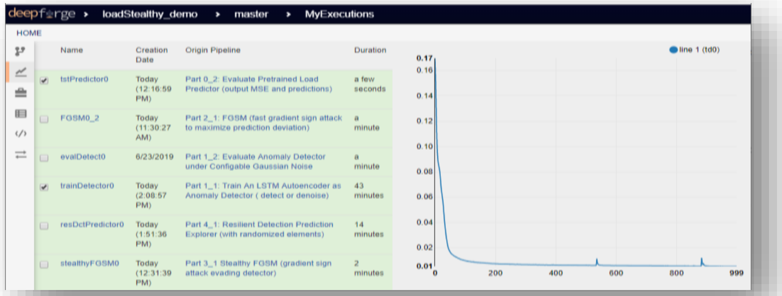
Pipeline Execution



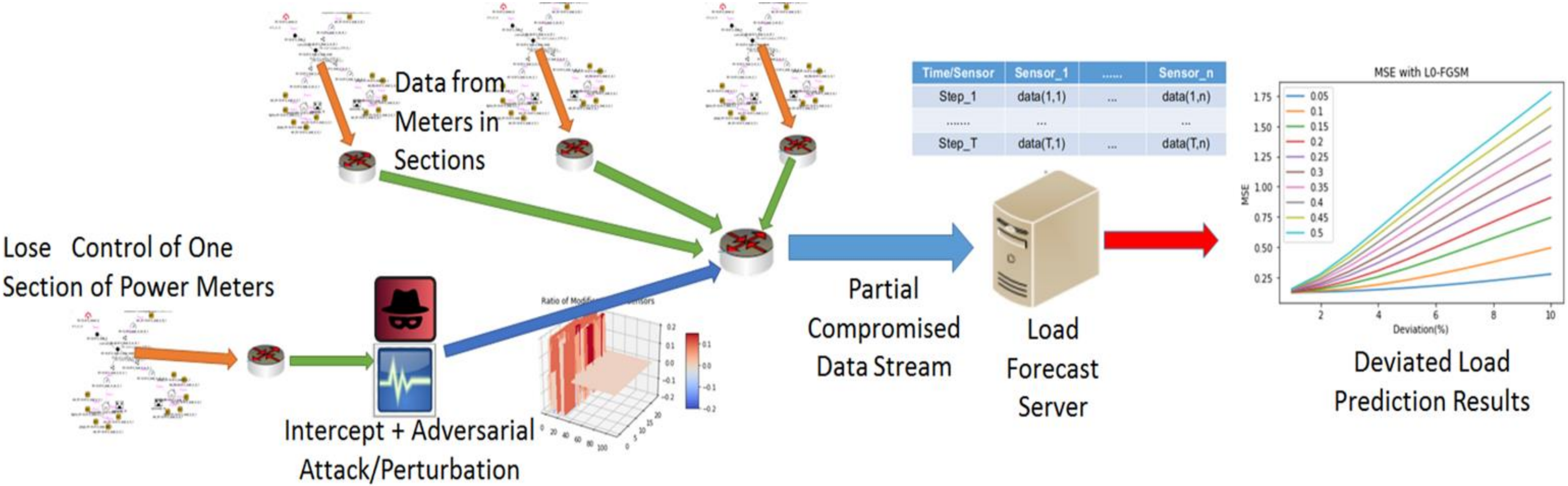
Code editor and console output view



Integrated plotting of executions



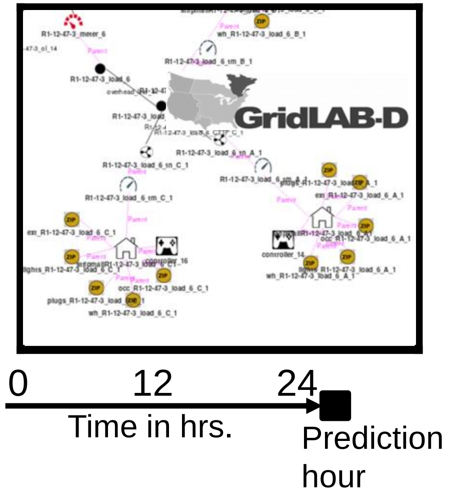
Evaluating Adversarial Attack Impact on Grid Forecasters



