Market & Control Mechanisms Enabling Flexible Service Provision by Grid-Edge Resources within End-to-End Power Systems

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PSERC

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Presentation Outline

- **Background References**

- **Project Overview:** *T*ransactive *E*nergy *S*ystem (*TES*) design for *I*ntegrated *T*ransmission & *D*istribution (*ITD*) Systems

  —**Project Task 1:** Design *L*ocal *I*ntelligent *S*oftware *A*gents (*LISAs*) able to manage distribution-system resources

  —**Project Task 2:** Design a *D*istribution *S*ystem *O*perator (*DSO*) able to extract flexible services from distribution-system resources via a TES design based on a network of LISAs

  —**Project Task 3:** Develop/analyze methods allowing this DSO to submit power & ancillary service bids into an otherwise standard ISO-managed wholesale power market

  —**Project Task 4:** Develop a platform to aid evaluation of Task 1-3 work

- **Illustrative Test-Case Outcomes**

- **Conclusion:** Key innovative project aspects

Background References

[1] L. Tesfatsion (2018), "Electric Power Markets in Transition: Agent-Based Modeling Tools for Transactive Energy Support," Chapter 13 (pp. 715-766) in Cars Hommes and Blake LeBaron (Eds.), *Handbook of Computational Economics 4: Heterogeneous Agent Models*, Handbooks in Economics Series, Elsevier, Amsterdam, the Netherlands.

http://www2.econ.iastate.edu/tesfatsi/ElectricPowerMarketDesign.TESHandbookChapter.LTesfatsion.pdf

[2] A. G. Thomas and L. Tesfatsion (2018), "Braided Cobwebs: Cautionary Tales for Dynamic Pricing in Retail Electric Power Markets," *IEEE Transactions on Power Systems* 33(6), 6870-6882.

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[3] S. Ma, Z. Wang, and L.Tesfatsion (2018), "Swing Contracts with Dynamic Reserves for Flexible Service Management," *IEEE Transactions on Power Systems*, to appear.

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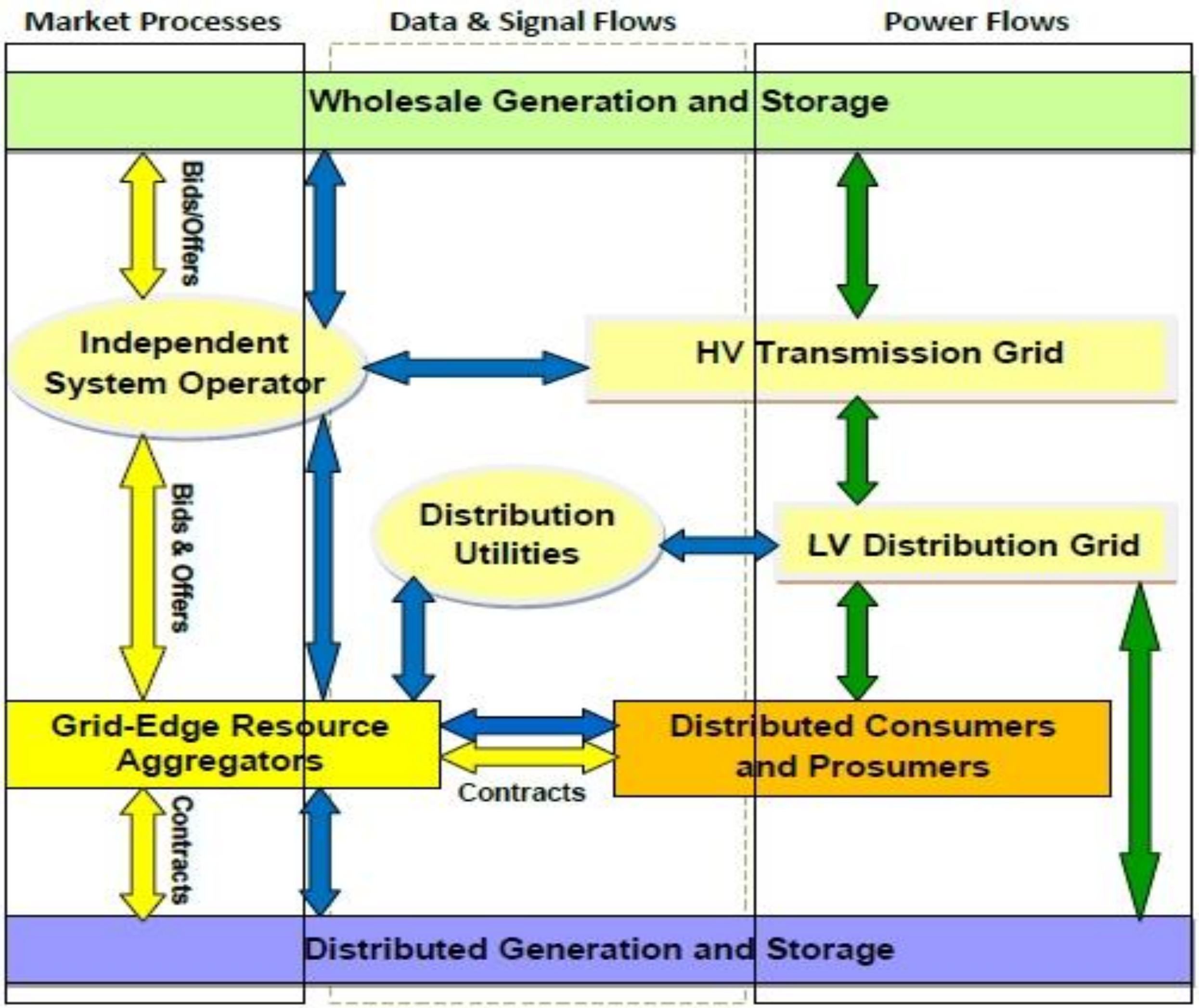
[4] H. Nguyen, S. Battula, R.R. Takkala, Z. Wang, L. Tesfatsion (2018), "An Integrated Transmission and Distribution Test System for Evaluation of Transactive Energy Designs," November 9th (journal-requested revision). Initial working paper version:

http://www2.econ.iastate.edu/tesfatsi/TESDesignITD.WP.ISUDigitalRepository.pdf

Project Overview

- Study of ***T***ransactive ***E***nergy ***S****ystem* ***(TES)*** designs for ***I***ntegrated ***T***ransmission & ***D***istribution (***ITD***) Systems



Defining Characteristics of a TES Design

- A collection of economic and control mechanisms;
- Permits supply and demand for power to be balanced over time across an entire electrical infrastructure;
- Enhances value for the transacting partners consistent with overall system reliability;
- Emphasis on decentralized designs, viewing power systems as societies of *grid-edge resources (GERs),* bulk generators, bulk storage, system operators, & other stakeholders.

Note: *G*rid-*E*dge *R*esource (*GER*) = Any resource with a direct point of connection to a distribution grid.

GER Examples: Households, commercial businesses, industrial plants, and any individual devices (e.g., wind turbines, storage devices, solar PV arrays, …) with direct distribution-grid connection (i.e., not behind-the-meter).

