IOWA STATE UNIVERSITY

Department of Electrical & Computer Engineering

Transactive Energy System Design for Integrated Transmission and Distribution Systems

PhD Final Oral Examination
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Outline

- ❑ Overview of Thesis Research
- ❑ Review of Related Literature
- ❑ Research Objectives and Approach
- ❑ Research Completed
- ❑ Research Contributions: Summary
- ❑ Conclusion
- ❑ References (*With Some Edits/Updating by L. Tesfatsion, 30 Oct 2023*)

Overview of Thesis Research: Motivation

- Why study ***Integrated Transmission and Distribution (ITD)*** systems?
  - Increasing penetration of variable energy resources in both transmission and distribution systems
  - Increasingly active demand-response participation by distributed resources in transmission system operations
  - Ensuring continual balance of grid supply & demand is increasingly challenging
  - Design changes thus needed at both transmission and distribution levels

- Why develop ***Transactive Energy System (TES)*** designs?
  - TES designs are collections of hybrid economic-control mechanisms for power systems that permit a balancing of power demands and supplies via value-based transactions, consistent with system reliability
  - TES designs use economic incentives to encourage and support efficient demand-side participation, subject to system reliability constraints

- Need for an ITD platform permitting ***efficiency and reliability performance evaluation*** of ITD TES designs in advance of implementation

Overview of Thesis Research: Scope

Transmission System

- AMES V5.0 Platform for performing DAM and RTM operations. Used for:
- ERCOT Test System - Transmission component for ITD test cases

Distribution System

- Household model: Permits bid-based TES design participation
- Distribution system model: LV grid populated by households

Integrated Transmission and Distribution (ITD) System

- Modeling of an IDSO functioning as a T-D linkage agent
- Formulation of a new IDSO-managed TES design for ITD systems
- Dynamic successive-day modeling of ITD operations
- Modification of wholesale power market implementation in AMES V5.0 platform to permit IDSO market participation
- Development of an ITD TES Platform permitting careful evaluation of TES designs

AMES: Agent-Based Modeling of Electricity Systems; **IDSO:** Independent Distribution System Operator; **DAM**: Day-Ahead Market; **RTM**: Real-Time Market; **ERCOT**: Electricity Reliability Council of Texas

Overview of Thesis Research: Contributions (Refs. [1-9])

Transmission System

- **S. Battula**, L. Tesfatsion, and T.E. McDermott (2020). “An ERCOT Test System for Market Design Studies,” *Applied Energy*, Vol. 275, October, 115182. [2]
- L. Tesfatsion and **S. Battula** (2020). “Analytical SCUC/SCED Optimization Formulation for AMES V5.0,” AMES V5.0 Documentation, Working Paper #20014, ISU Digital Rep. [5]
- **S. Battula** and L. Tesfatsion (2020). *AMES V5.0 GitHub Code/Data Repository*. https://github.com/ames-market/AMES-V5.0 [7]
- **S. Battula**, L. Tesfatsion, and T.E. McDermott (2020). *ERCOT Test System Code/Data Repo.* https://github.com/ITDProject/ERCOTTestSystem [8]

ITD System

- **S. Battula**, L. Tesfatsion, and Z. Wang (2020). “A Customer-Centric Approach to Bid-Based Transactive Energy System Design,” *IEEE Transactions on Smart Grid*, 11(6), 4996-5008. [1]
- **S. Battula**, L. Tesfatsion, and Z. Wang (2020). “IDSO managed bid-based TES design for linked market operation of ITD systems,” *in preparation*. [4]
- H.T. Nguyen, **S. Battula**, R.R. Takkala, Z. Wang, L. Tesfatsion, “An ITD Test System for Evaluation of TES Designs,” Applied Energy, Vol. 240, 666-679. [3]

Distribution System

- L. Tesfatsion and **S. Battula** (2020). “Notes on the GridLAB-D Household Equivalent Thermal Parameter Model,” ITD TES Platform V2.0 Documentation, Econ Working Paper #19001, ISU Digital Rep., July revision. [6]
- **S. Battula** and L. Tesfatsion (2020). *ITD Project/Household Formulation (Python): Code/Data Repository*. https://github.com/ITDProject/HouseholdFormulationRepository [9]

