Architecture Design and Validation for Autonomous Energy Systems

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Architecture Design

- Managing heterogeneous elements of a highly distributed energy system requires holistic **communication, control, and operation architectures** that seamlessly integrate dispersed controllers with newly developed algorithms and existing legacy systems—each of which could be of distinct ownership, platform, or manufacturer.

- Goal: Develop an architectural description that clearly defines and specifies autonomous energy systems (AES).

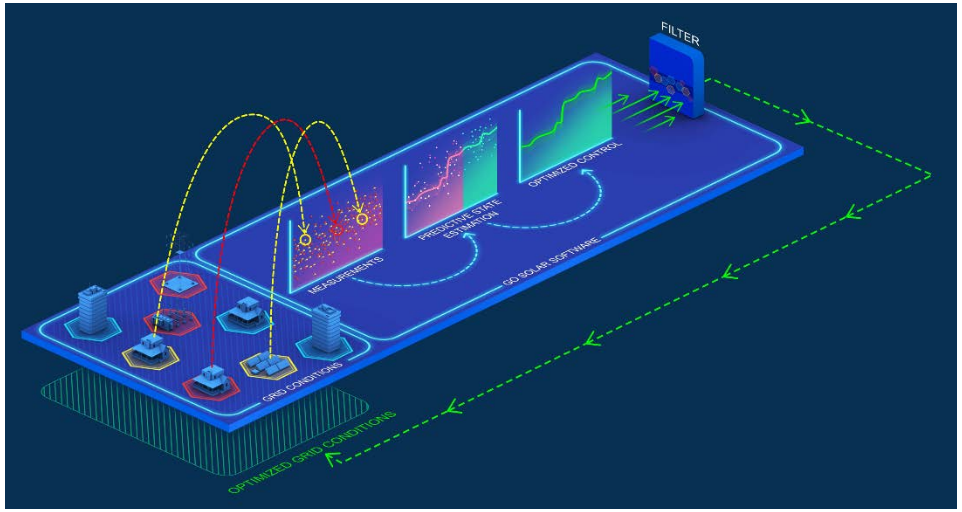
Architecture Requirement for AES

- Hierarchical control: Needs to be able to control millions of devices (scalable)
- Distributed control: Needs to be fast enough to operate in real time
- Data aware: Makes the best use of time-varying asynchronous measurements
- Interoperability: Integrates diverse devices, platforms, and decisions using standards-based protocols
- Compatibility: Considers the current grid structure and realistic adoption pathways to accommodate millions of devices across the transmission-and-distribution (T&D) boundary.

AES Reference Implementations

- Control architecture and communication architecture developed in completed and existing projects to validate and test AES solutions
- Reference implementations and deployment:
  - Grid Optimization with Solar (GO-SOLAR, completed)
  - Enhanced Control, Optimization, and Integration of Distributed Energy Applications (ECO-IDEA, completed)
  - Federated Architecture for Secure and Transactive Distributed Energy Resource Management Solutions (FAST-DERMS, current).