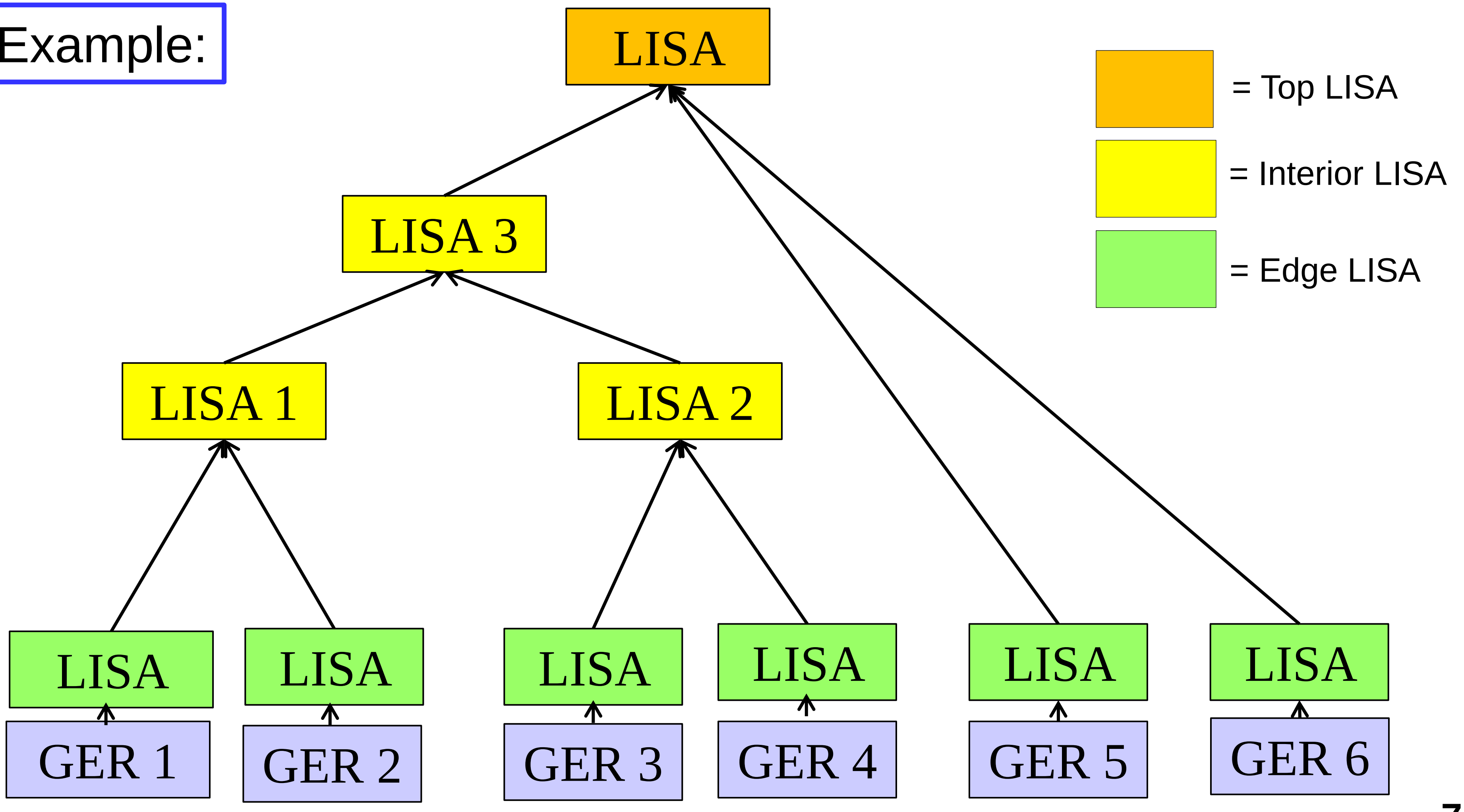
Intended Project Deliverables

- ***Scalable TES designs for ITD systems*** that enable
  - — extraction of flexible services from numerous & diverse locally-controlled GERs with appropriate compensation
  - — use of these services to enhance the performance of ITD system operations
- An open source ***ITD TES Platform*** to facilitate comprehensive performance evaluations of TES designs for ITD systems with respect to:
  - — *reliability & resiliency* of ITD system operations
  - — *efficiency* of ITD system operations (non-wastage of resources)
  - — *welfare* of all ITD system participants
  - — *robustness* against gaming & strategic manipulation

Project Task 1 … LISA Network

❑ **Task 1:** Design a network of *L*ocal *I*ntelligent *S*oftware *A*gents (*LISAs*) able to manage *G*rid-*E*dge *R*esources (*GERs*)

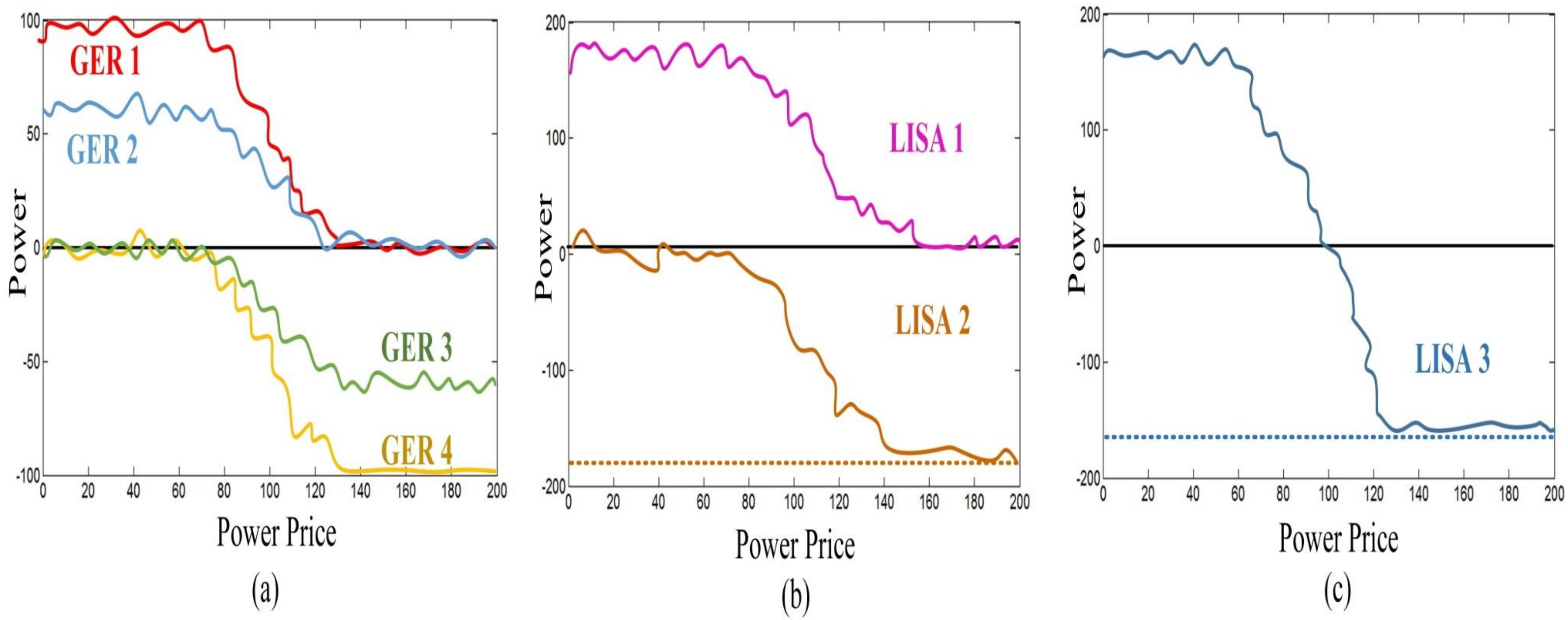
Example:



Project Task 1 … LISA Network Continued

- ***Edge LISAs*** manage individual GER bids for power usage and/or ancillary service provision

- ***Interior LISAs*** are GER aggregators, i.e., entities that aggregate the bids received from lower-level LISAs



The demand/supply bids of four individual GERs

Interior LISAs aggregate bids received from lower-level LISAs

Project Task 2 … DSO Design

- Design an independent ***D***istribution ***S***ystem ***O***perator (***DSO***) that operates at a T-D interface, as follows:

  - *The DSO participates in the transmission system* as a power procurer, power supplier, and/or provider of ancillary services;

  - *The DSO participates in the distribution system* as a top LISA in a network of LISAs (GER aggregators);

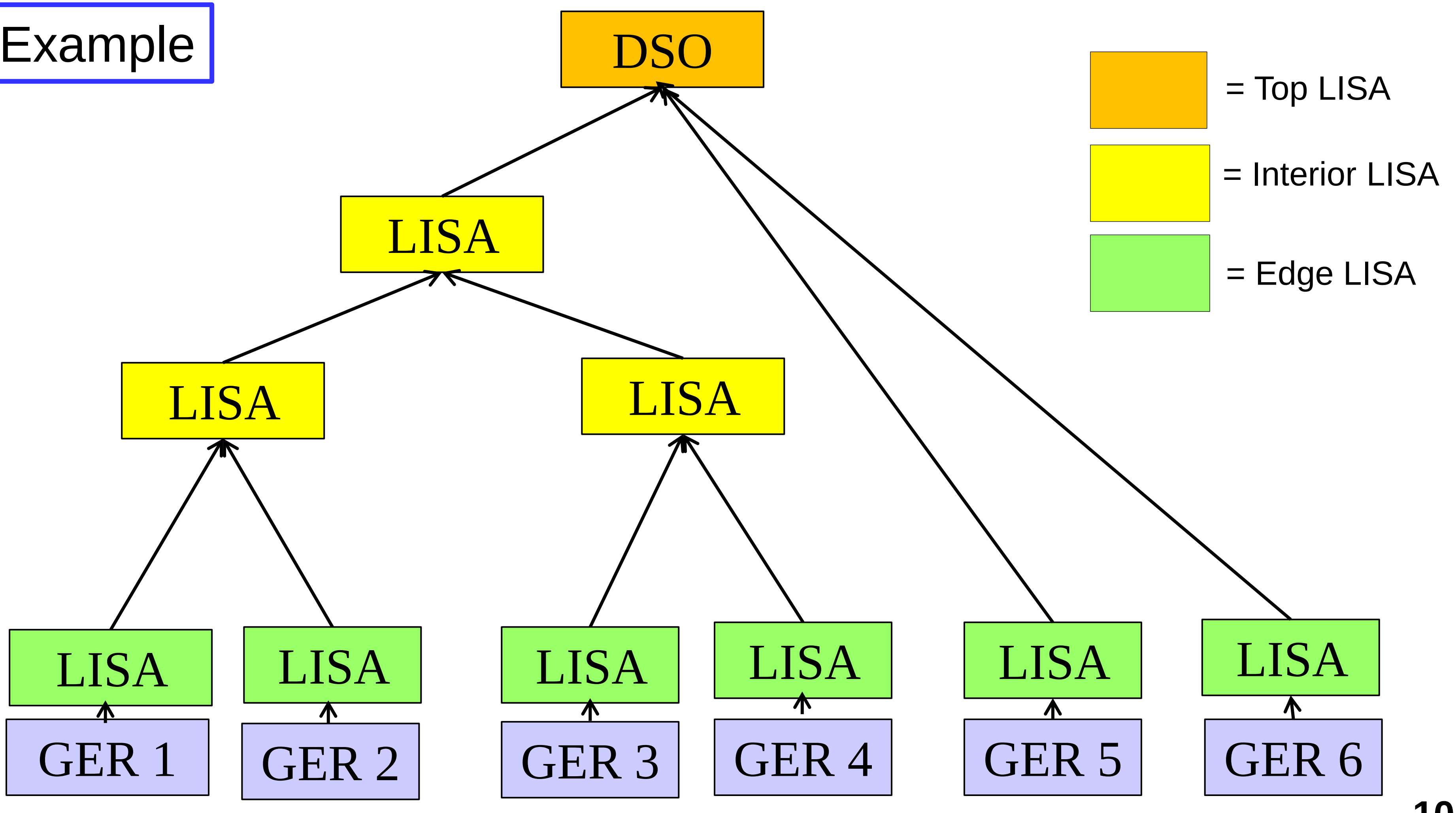
  - *The DSO is independent* in the sense it has no ownership or financial stake in T/D system operations.