Review of Related Literature

Category	Sub-Category	Literature
Day-Ahead & Real-Time Market Operations over an HV Transmission Grid	Simulation Platform, Conceptual Design	AMES Wholesale Power Market Test Bed [10], MATLAB [11], Linked Swing-Contract Market Design [12]
Retail Market Operations	Simulation Platform	Huang et al. (2018), Ref. [13]
	Conceptual	Fuller et al. (2011), Hao et al. (2016), Nazir and Hiskens (2017), Ramdaspalli et al. (2016), Adhikari et al. (2016), Behboodi et al. (2016), Hu et al. (2016), Koen Kok (2013); Refs. [14-22]
Integrated Transmission & Distribution (ITD) System Operations	General Overview	Rahimi and Albuyeh (2016), Ref. [23]
	Modeled Day-Ahead ITD operations	Parandehgheibi et al. (2017), Renani et al. (2017), Lezama et al. (2018); Refs. [24-26]
	ITD TES design, one-way communication	Thomas and Tesfatsion (2018), Ref. [27]
	ITD TES Platform V1	Nguyen, Battula et al. (2019), Ref. [3]

Review of Related Literature … Continued

Category		Literature	Brief Description
TCL* Control	Direct Control	Wu (2018), Ning Lu (2012, 2013), Zhang (2013); Refs. [28-31]	No attention is paid to benefit obtained or lost due to thermal comfort
	Price Based Control	Nguyen et al. (2019), Fuller et al. (2011), Nazir and Hiskens (2018), Kok (2013); Refs. [3, 14, 16, 18]	Different variants of linear bid functions, e.g., bid value based on average retail price, proportional difference between actual and desired temperature levels, etc., are proposed. These bid function forms are justified based on general heuristic grounds.
		Li et al. (2015), Radaideh (2017); Refs. [32-33]	Benefit obtained due to thermal comfort is taken into consideration. However, bid function is not optimally derived.

*TCL – Thermostatically Controlled Load

Research Objectives and Approach

Formulate an IDSO-managed bid-based TES design for ITD systems; Develop and use an ITD TES platform to evaluate design performance by means of empirically-based test cases

- Approach: Steps involved
  - Construct an ***Independent Distribution System Operator (IDSO)*** as a T-D linkage agent
  - Develop a bid-based IDSO-managed ***Transactive Energy System (TES) design*** for a distribution system
  - Model distribution system ***Grid-Edge Resources (GERs)*** as TES design participants operating to meet their local goals
  - Develop an ITD TES platform for TES design evaluation
  - Develop test cases for TES design evaluation, using the Electric Reliability Council of Texas (ERCOT) energy region as the principal empirical anchor
  - Conduct systematic test cases and analyze test case results