GO-SOLAR

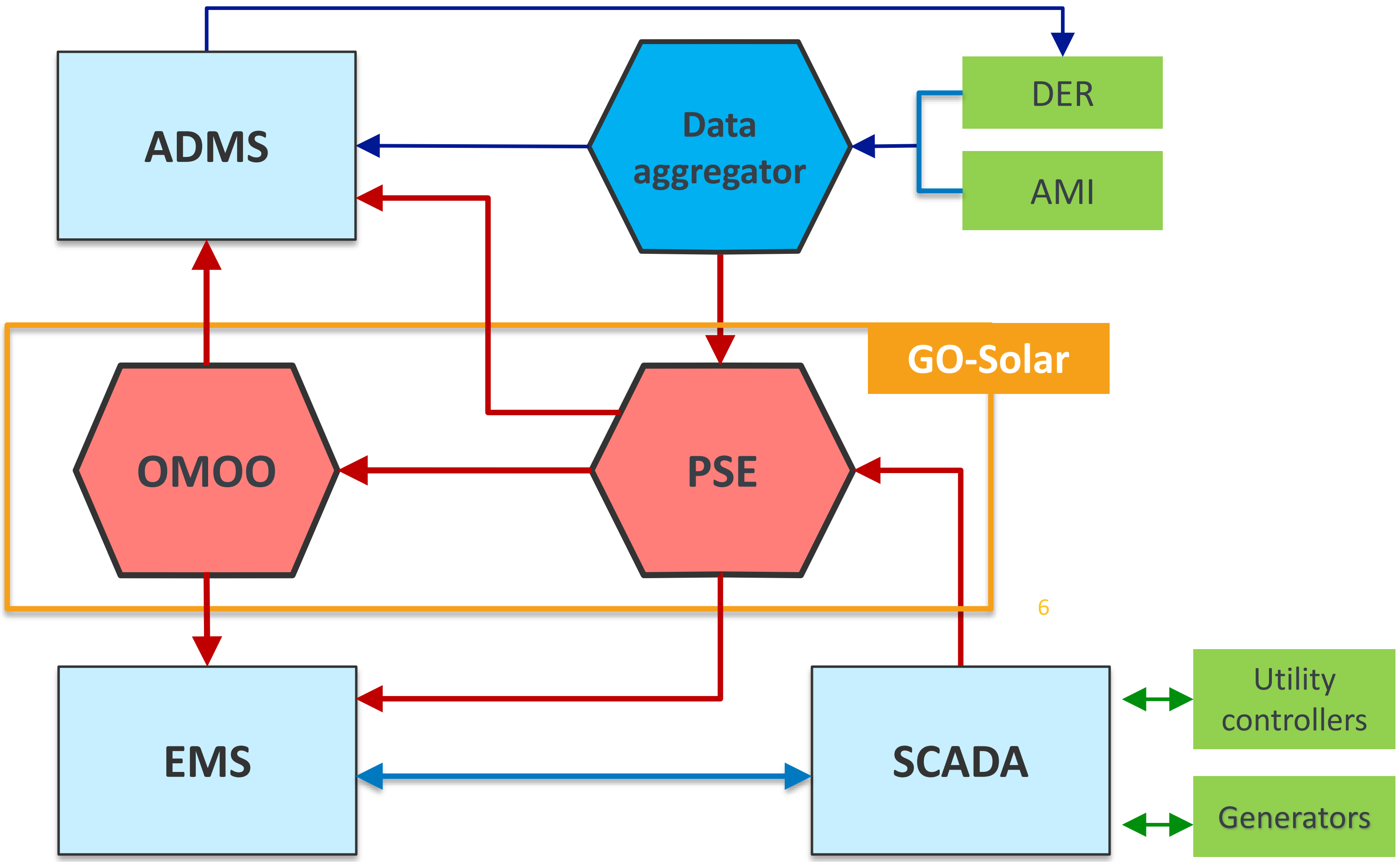


Solar Energy Technologies Office (SETO)-funded project (completed)

Manage **extreme penetrations of solar** and other distributed energy resources (DERs) **using only a few measurement points** through matrix completion, multi-kernel learning-based **predictive state estimation (PSE)**, **and only a few control nodes** dispatched through a dual-timescale **online multi-objective optimization (OMOO)** using voltage-load sensitivities to guide the fast feedback response (Yang et al. 2022; Bernstein and Dall'Anese 2017).

GO-Solar Interface with Enterprise Systems

- Hierarchical control
- Single-step gradient



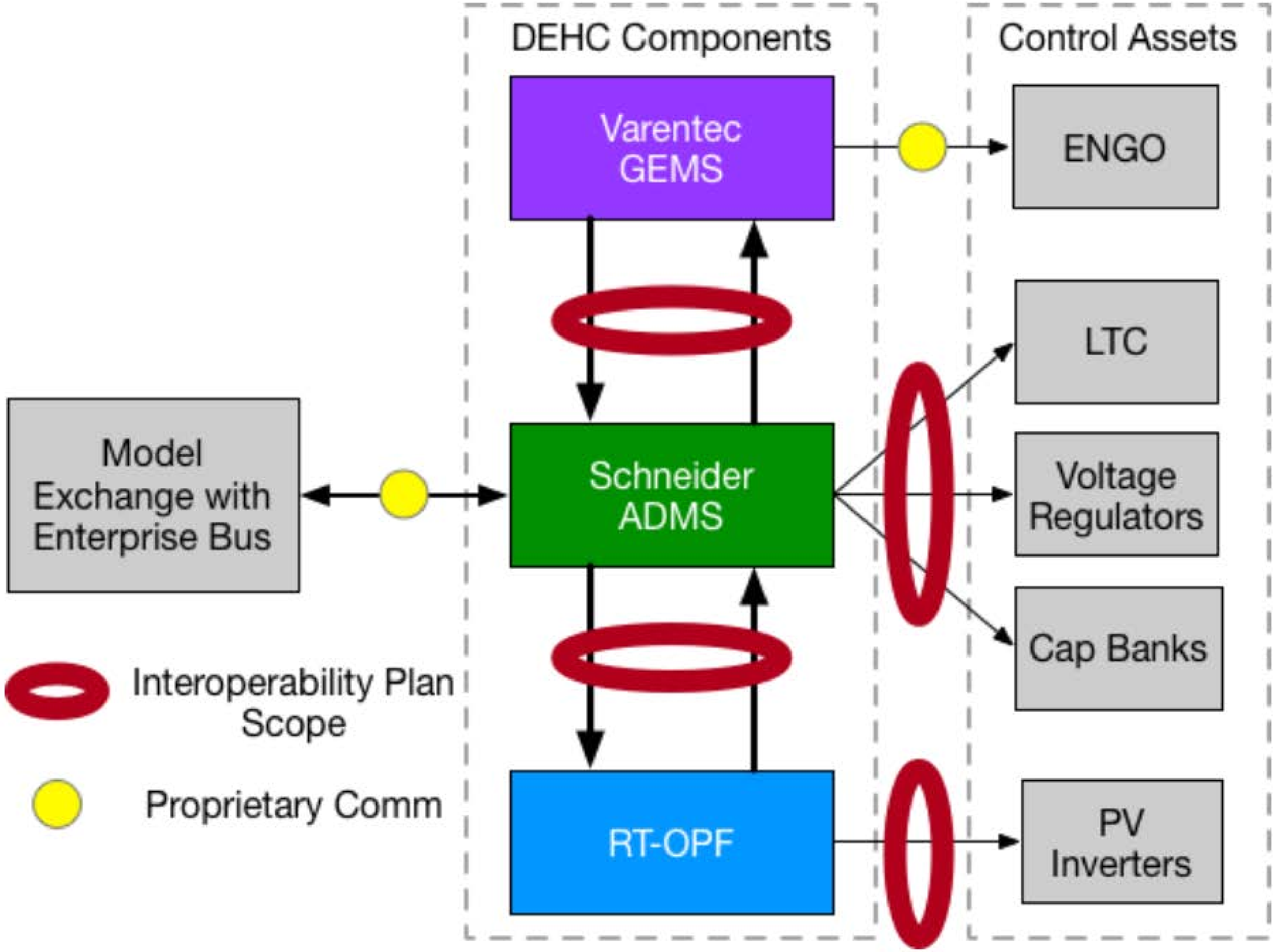
ECO-IDEA

SETO-funded project (completed)

Develop, validate, and deploy a unique and innovative data-enhanced hierarchical control (DEHC) architecture that comprehensively addresses the formidable challenges associated with the proliferation of high penetrations of distributed photovoltaics (PV).