  - *The fiduciary responsibilities of the DSO are to ensure:*
    - reliability & resiliency of distribution system operations
    - efficiency of distribution system operations
    - welfare of distribution system participants
    - robustness against gaming and strategic manipulation

Project Task 2 … DSO Design Continued

- The DSO is the top-level LISA in a network of LISAs (GER aggregators) for a distribution system

Example



Project Task 2 … DSO Design Continued

DSO Goal 1: Coordinate with distribution utilities to maintain the reliability and resiliency of distribution system operations.

DSO Goal 2: Maintain efficiency of distribution system operations by ensuring prices charged to GERs for power usage, and paid to GERs for generation and ancillary services, are properly aligned with costs and with individual GER valuations.

DSO Goal 3: Determine individual GER valuations by means of bid functions that (i) reflect local GER goals & constraints and (ii) maintain GER privacy.

DSO Goal 4: Maintain independent status of DSO by allocating back to GERs any non-zero net revenues (positive or negative) that the DSO incurs through its operations.

Project Task 3…DSO Upstream Participation

❑ Develop methods permitting the DSO to participate in standard U.S. ISO-managed wholesale power markets

- These methods should permit the DSO to operate as a ***prosumer*** able to:

1) procure power to meet conventional GER power usage needs;
2) provide power from GER generation facilities
3) provide ancillary services (power absorption, load absorption) harnessed from GERs with some degree of dispatchable flexibility in their power usage and/or power generation

- One possible method for 3) is ***"swing contracting"***.

Project Task 3 … Swing Contracting Continued

- A ***S*wing *C*ontract SC_m** offered into an ISO-managed market by a dispatchable resource *m* is a **complete blue-print for a collection PP_m of power paths**.

— Each power path in PP_m must be feasible for *m* to deliver at an SC_m designated location during an SC_m designated future operating period

— Resource *m* must be able to provide this delivery in response to ISO real-time electronically-signaled dispatch instructions.

— Power paths in PP_m can include positive regions (power generation) & negative regions (power usage/absorption)

Project Task 3 …Swing Contracting Continued

- SCs are ***two-part pricing contracts***

—The ***offer price*** requested by a resource *m* for an offered SC_m should *cover up front* any costs *m* would have to incur to ensure *service availability*.

Examples: Start-up, no-load, & lost opportunity costs

—The ***performance payment method*** included in SC_m should *cover ex post* any costs incurred by *m* for *service performance* in real-time operations.

Examples: Fuel costs, labor costs

A Simple Illustrative Swing Contract

$$\text{SC} = [b, t_s, t_e, \mathcal{P}, \mathcal{R}, \phi]$$

b = location where service delivery is to occur;

t_s = power delivery start time;

t_e = power delivery end time;

$\mathcal{P} = [P^{min}, P^{max}]$ = range of power levels p;

$\mathcal{R} = [-R^D, R^U]$ = range of down/up ramp rates r;

swing

ϕ = Performance payment method for real-time services.

- The above swing contract offers *swing (flexibility) in power levels & ramp rates* to facilitate net load balancing at the SC-designated location b during the SC-designated future operating period [t_s, t_e].

- The above swing contract is a “product” that an issuer can offer into a market in return for a requested *offer price*.

Numerical Swing Contract Example

b = bus b;

t_s = 8:00am;

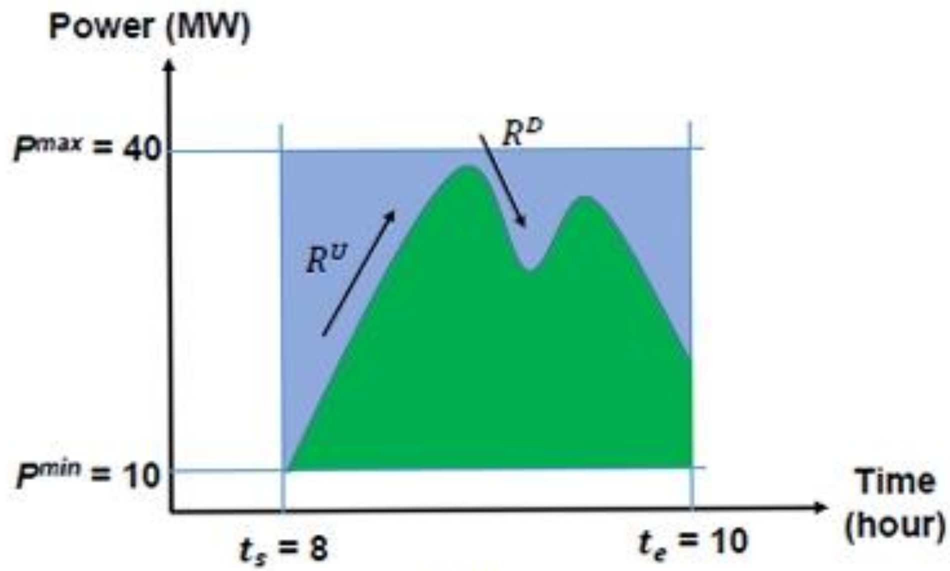
t_e = 10:00am;

$\mathcal{P} = [P^{min}, P^{max}] = [10\text{MW}, 40\text{MW}]$;

$\mathcal{R} = [-R^D, R^U] = [\text{-38MW/h}, \text{28MW/h}]$;

$\phi = \$35/\text{MWh}$.

(a)



(b)

(a) Swing contract with power & ramp-rate swing offered into a DAM at transmission bus b by a DSO for offer price π = \$100.

(b) Possible power path the ISO could signal the DSO to deliver during next-day operations, if the ISO clears swing contract (a).

NOTE: The **green region** in (b) denotes delivered energy that must be compensated ex post at \$35/MWh, in accordance with the swing contract's performance payment method ϕ.

Can a DSO submit swing contracts into an otherwise standard ISO-managed wholesale power market?

- **YES**

  — For example, a DSO can offer a swing contract (SC) into an otherwise standard Day-Ahead Market (DAM) or Real-Time Market (RTM).

  — SC offer prices & expected performance costs can be incorporated into the DAM/RTM objective functions.

  — SC-designated power-path attributes can be incorporated into the DAM/RTM constraints.

- **BUT …**

— *Accurate* merit-order dispatch will *not* result *unless* DAM/RTM objective functions correctly account for *all* remuneration paid to (or received from) DAM/RTM participants.

— Currently this is not the case.

— The ITD TES Platform to be developed in this project will include DAM/RTM SCUC/SCED optimization formulations whose objective functions more fully account for all DAM/RTM participant remuneration.

Another possibility: Switch to a full SC Market Design

- DAM Example: Standard Design vs. SC Design

		Standard DAM	SC DAM
Similarities		• Conducted day-ahead to plan for next-day operations • ISO-managed • Participants include LSEs & dispatchable energy resources • Subject to same system constraints: e.g. transmission, generation, ramping, & power-balance constraints	
Differences	• Optimization formulation	SCUC & SCED	Swing contract clearing
	• Settlement	Locational marginal pricing	Contract-determined prices
	• Payment	Payment for next-day service before actual performance	Payment for availability now & performance ex post
	• Out-of-market payments	Make-whole payments (e.g., for unit commitment)	No out-of-market payments
	• Info released to participants	UC, DAM LMPs, & next-day dispatch schedule	Which swing contracts have been cleared