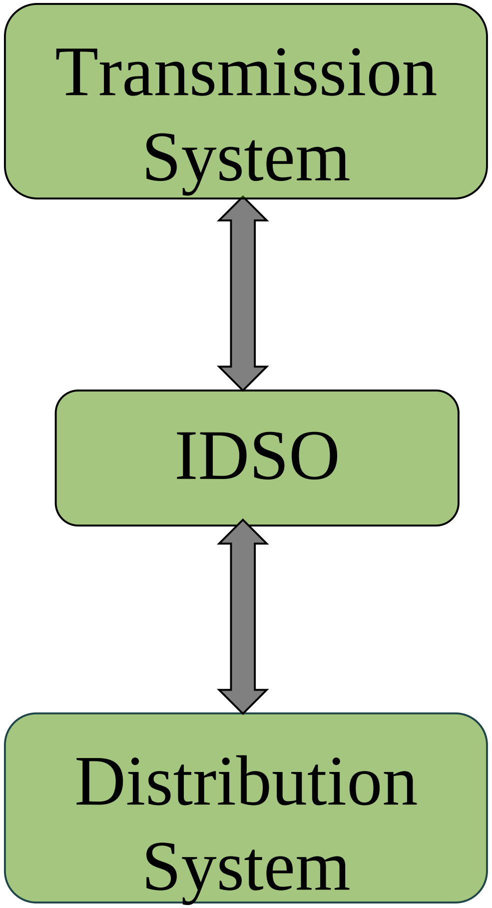


Fig. 1. ITD System

Research Completed

IDSO-Managed Bid-Based TES Design
for an ITD System

Conceptual Formulation

IDSO-Managed Two-Way Communication Network

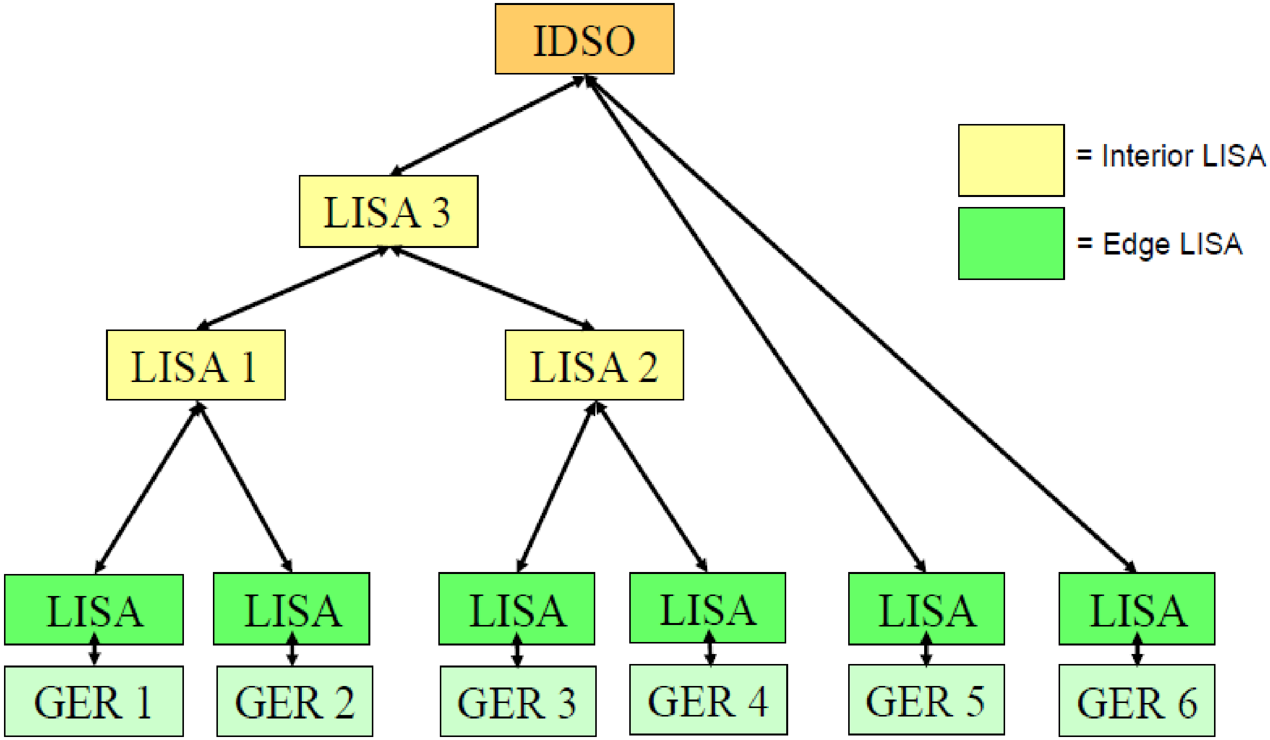

IDSO
LISA 3
LISA 1
LISA 2
LISA
LISA
LISA
LISA
LISA
LISA
GER 1
GER 2
GER 3
GER 4
GER 5
GER 6
🟨 = Interior LISA
🟩 = Edge LISA