- **Advanced distribution management systems (ADMS) coordinate legacy grid control and grid edge control.**
- **Real-time optimal power flow (RT-OPF) solves optimal active/reactive power set points for PV inverters.**
- **Control and communication at different timescales are coordinated.**

DEHC



Grid-edge reactive power control
Time step = 1 second

Legacy device control

Time step = 15 minutes

PV active/reactive power control
Time step = 10 seconds

From Baggu (2022)

FAST-DERMS

Grid Modernization Laboratory Consortium (GMLC)-funded project

(ongoing)

An **architecture** that can manage a broad range of DERs—PV, storage, electric vehicles, flexible loads, combined heat and power, and other distributed generators—across the grid for bulk system services *through transactive, aggregation, and direct control methods*.

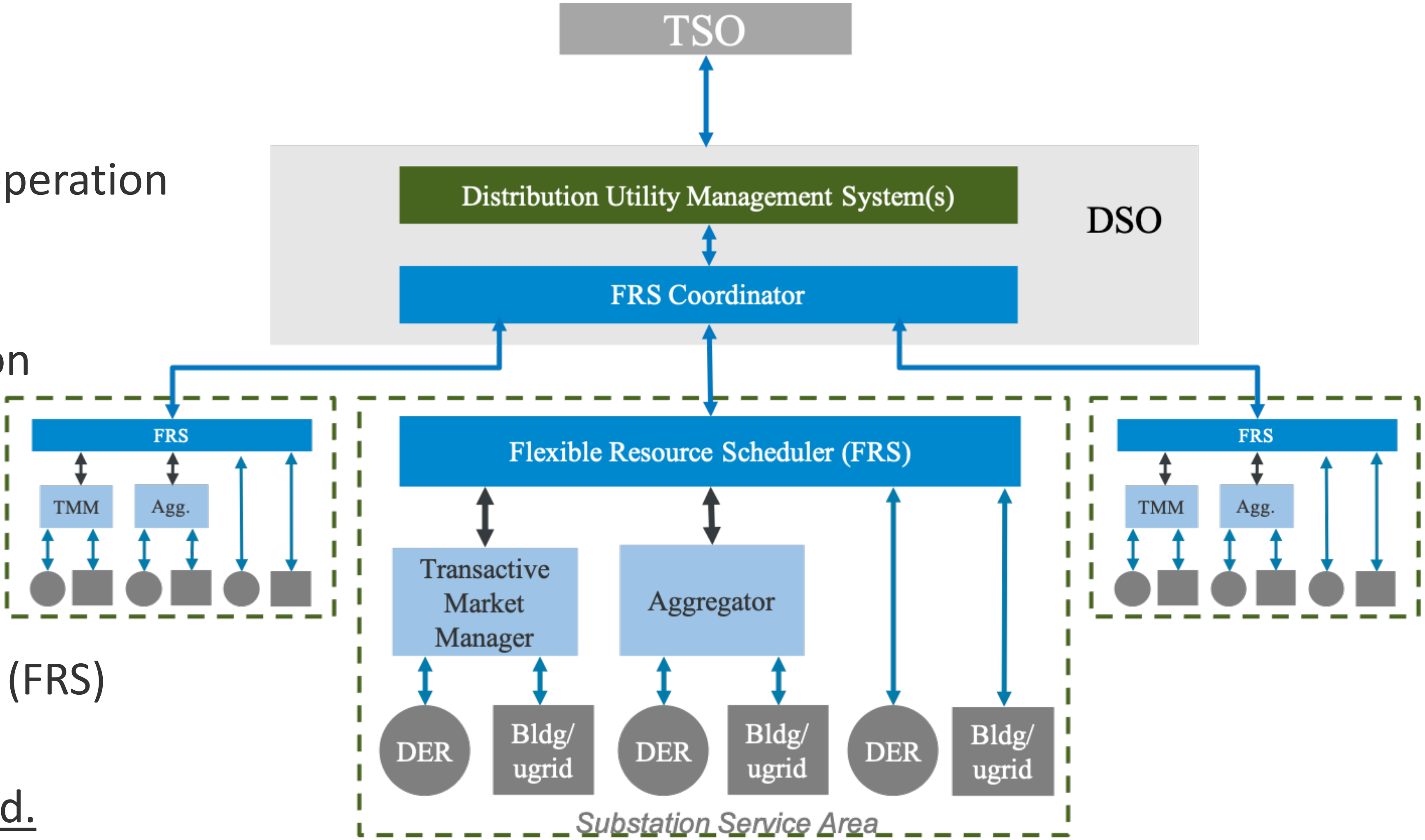
Worked with grid architecture team to develop a grid architecture guidance document: https://gridarchitecture.pnnl.gov/media/Grid_Arch_Guidance_for_FAST%20DERMS.pdf **:**

See Ding et al. (2022) for system architecture and a reference implementation document.

FAST-DERMS

Key features:

- "Total distribution system operation (DSO)" approach
- Hierarchical
- Follows laminar coordination
- Distributed.