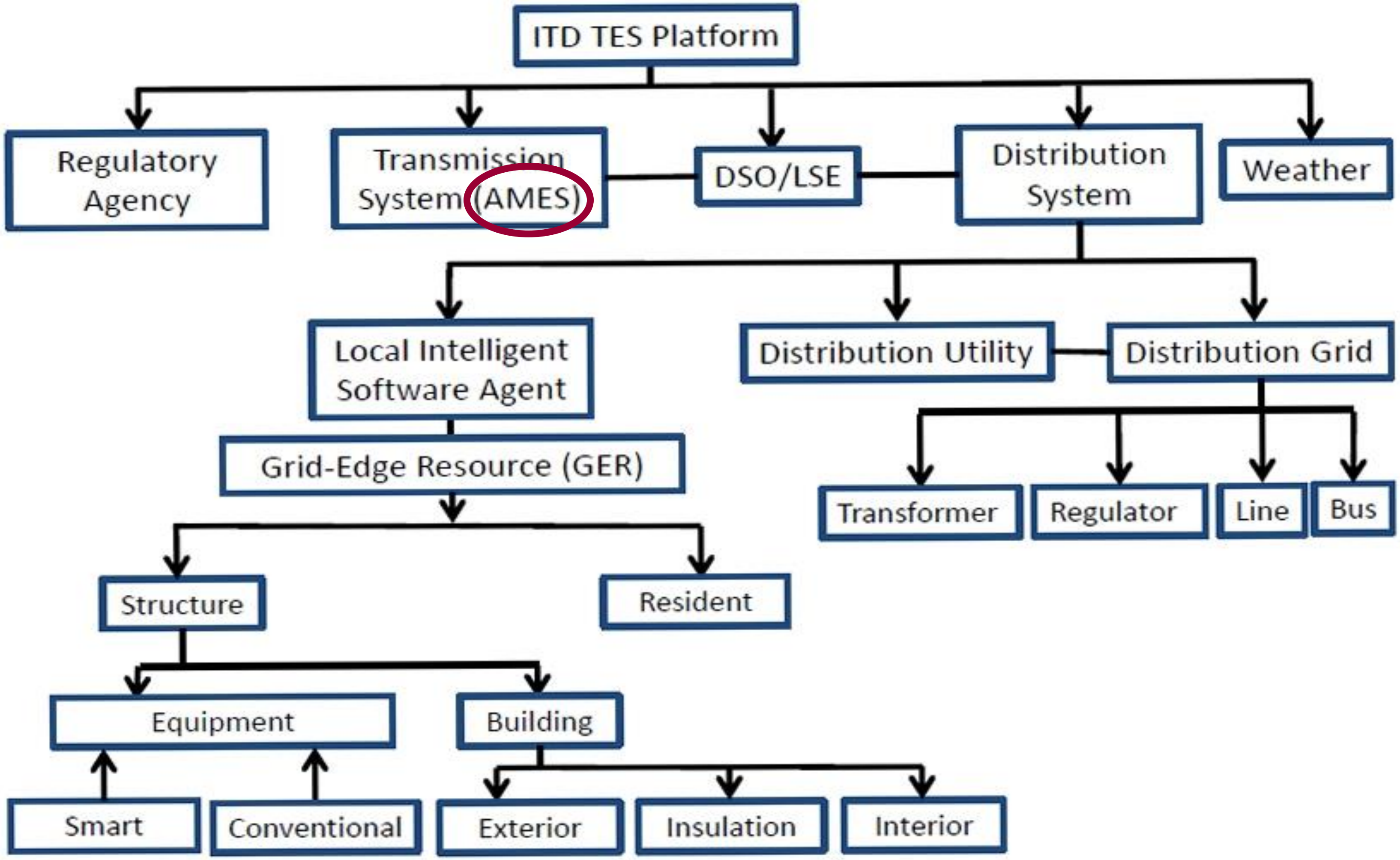
Another possibility: Switch to a full SC Market Design … Continued

- DAM Example: Standard Optimization vs. SC Optimization

		Standard DAM SCUC	Standard DAM SCED	SC DAM Optimization
Similarities		• Both SCUC and swing contract (SC) clearing are solved as mixed integer linear programming (MILP) problems subject to system and reserve constraints		
Differences	• Objective	Min [Start-up /shut-down costs + no-load costs + dispatch costs + reserve costs]	Min [Dispatch costs + reserve costs]	Min [Offer cost + expected performance cost + expected imbalance cost]
	• Start-up & shut-down constraints	Yes	No	Start-up/shut-down constraints are implicit in submitted swing contracts
	• Key decision variables	Unit Commitment vector	Energy dispatch & reserves	Which swing contracts are cleared
	• Settlement	No	LMPs calculated as SCED dual variables	Offer prices paid for cleared swing contracts

Project Task 4 … ITD TES Platform

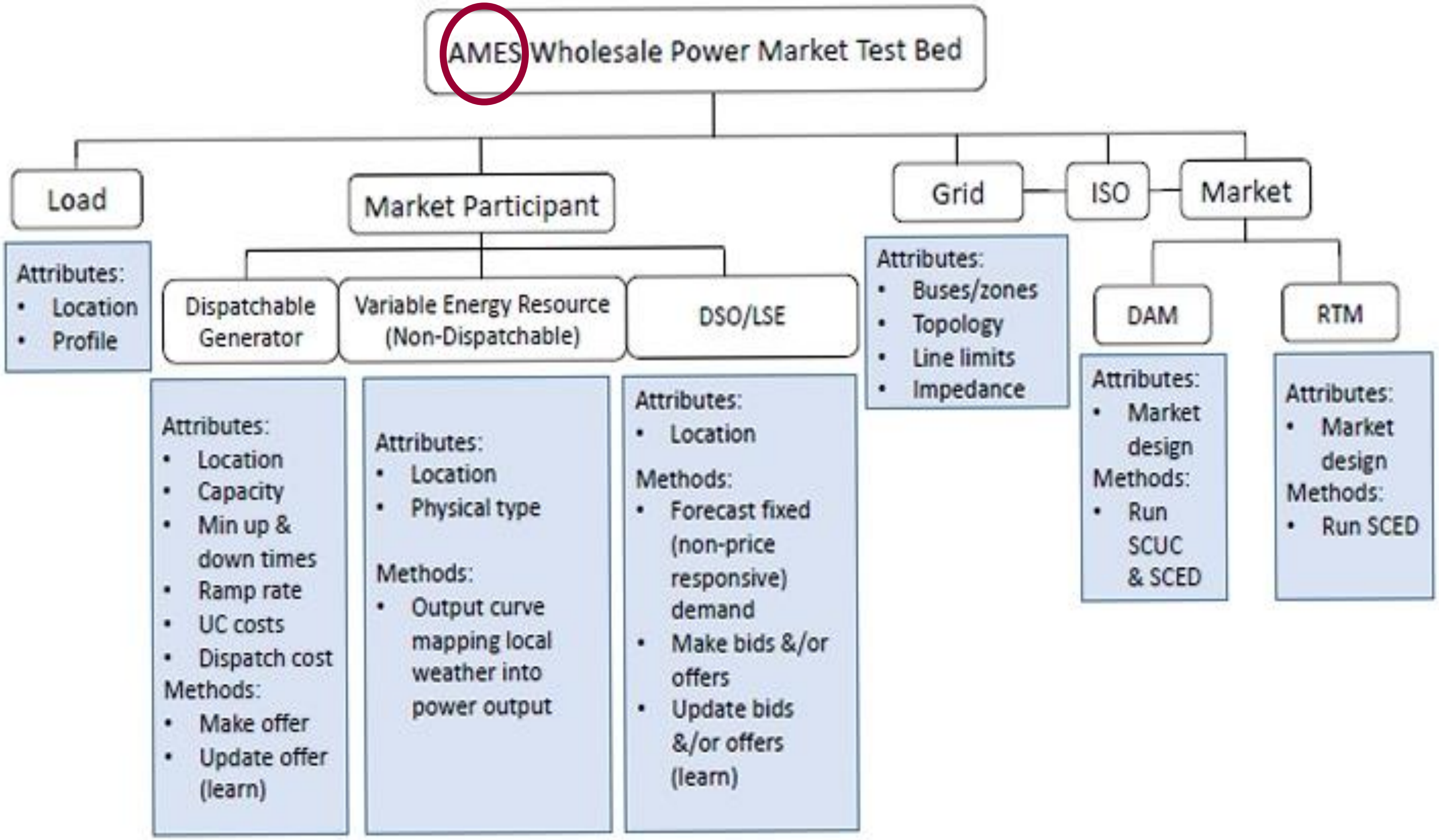
- Develop a platform to aid evaluation of Task 1-3 work



Partial agent taxonomy for ITD TES Platform (V2.0), a *major extension* of the ITD TES Platform (V1.0) reported in our earlier work **[4]**