Fig. 2: Illustrative two-way communication network of *Local Intelligent Software Agents (LISAs)* for an IDSO-managed bid-based TES design with *Grid-Edge Resource (GER)* participants

Requirements:

- Scalability
- GER privacy protection
- Alignment of system goals and constraints with local GER goals and constraints

Design Implementation

Five-Step Bid-Based TES Design

- Step 1: Edge LISA for each GER g collects data on the state of each smart device v(g) owned by g at a ***Data Check Rate*** and uses these data to form state-conditioned device bid functions $B_v(g)$.
- Step 2: Edge LISA for each GER g uses device bid functions $B_v(g)$ to form a state-conditioned vector **Bid**(g) of bid functions for g and communicates **Bid**(g) to the IDSO at a ***Bid Refresh Rate***.
- Step 3: IDSO combines latest bid functions **Bid**(g) received from all GERs g into a vector **AggBid** of one or more aggregate bid functions at an ***Aggregate Bid Refresh Rate***.
- Step 4: IDSO uses **AggBid** to determine and communicate price signals back to edge LISAs at a ***Price Signal Rate***.
- Step 5 (Control Step): Edge LISA for each GER g inserts its latest received price signals into its latest refreshed state-conditioned device bid functions $B_v(g)$ at a ***Power Control Rate***, which triggers a power response from each smart device v(g).