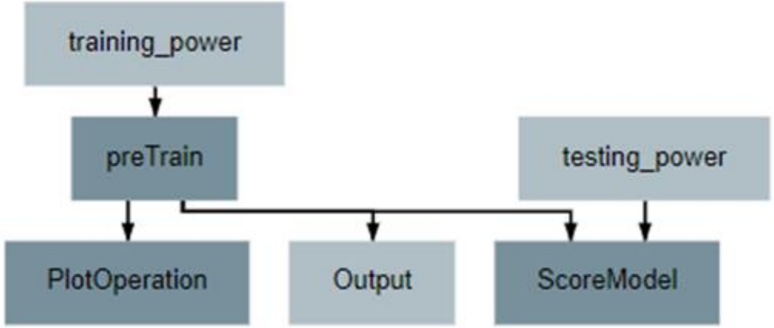
- *Neema, Himanshu, Peter Volgyesi, Xenofon Koutsoukos, Thomas Roth, Cuong Nguyen. "Online Testbed for Evaluating Vulnerability of Deep Learning Based Power Grid Load Forecasters." In 2020 8th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), IEEE 2020.*

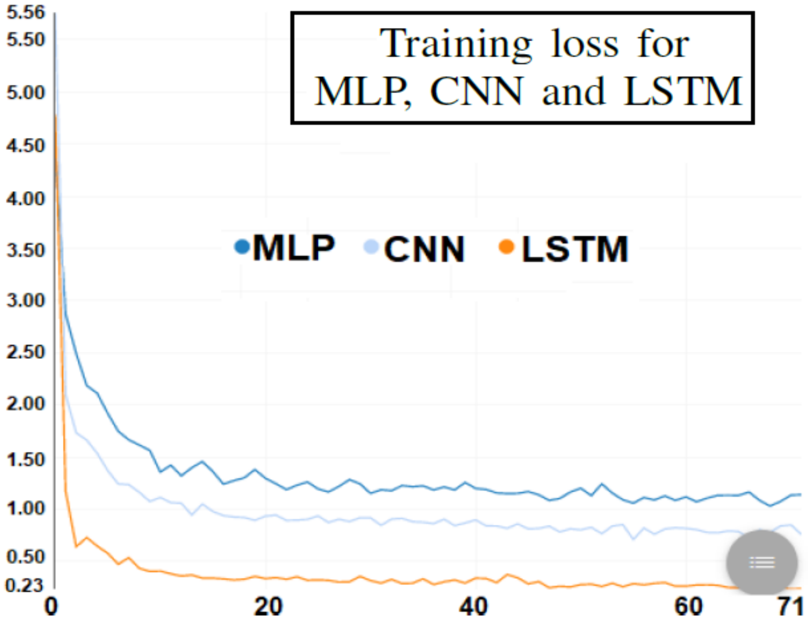
Ex 1: Comparing Deep Learning Based Load Predictors

Medium scale feeder in GridLAB-D (109 smart meters)