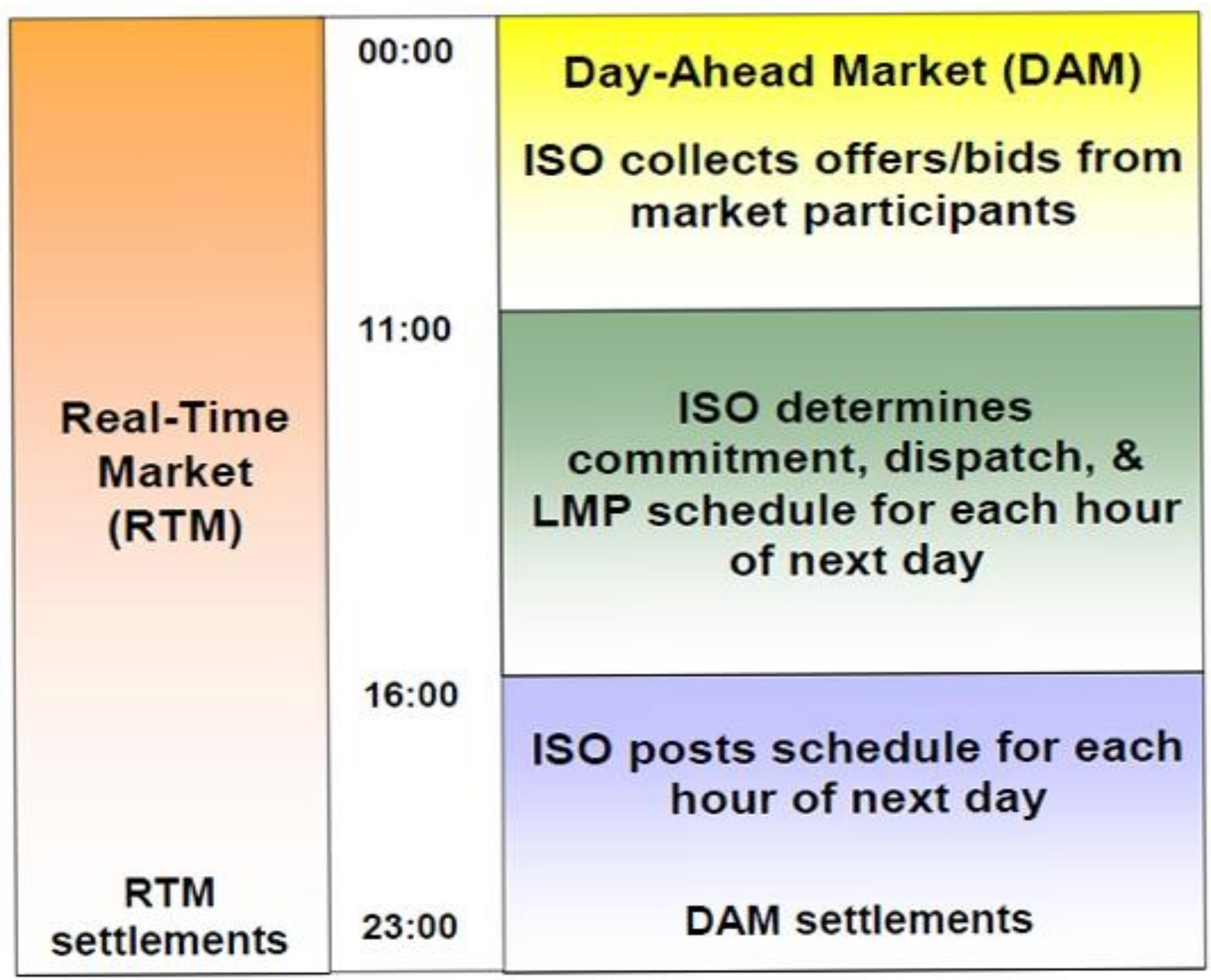
Project Task 4 … ITD TES Platform Continued

- Transmission System for ITD TES Platform (V2.0), implemented by means of ***A***gent-based ***M***odeling of ***E***lectricity ***S***ystems (***AMES***), Version 5.0



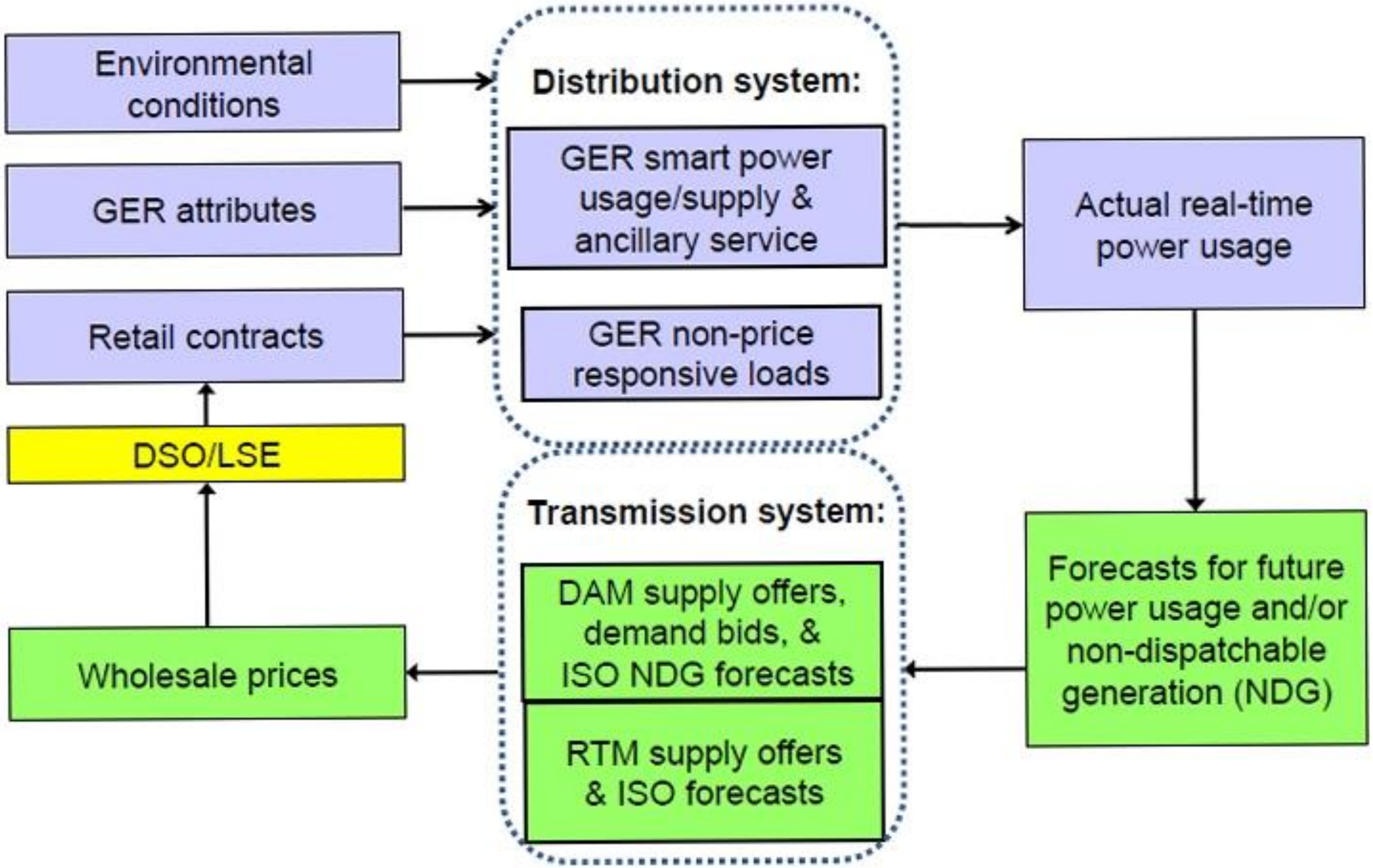
Project Task 4 … ITD TES Platform Continued

- AMES (V5.0) models daily market operations in U.S. ISO/RTO-managed wholesale power markets



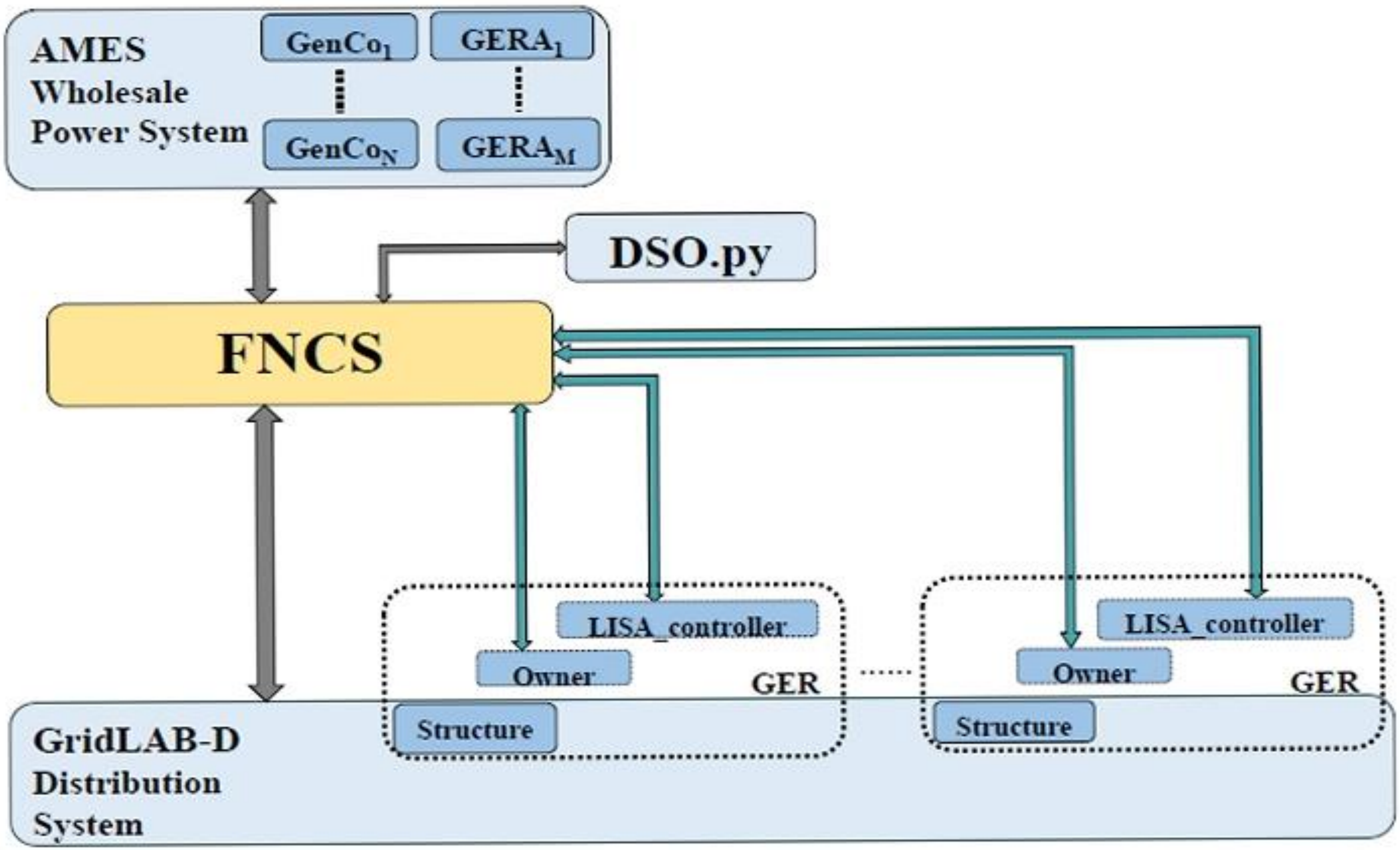
Project Task 4 … ITD TES Platform Continued