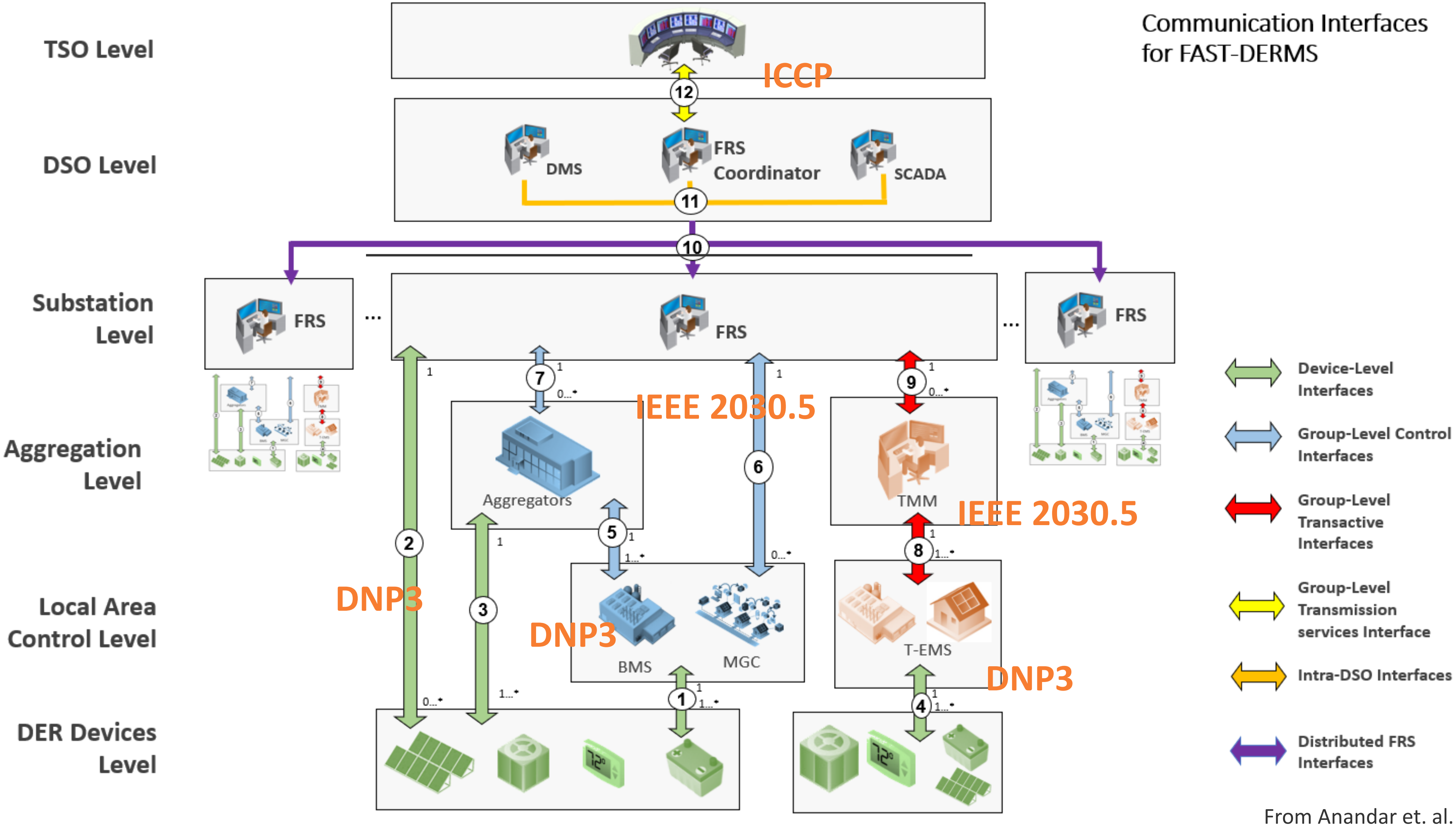
Key control element:

- Flexible resource scheduler (FRS)

Architecture design: Completed.

FAST-DERMS Communication Architecture

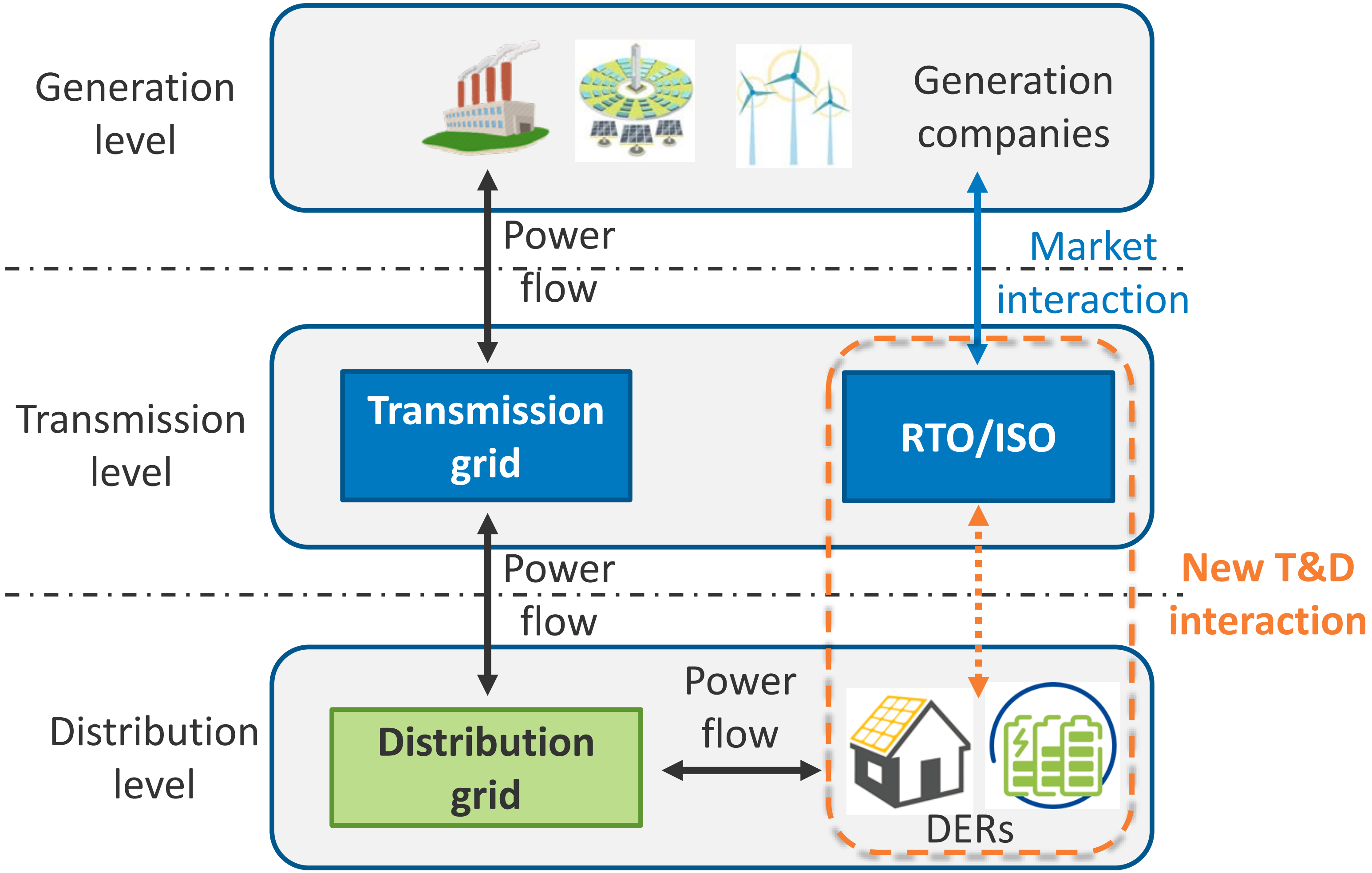
Communication Interfaces for FAST-DERMS



From Anandar et. al. (2022)