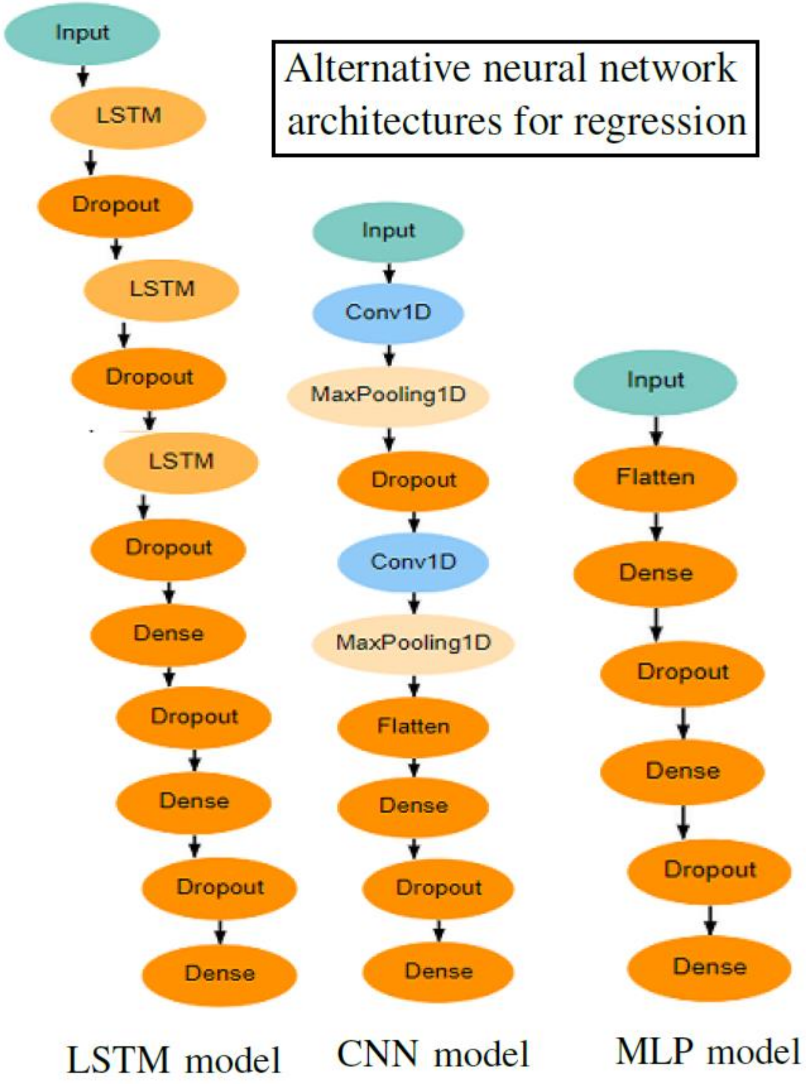


Pipeline model for training predictors





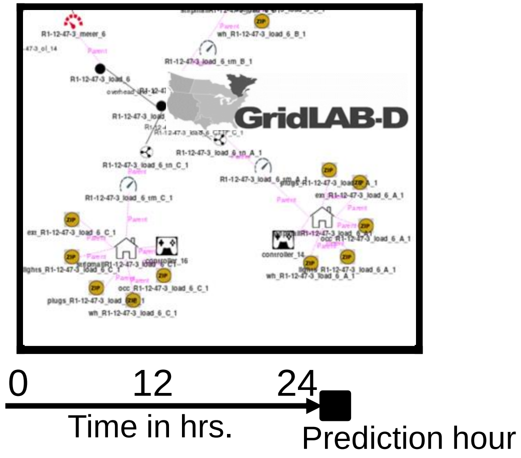
Training loss for MLP, CNN and LSTM



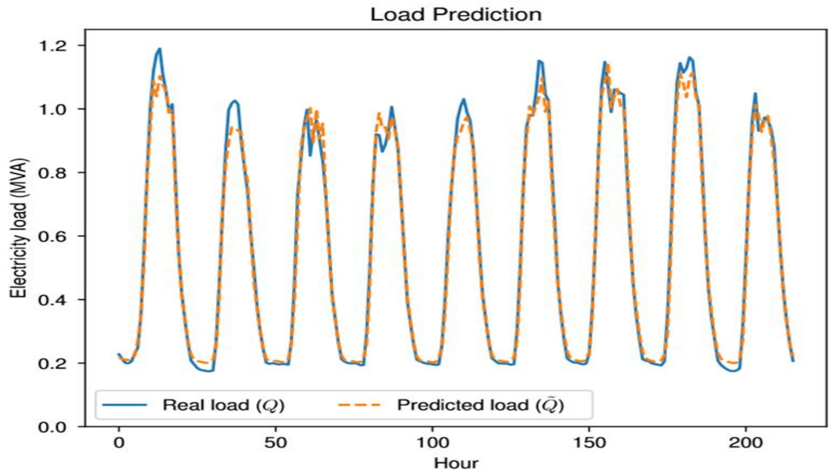
Alternative neural network architectures for regression