- Flow diagram depicting the T-D feedback loop in ITD TES Platform (V2.0)



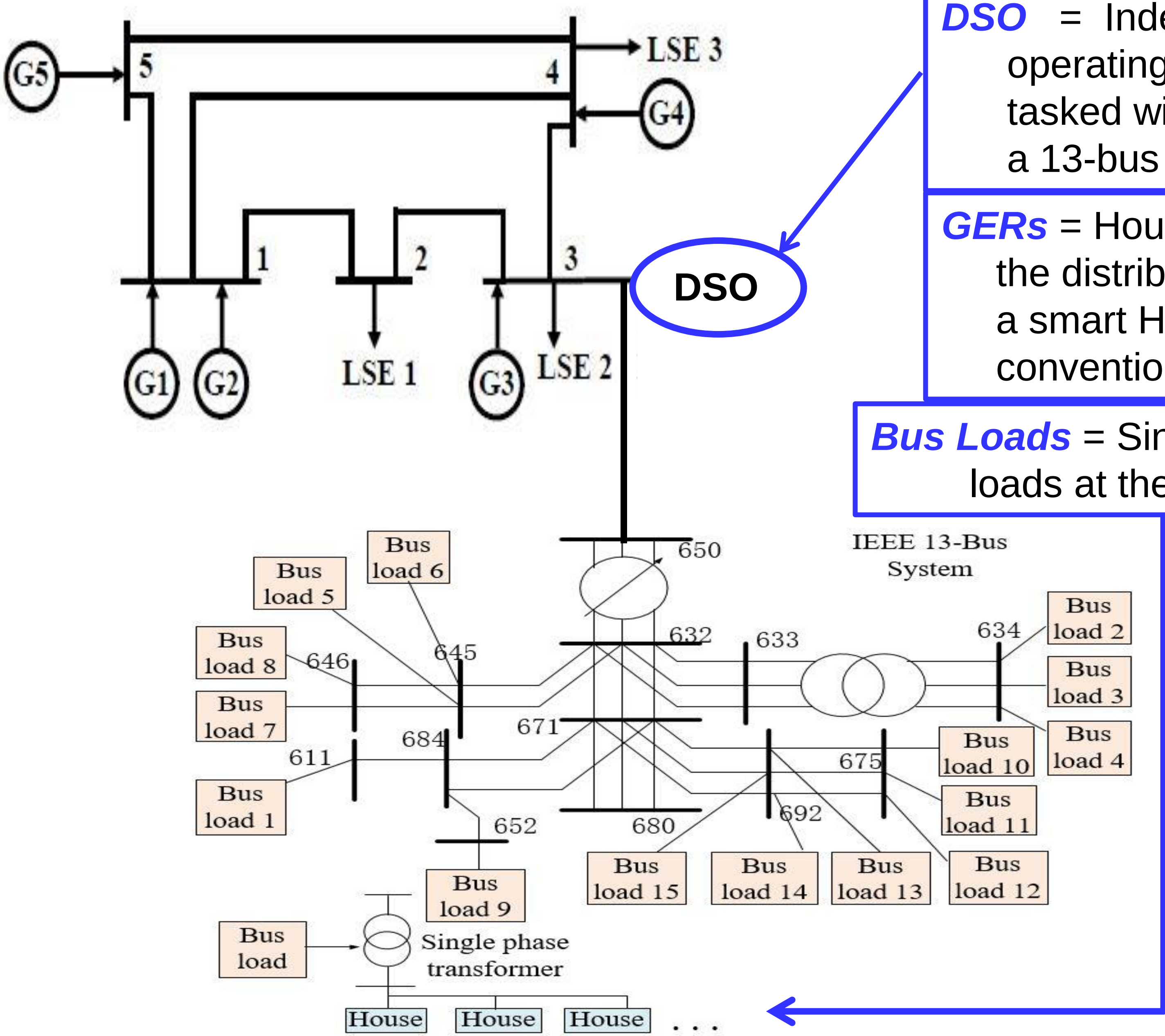
Project Task 4 … ITD TES Platform Continued

- Key Software Components for the ITD TES Platform (V2.0)



Note: ***FNCS*** = PNNL's ***F***ramework for ***N***etwork ***C***o-***S***imulation

Illustrative Test-Case Outcomes: ITD TES Platform (V1.0)



DSO = Independent entity operating at T-D interface tasked with management of a 13-bus distribution system

GERs = Households connected to the distribution grid, each with a smart HVAC system plus conventional loads

Bus Loads = Single-phase household loads at the 13 distribution buses

DSO Implements a **Five-Step PowerMatcher TES Design**

for a LISA network = {DSO, collection of edge LISAs}

Step 1: Each edge LISA (smart HVAC system controller) collects data about its household at a *data check rate*

Step 2: Each edge LISA sends a state-conditioned household bid for power usage and/or ancillary service provision to the DSO at a *bid refresh rate*

Step 3: DSO aggregates bids at an *aggregate bid refresh rate*

Step 4: DSO uses aggregate bids to determine a price signal consistent with DSO goals & communicates this price signal back to edge LISAs at a *price signal rate*

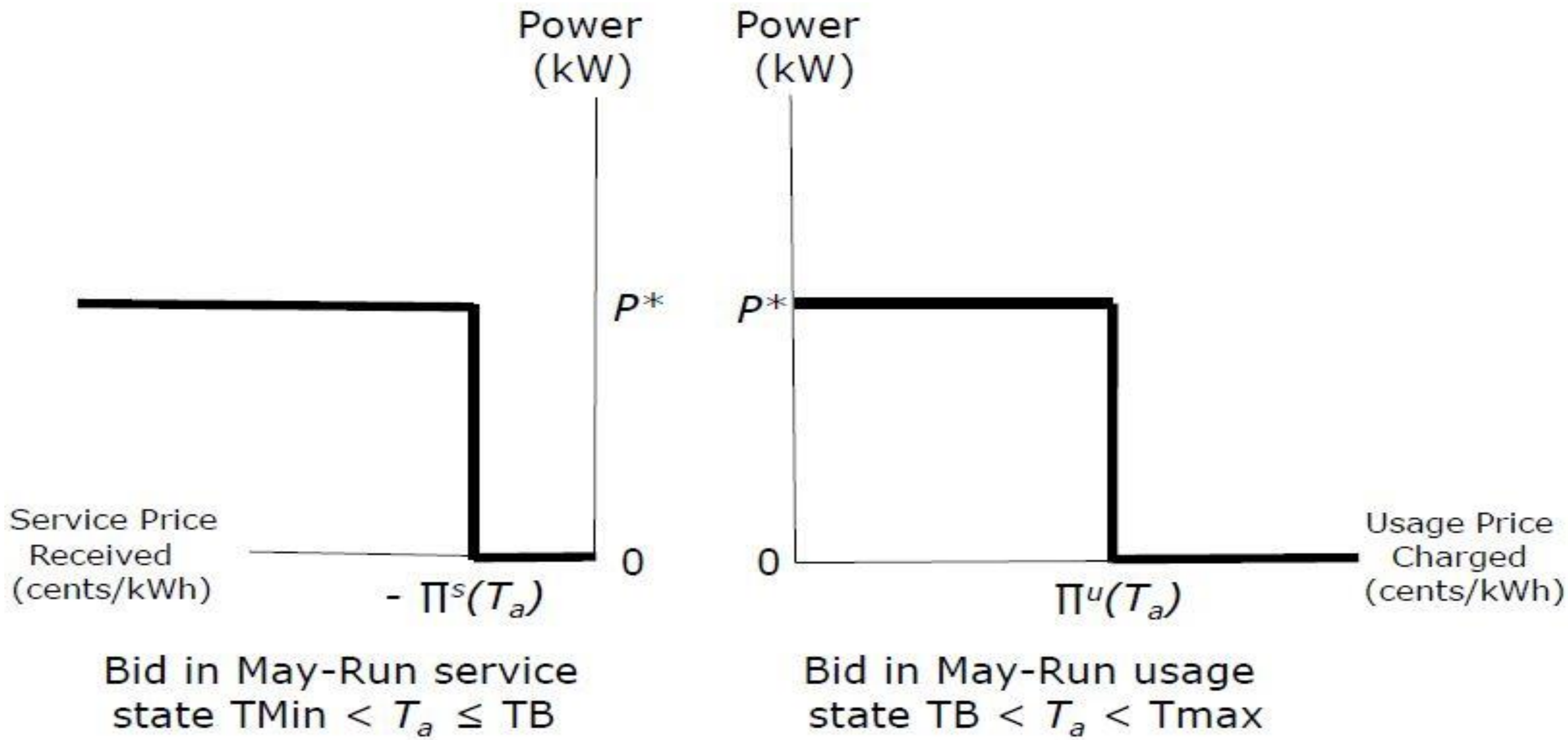
Step 5: Each edge LISA inputs this price signal into its latest refreshed household bid at a *power control rate*, which triggers a power response from the household's HVAC system.