T&D Interaction

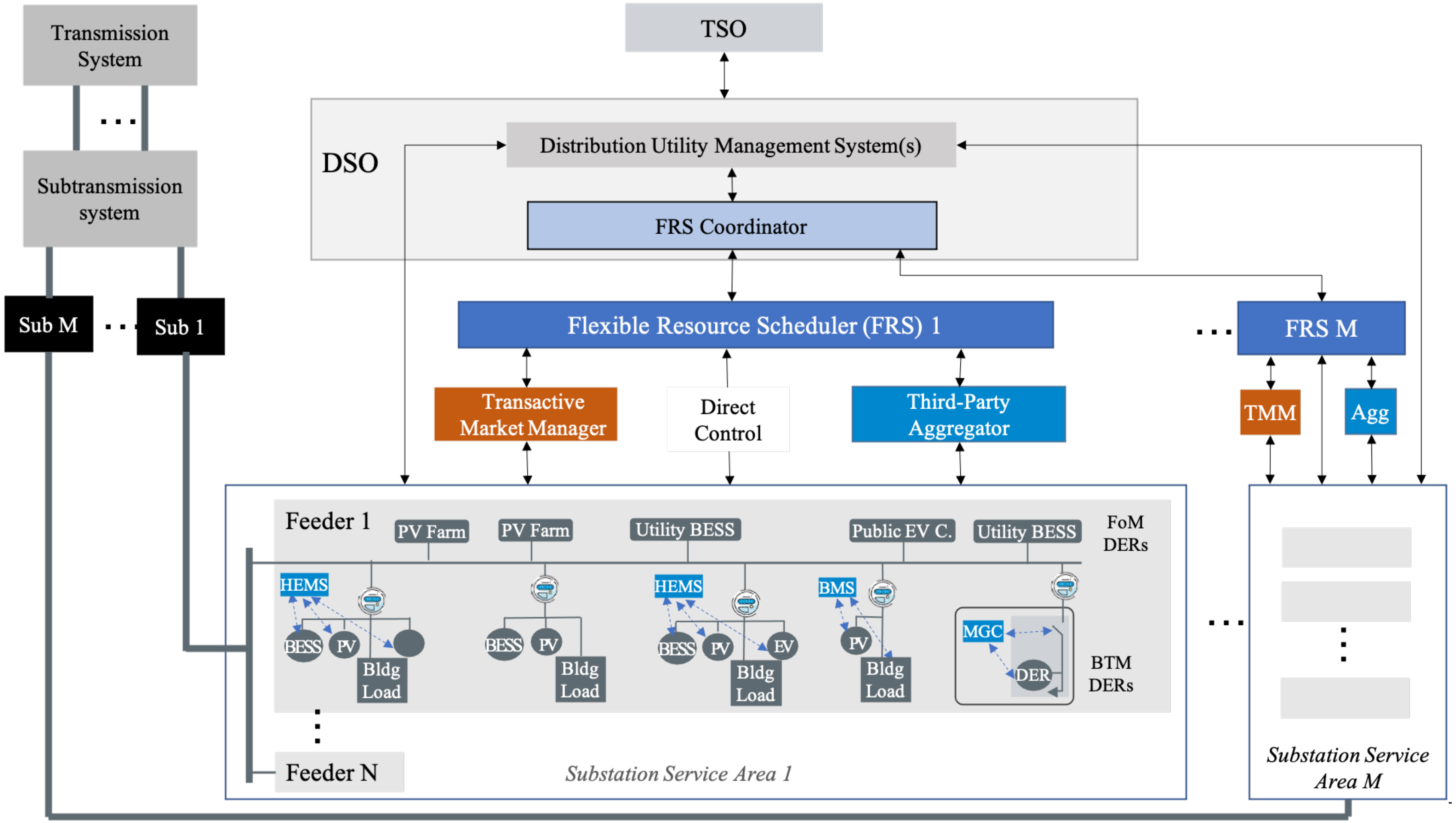
- Wholesale market will open to aggregated DERs (Federal Energy Regulatory Commission Order 2222)
- Leveraging AES, DERs can be efficiently aggregated to provide various services and ensures local constraints are not violated.



FAST-DERMS—T&D Interaction

- The DSO aggregates and controls individual DERs to provide transmission services defined and measured at the T&D interface.