Ex2: Load Predictions under Stealthy Adversarial Attacks

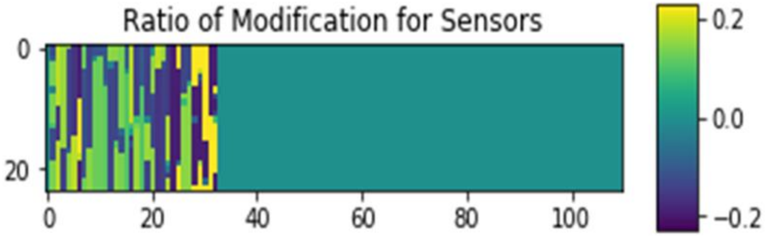
- Medium scale feeder in GridLAB-D (109 smart meters)



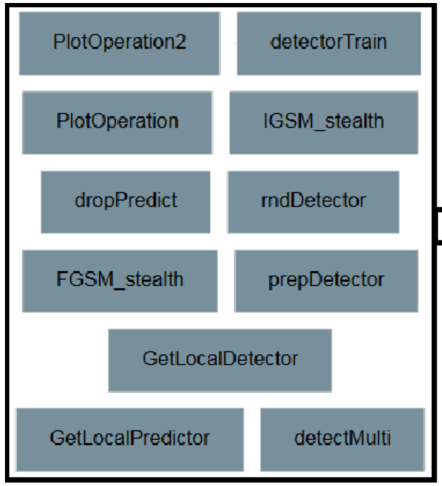
- LSTM load forecast predictor
- Auto-encoder anomaly detector



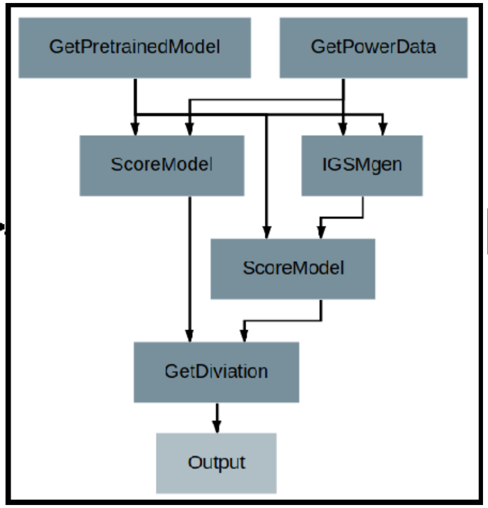
- Threat constraints: 30% of sensors compromised, each modified no more than 20%
- Assume worst-case **white-box** attacks (i.e., full knowledge of predictor and anomaly detector)