State-Conditioned Household Bid Formulation for an HVAC System Running in Cooling Mode

$T_a(t)$ = House inside air temperature at time t

Tmin,Tmax = Acceptable min/max limits for $T_a(t)$

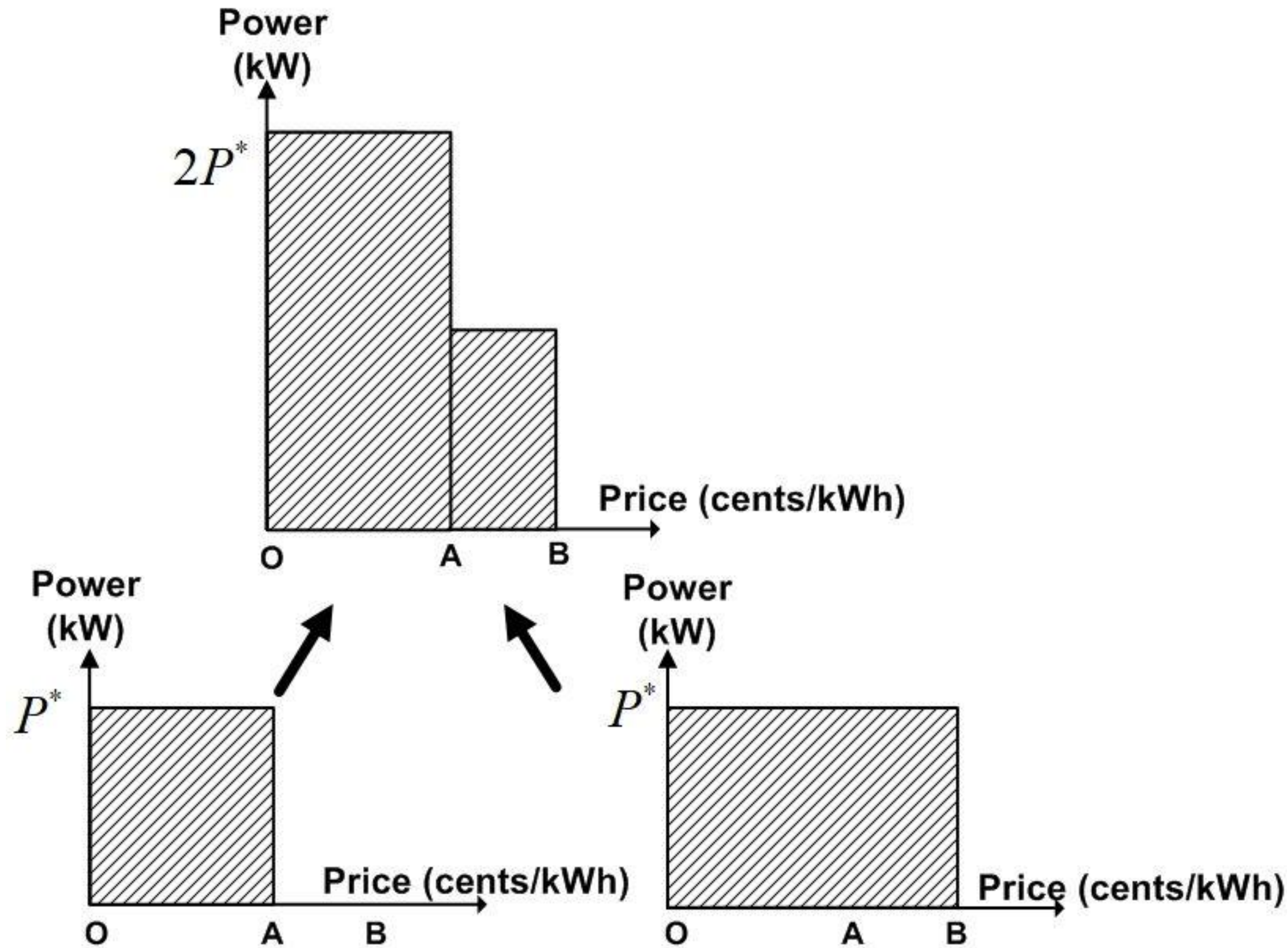
TB = Bliss value for $T_a(t)$



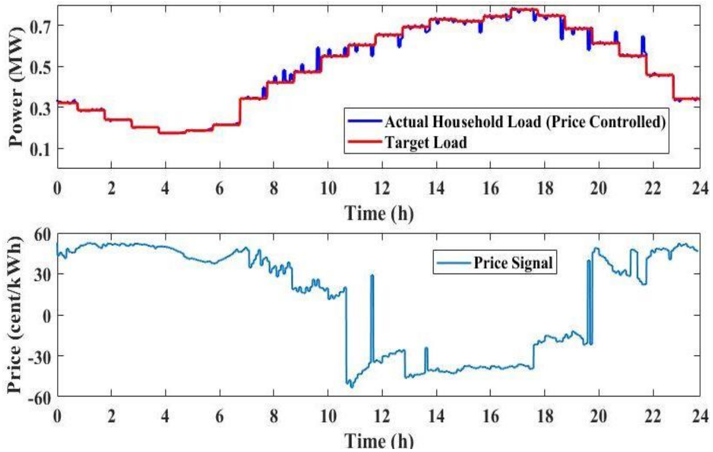
Ancillary Service Offered

Power Usage Demanded

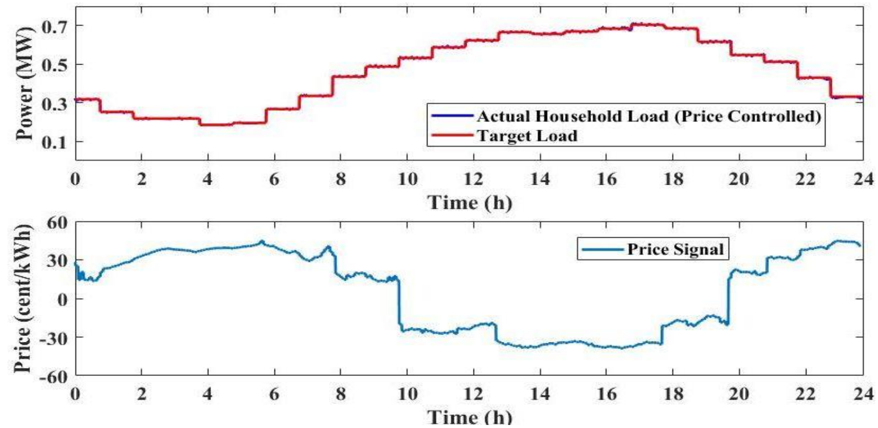
DSO Aggregation of Household Bids



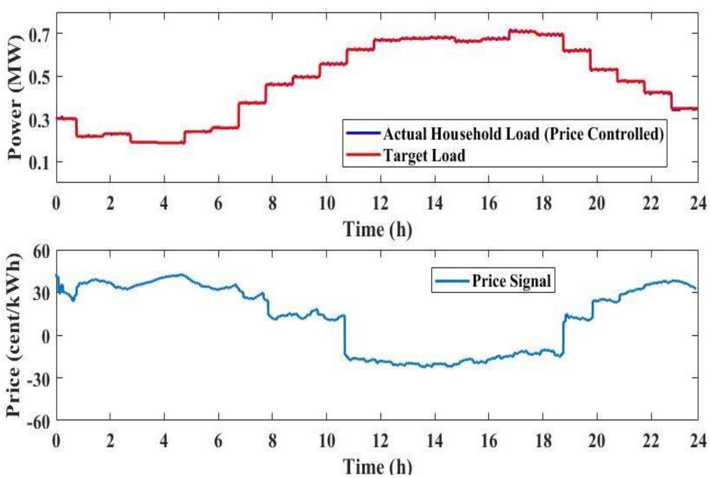
Load-Matching Test Cases: DSO implements the Five-Step PowerMatcher TES Design with a load-matching goal