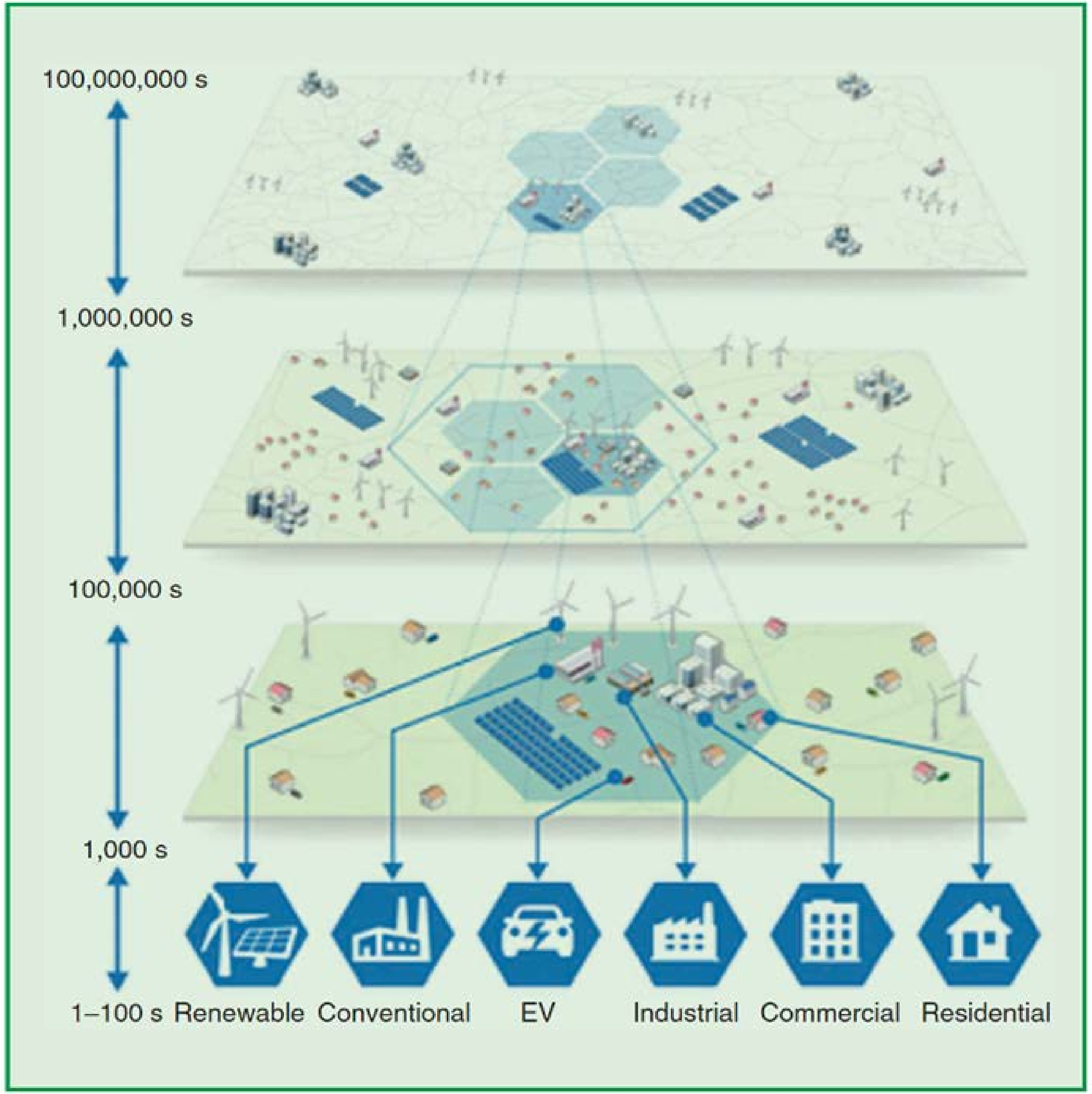
The distribution substation is the transmission resource



Validation

AES provides effective optimization and control solutions to handle massively deployed DERs.

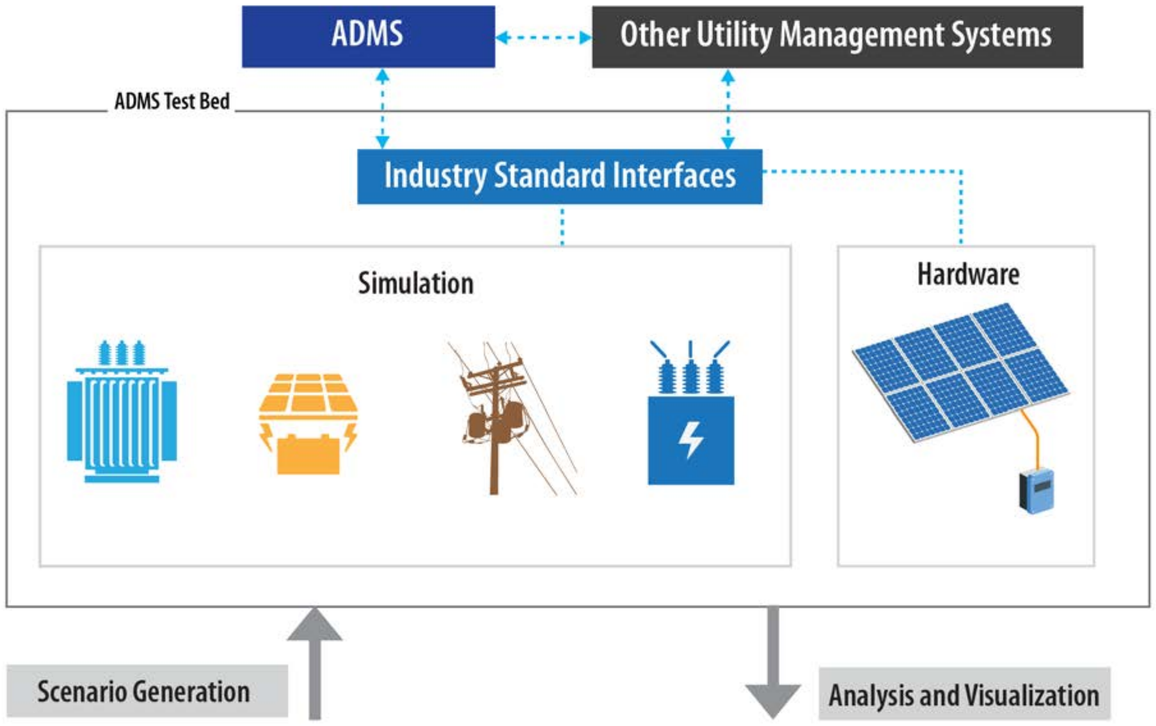
- How to validate and test AES models/algorithms in realistic environment?
- How can AES be integrated into utility practice and coordinate with other grid control technologies?
- What are the use cases/scenarios to validate the benefits?