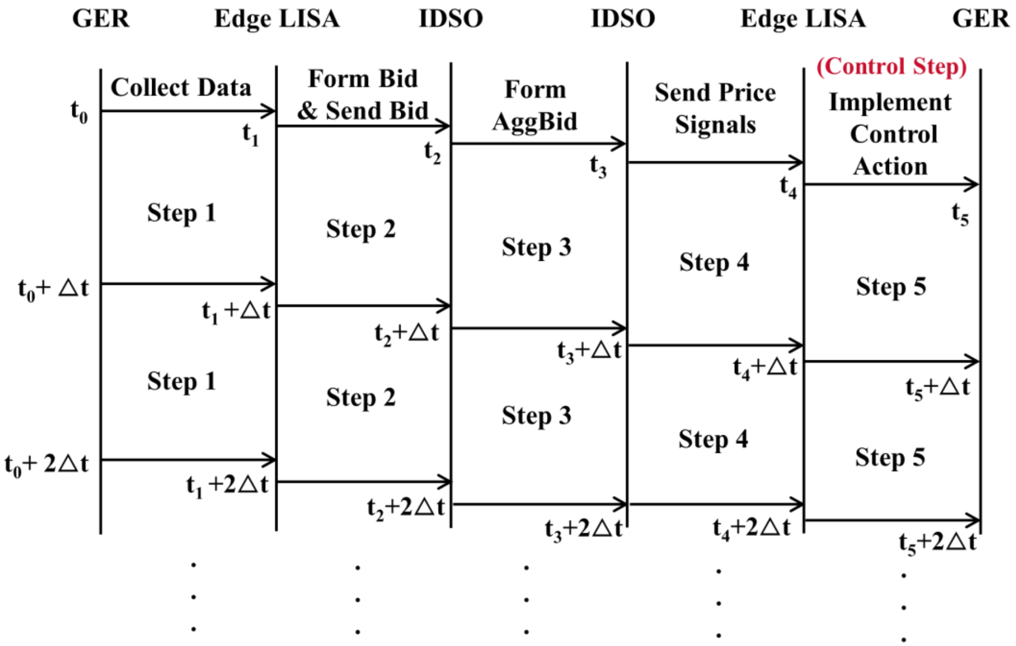
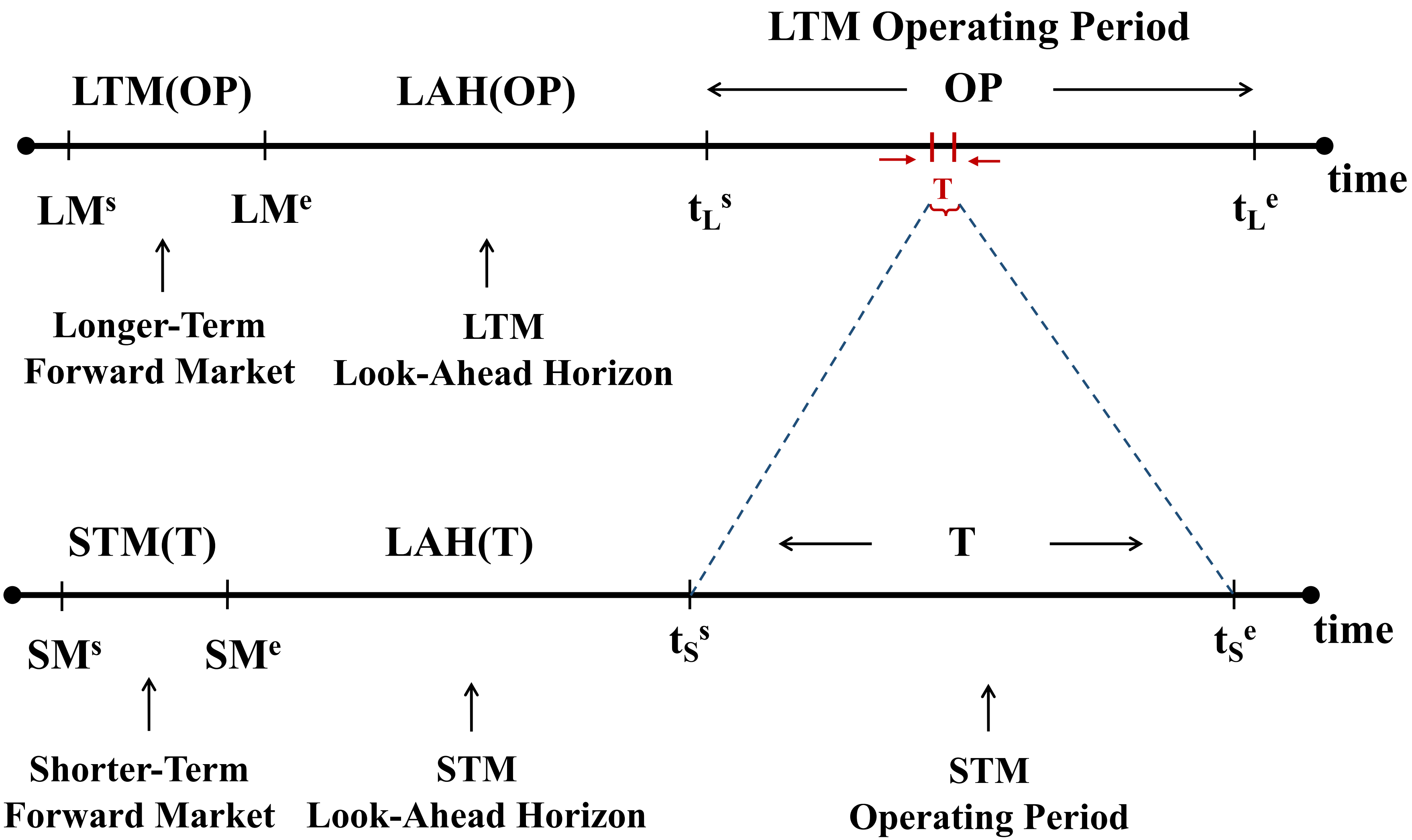


Fig. 3. Staggered implementation of an IDSO-managed bid-based Five-Step TES design