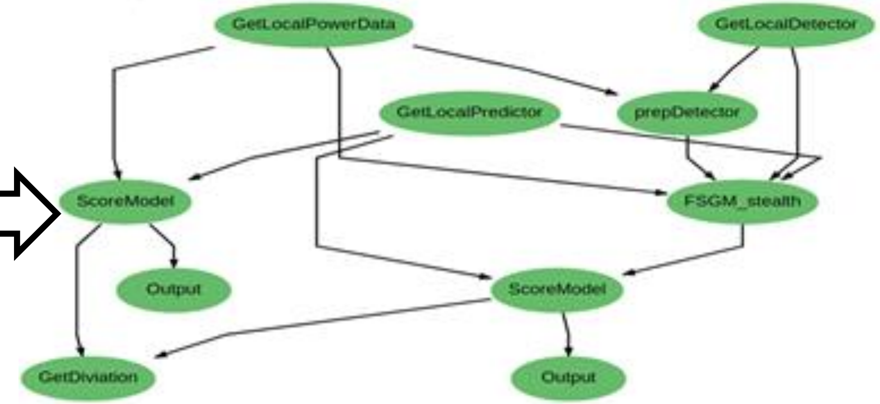
<u>Reusable **Operations** in TeSER</u>



<u>ML **Pipelines** in TeSER</u>



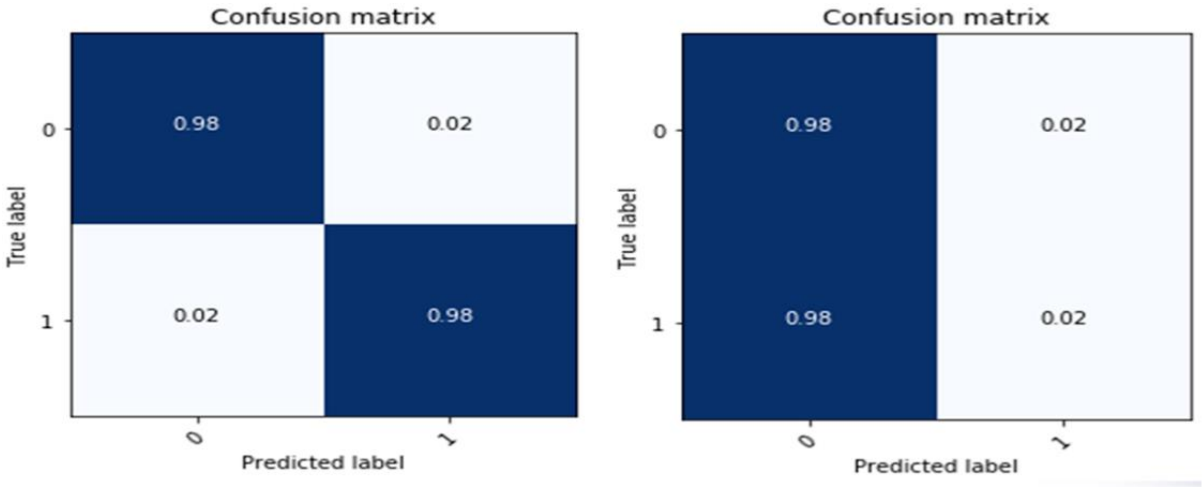
<u>ML Pipelines “**Executions**” in TeSER</u>



Ex2: Experiment Results

Four adversarial attack settings:

- **Fast Gradient Sign Method (FGSM)**: Single step attack to maximize the prediction deviation from the original predictor
- **Iterative GSM**: Iterative attack to maximize the prediction deviation from the original predictor
- **Directed GSM** (reverse = 1): Iterative attack to minimize the predicted values
- **Directed GSM** (reverse = −1): Iterative attack to maximize the predicted values



Prediction Results (MSE) with Different Prediction Deployment Settings

Attack/Detection Settings	Original/NoAttack	Adversarial/NoDetect	Original/StaticDetect	Adversarial/StaticDetect
Fast-GSM (rate=0.3,step_len=0.2)	0.1255	0.5375	0.1287	0.5322
Iterative-GSM (rate=0.3, step_len=0.01,step_num=20)	0.1255	0.7801	0.1287	0.7606
DirectedGSM (rate=0.3, step_len=0.01 ,step_num=20, reverse=1)	0.1255	0.4785	0.1287	0.4913
DirectedGSM (rate=0.3, step_len=0.01 ,step_num=20, reverse=-1)	0.1255	1.025	0.1287	0.9899