From Kroposki et al. (2020a)

ADMS Test Bed

- A vendor-neutral test bed to evaluate existing and ADMS functionalities in a realistic laboratory setting
- Real-time software simulation and distribution system hardware
- Industry-standard communications
- Advanced 2D and 3D visualization capability
- Can integrate other utility management systems, e.g., DERMS.



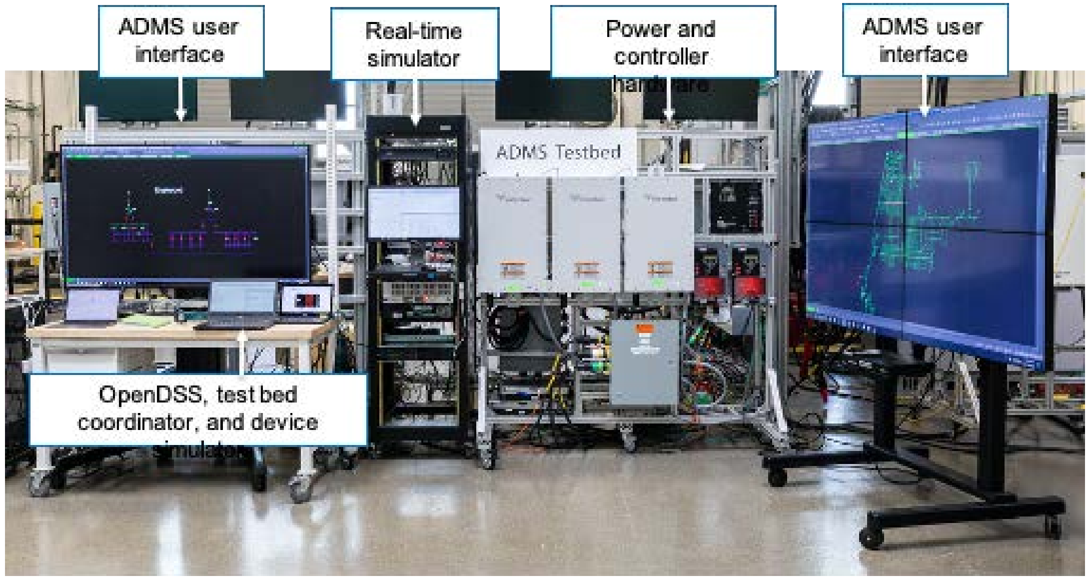


Photo by NREL

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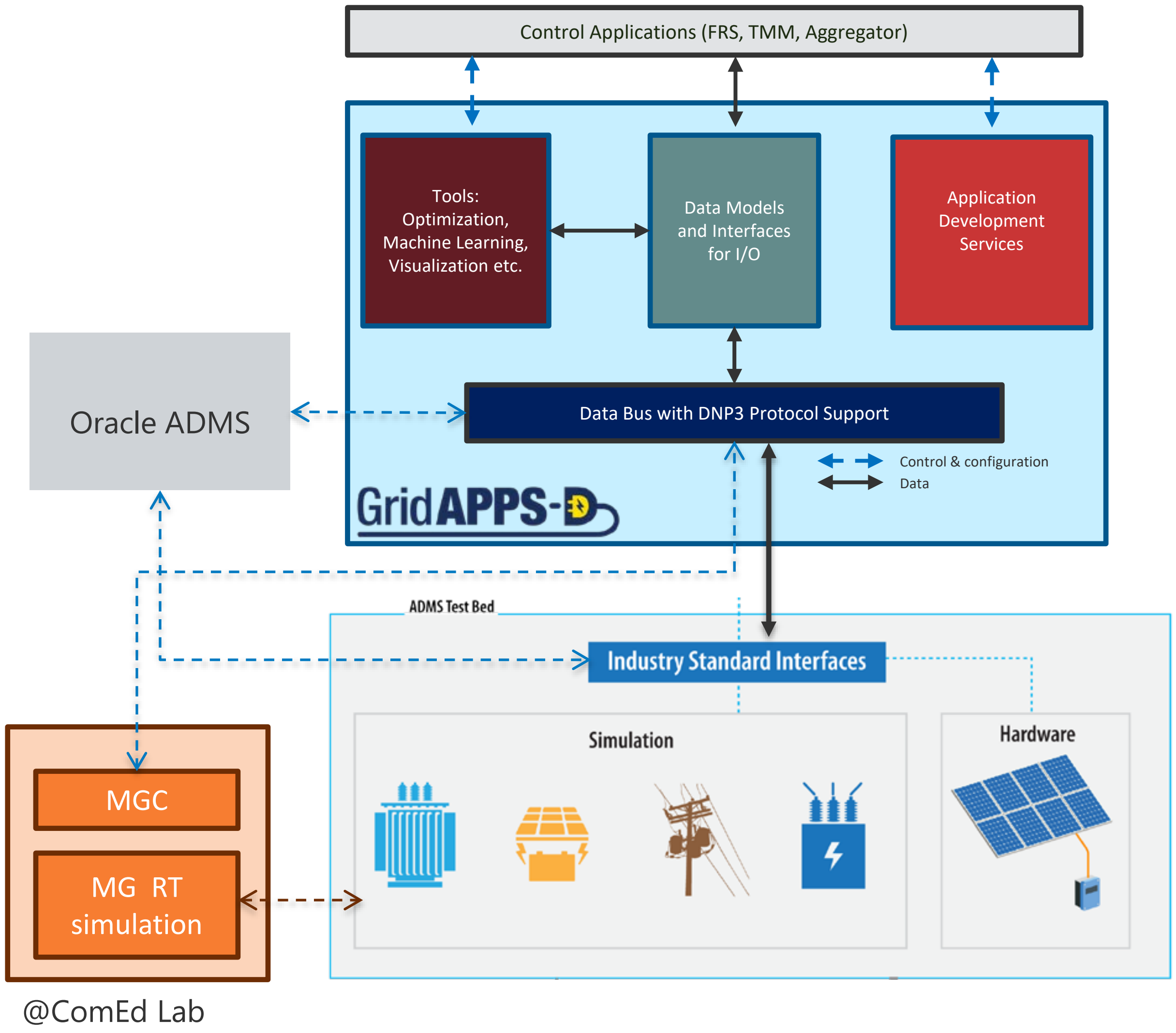
ADMS Test Bed and GridAPPS-D Platform Integration for FAST-DERMS Validation

- The ADMS Test Bed emulates the utility environment.
- FAST-DERMS controls are implemented as applications on GridAPPS-D.
- Integrated with commercial (Oracle) ADMS.