Wholesale Power Market Modeling



LTM Operating Period

LTM(OP) **LAH(OP)** **OP**

LM^s LM^e $t_L{}^s$ T $t_L{}^e$ **time**

Longer-Term Forward Market

LTM Look-Ahead Horizon

STM(T) **LAH(T)** **T**

SM^s SM^e $t_S{}^s$ $t_S{}^e$ **time**

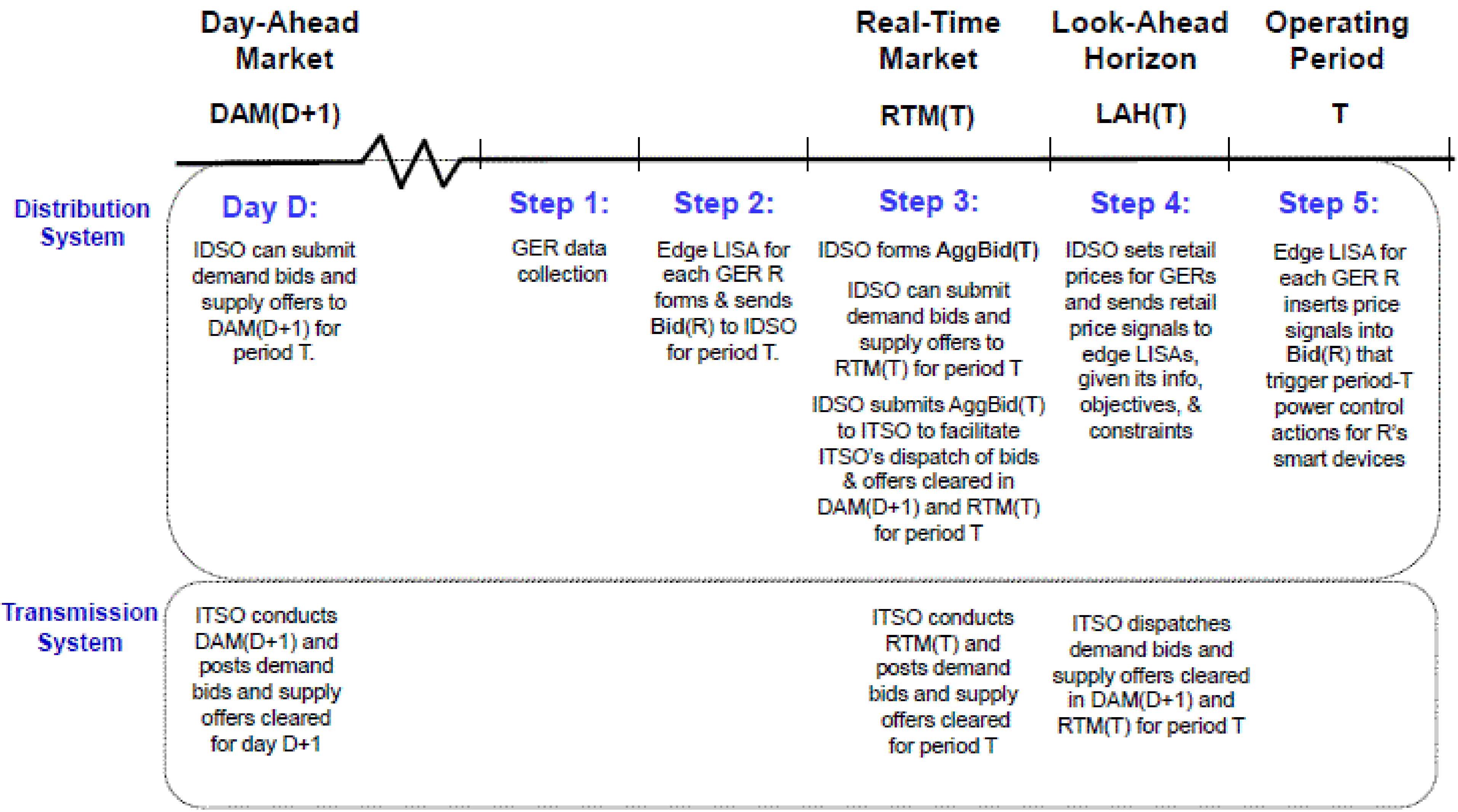
Shorter-Term Forward Market

STM Look-Ahead Horizon

STM Operating Period

Fig. 4. Typical wholesale power market timing of a longer-term forward market LTM(OP) operating in relation to a shorter-term forward market STM(T), where T lies within OP