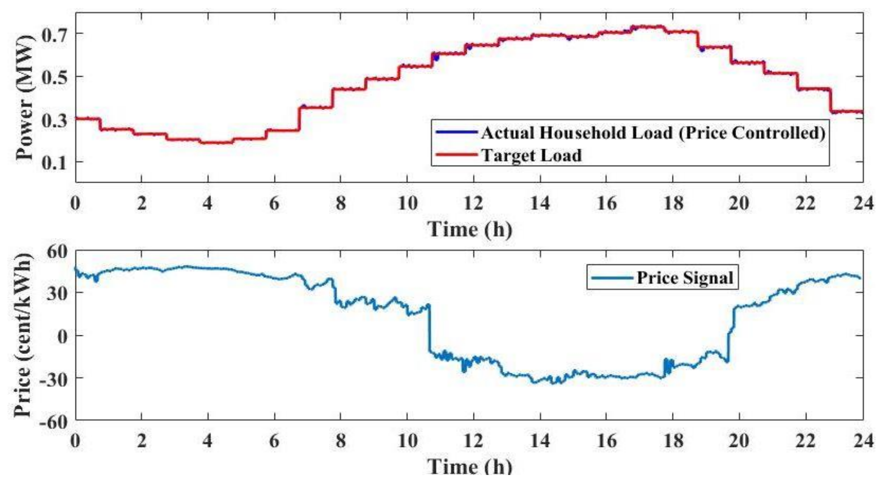
100% Low-Quality Houses



100% Medium-Quality Houses



100% High-Quality Houses



(1/3,1/3/1/3) House Quality Mix

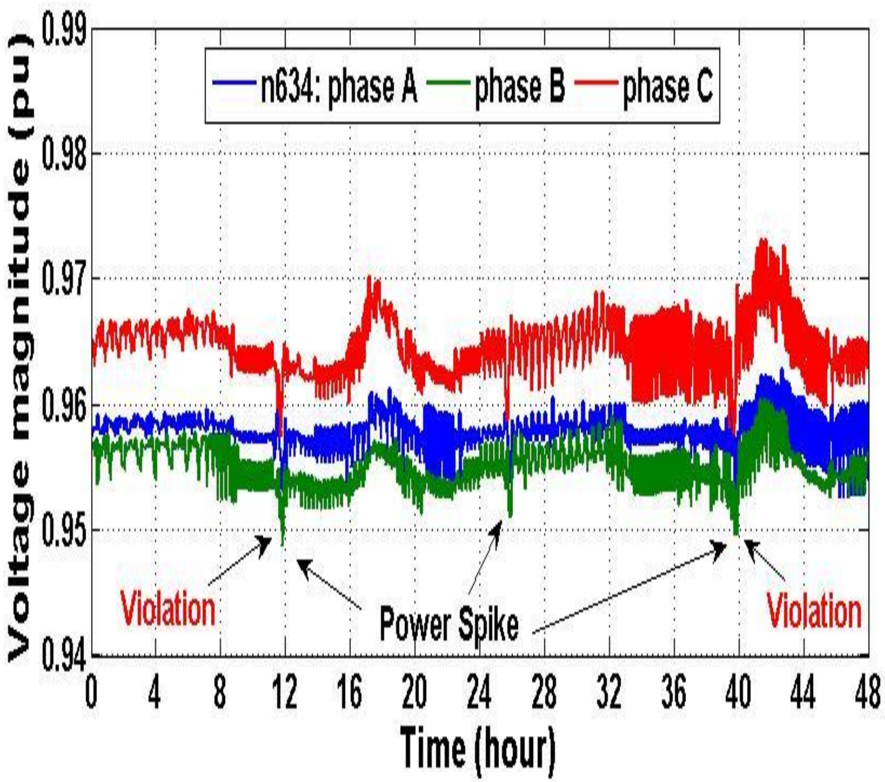
Welfare/Reliability ITD Test Cases: DSO implements Five-Step PowerMatcher TES Design with welfare & reliability goals

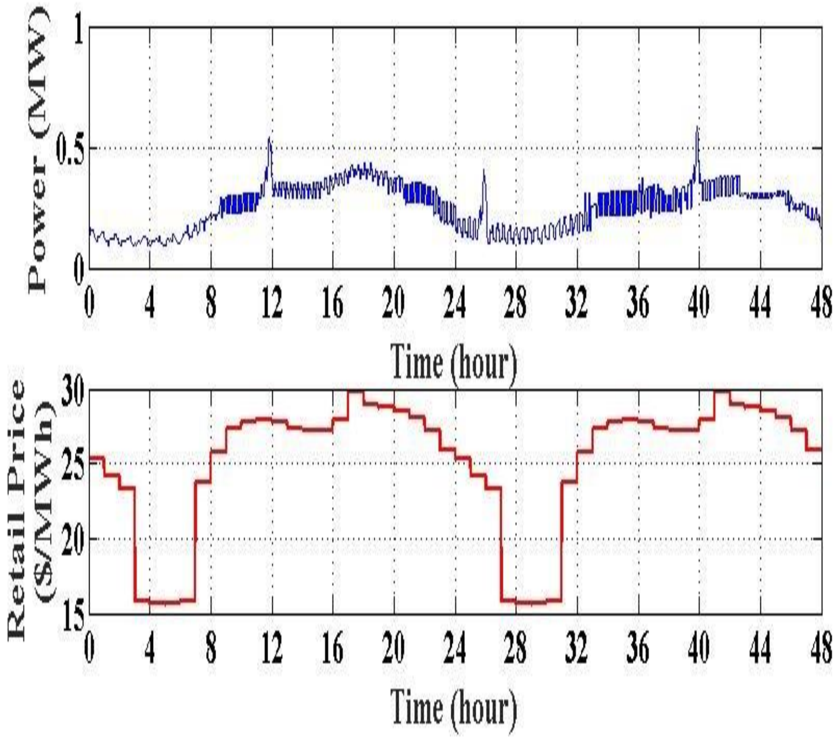
Case	NH	$\widehat{\theta}^u$ (\$/MWh)	CM^{AvH} (Utils/hr)	NEP^{AvH} (\$/hr)	A^{AvD} (\$/day)
1	180	1	1.17	0.0060	-0.0278
2	180	40	1.34	0.0062	-0.0280
3	180	80	1.44	0.0064	-0.0283
4	180	10,000	1.47	0.0065	-0.0287
5	360	1	1.17	0.0060	-0.0300
6	360	40	1.34	0.0062	-0.0305
7	360	80	1.44	0.0063	-0.0311
8	360	10,000	1.47	0.0065	-0.0323

Welfare outcomes: Welfare metrics averaged over two successive days. DSO submits agg. household load forecasts into day-ahead market (DAM) and sends retail price signals back to households based on past DAM LMPs.

NH=#Households, CM=Comfort; NEP=Net Energy Payment; A=DSO allocation

Welfare/Reliability ITD Test Cases...Continued





Reliability Outcomes: Phase voltage magnitudes (distribution bus 634), retail prices, & aggregate household power usage over 2 successive days, given DSO target voltage magnitude limits [0.95pu, 1.05pu] used for *feedback* volt/VAR control.

ITD Test Cases: Reliability Outcomes…Continued

Upper/lower limit violations for phase p at bus b = 634

% voltage imbalance across phases at bus b = 634

(a) Voltage Magnitude Limits: $0.90\text{pu} \leq V \leq 1.10\text{pu}$

Bus	Metrics	Phase A	Phase B	Phase C
634	$V_{b,p}^{\text{hi}}/V_{b,p}^{\text{lo}}$	0/0	0/0	0/0
	$\%\text{VIB}_b$		**0.86%**	
675	$V_{b,p}^{\text{hi}}/V_{b,p}^{\text{lo}}$	0/0	0/0	0/0
	$\%\text{VIB}_b$		**1.27%**	

(b) Voltage Magnitude Limits: $0.95\text{pu} \leq V \leq 1.05\text{pu}$

Bus	Metrics	Phase A	Phase B	Phase C
634	$V_{b,p}^{\text{hi}}/V_{b,p}^{\text{lo}}$	0/0	0/**0.0012**	0/0
	$\%\text{VIB}_b$		**0.14%**	
675	$V_{b,p}^{\text{hi}}/V_{b,p}^{\text{lo}}$	0/0	0/0	0/0
	$\%\text{VIB}_b$		**2.01%**	

Findings: Voltage limit violations and imbalance can occur.

Indication: It would be prudent to augment the Five-Step PowerMatcher TES Design with additional volt/VAR controls.

Future Research Direction: Bid-based TES designs permit DSO to make use of *pro-active* volt/VAR controls.

Conclusion: Key Innovative Project Aspects

- Our proposed ***T***ransactive ***E***nergy ***S***ystem (***TES***) research focuses on scalable hierarchical grid-edge resource aggregation methods that place equal emphasis on economic and control concerns.

- The TES designs to be formulated and analyzed in this project are intended for ***I***ntegrated ***T***ransmission and ***D***istribution (***ITD***) system operations.

- Our ITD TES Platform will aid comprehensive ITD performance evaluation of TES designs with regard to reliability, resiliency, efficiency, welfare, & robustness.