RTAG as Transmission Simulator for T&D Co-Simulation

- Real-time analytics for bulk grid (RTAG) for transmission system simulation
- A control room type tool—easy to interface with real-time data
- Production-grade operational models containing the entire Western Interconnection elements.

Real-Time Transient Security Assessment Tool (TSAT)

Frequency monitoring, rotor angle stability, available transfer capability calculation

Replica of Full Energy Management System (EMS) Applications

SCADA, alarms, automatic generation control, network applications

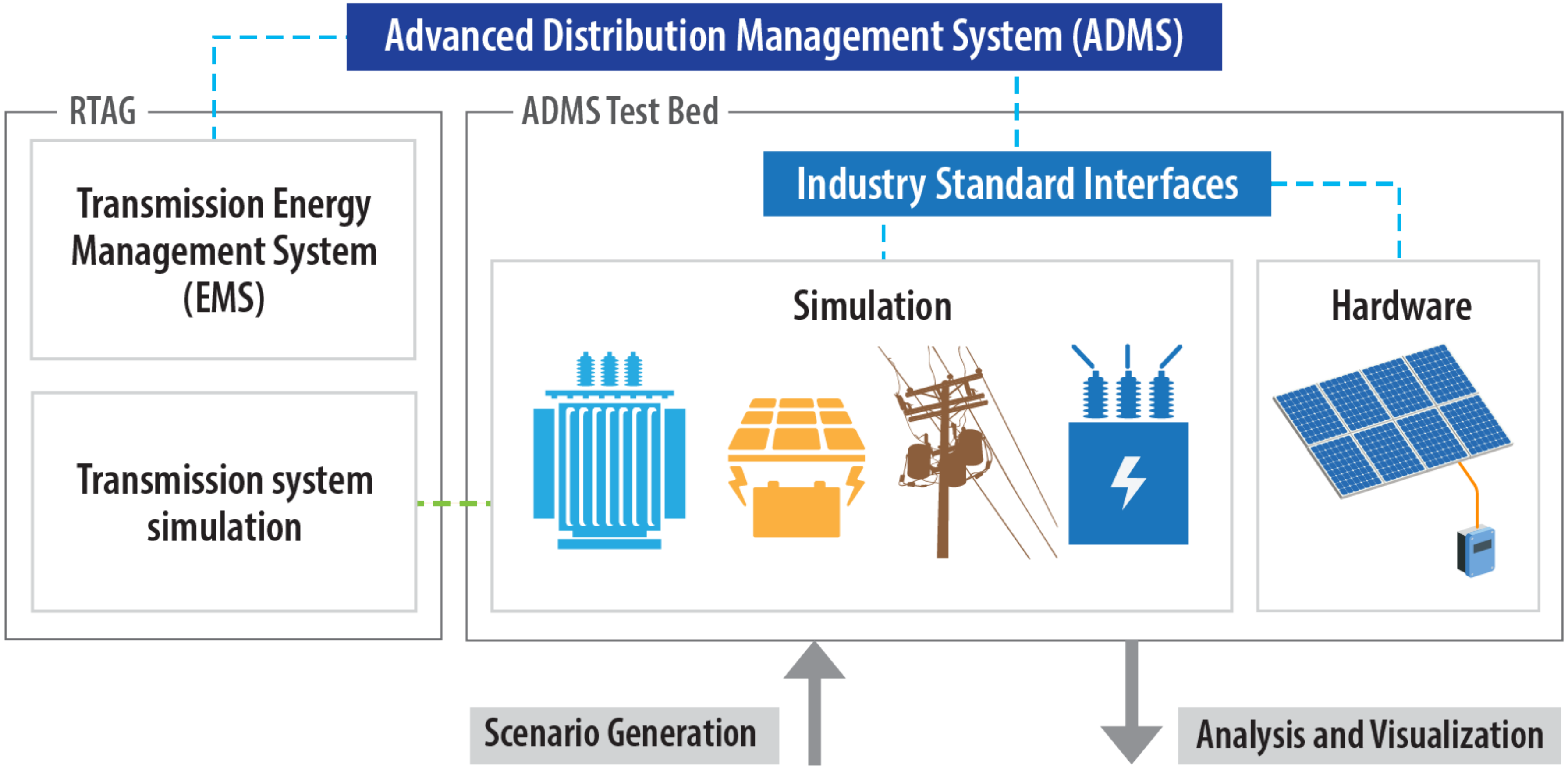
Dispatcher Training Simulator (DTS)

Simulation vs. replay

Power flow, prime movers, protective relays and events processor, etc.

ADMS Test Bed and RTAG Integration

- OpenDSS for distribution system simulation
- GridAPPS-D platform to integrate T&D simulators and host DER control algorithms.



Real-World Experience with Holy Cross Energy

Smart homes in Basalt, Colorado, demonstrate real-world operation of advanced controls.

Photos by NREL

See Kroposki et al. (2020b), https://spectrum.ieee.org/energy/the-smarter-grid/tomorrows-power-grid-will-be-autonomous.

Summary

- Successfully control large numbers of distributed assets to achieve objectives using AES.
- Grid architecture design to integrate AES
- Testing platforms for validation
- Extendable to diverse use cases and scenarios.

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Thank You

https://www.nrel.gov/grid/autonomous-energy.html

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