Key References

- GDSim: GridLAB-D Design Studio: http://cps-vo.org/group/gridlabd
- CPSWT-TE Co-Simulation Design Studio for Transactive Energy: http://cps-vo.org/group/C2WTTE
- Testbed for Simulation-based Evaluation of Resilience (TeSER): http://lablet.webgme.org
- Cyber-Physical Systems – Virtual Organization: http://cps-vo.org
- Vulcan Forge Project Hosting Platform: http://vulcan.isis.vanderbilt.edu
- WebGME Web-Based Generic Modeling Environment: http://webgme.org
- Functional Mock-up Interface – www.fmi-standard.org
- HLA standard – IEEE standard for modeling and simulation (M&S) high-level architecture (HLA) – framework and rules http://ieeex-plore.ieee.org/servlet/opac?punumber=7179
- Neema, Himanshu, "Large-Scale Integration of Heterogeneous Simulations", PhD Dissertation, Vanderbilt University, Jan. 2018.
- Neema, H., J. Sztipanovits, M. Burns, and E. Griffor, "C2WT-TE: A Model-Based Open Platform for Integrated Simulations of Transactive Smart Grids", 2016 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems, Vienna, Austria, 04/2016.
- H. Neema, G. Karsai, and A. Levis, “Next-Generation Command and Control Wind Tunnel for Courses of Action Simulation,” Technical Report ISIS-15-119, Institute for Software-Integrated Systems, Vanderbilt University, Nashville, TN. May 2015.
- Neema H., Emfinger W., Dubey A., “A Reusable and Extensible Web-Based Co-Simulation Platform for Transactive Energy Systems,” 3rd Int. Conf. and Workshop on Transactive Energy (TES 2016), Portland, OR, USA, 05/2016.
- Hemingway, G., H. Neema, H. Nine, J. Sztipanovits, and G. Karsai, “Rapid Synthesis of High-Level Architecture-Based Heterogeneous Simulation: A Model-Based Integration Approach,” SIMULATION, vol. March 17, 2011 0037549711401950, no. Online, Simulation: Transactions of the Society for Modeling and Simulation International, pp. 16, 03/2011.
- H. Neema, H. Nine, G. Hemingway, J. Sztipanovits, and G. Karsai, “Rapid Synthesis of Multi-Model Simulations for Computational Experiments in C2,” Armed Forces Communications and Electronics Association - George Mason University Symposium, issue Critical Issue in C4I, Lansdowne, Virginia.
- M. Mar´oti, R. Keresk´enyi, T. Kecsk´es, P. V¨olgyesi, and A. L´edeczi, “Online collaborative environment for designing complex computational systems,” Procedia Computer Science, vol. 29, pp. 2432–2441, 2014.
- H. Neema, H. Vardhan, C. Barreto, and X. Koutsoukos, “Web-based platform for evaluation of resilient and transactive smart-grids,” in 2019 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES). IEEE, 2019, pp. 1–6.
- Y. Barve, H. Neema, S. Rees, and J. Sztipanovits, “Towards a Design Studio for Collaborative Modeling and Co-Simulations of Mixed Electrical Energy Systems,” in 2018 IEEE International Science of Smart City Operations and Platforms Engineering in Partnership with Global City Teams Challenge (SCOPE-GCTC). IEEE, 2018, pp. 24–29.
- Zhou, Xingyu, et al., “Evaluating Resilience of Grid Load Predictions under Stealthy Adversarial Attacks,” 2019.
- N. Carlini, “Recent advances in adversarial machine learning,” 2019.
- A. Kurakin, I. Goodfellow, and S. Bengio, “Adversarial machine learning at scale,” arXiv preprint arXiv:1611.01236, 2016.
- A. Ghafouri, Y. Vorobeychik, and X. Koutsoukos, “Adversarial regression for detecting attacks in cyber-physical systems,” in Proc. of the 27th Int. Joint Conference on Artificial Intelligence, 2018, pp. 3769–3775.
- B. Broll, M. Maroti, P. Volgyesi, and A. Ledeczi, “Deepforge: A scientific gateway for deep learning,” Gateways, vol. 9, p. 2018, 2018.
- D. P. Chassin, K. Schneider, and C. Gerkensmeyer, “GridLAB-D: An open-source power systems modeling and simulation environment,” in IEEE PES T&D Conference and Exposition, 2008, pp. 1–5.
- J. Sztipanovits, “Composition of cyber-physical systems,” in Proc. of the 14th Annual IEEE Int’l. Conference and Workshops on the Engineering of Computer-Based Systems (ECBS ’07), Washington, DC.
- S. Weerakkody and B. Sinopoli, “Challenges and Opportunities: Cyber-Physical Security in the Smart Grid,” in Smart Grid Control, 2019.
- Rees, Stephen A., et al., “Cyber-Physical Systems Virtual Organization: Active resources: Enabling reproducibility, improving accessibility, and lowering the barrier to entry,” 2019.
- H. Vardhan, N. Sarkar, and H. Neema, “Modeling and Optimization of a Longitudinally-Distributed Global Solar Grid,” 12 2019.

Thank you!

for

YOUR

Attention!

ANY QUESTIONS?