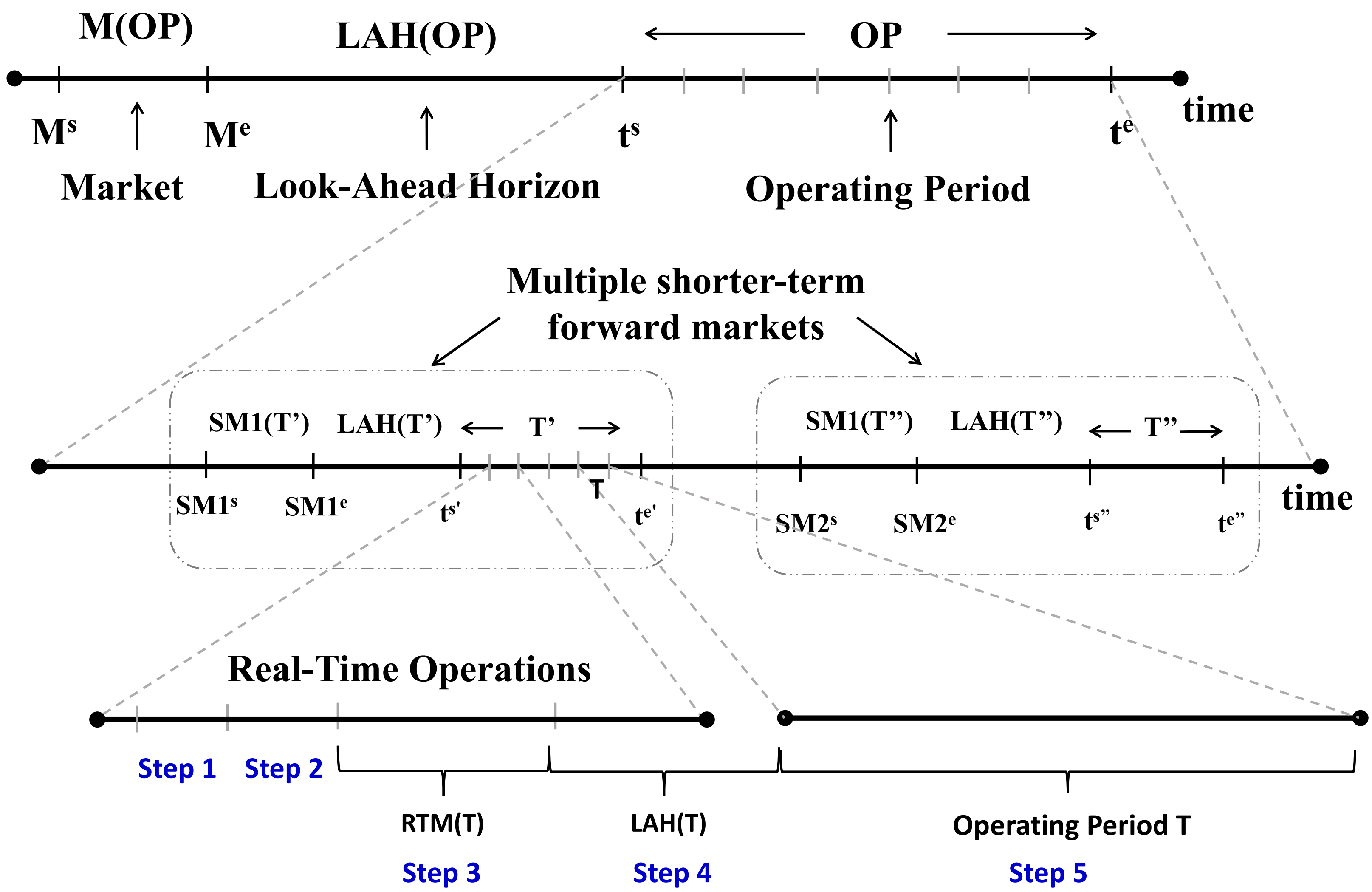
Timing coordination between Five-Step TES Design for control-step T during Day D+1 and the operations of DAM(D+1) and RTM(T)



	Day-Ahead Market DAM(D+1)			Real-Time Market RTM(T)	Look-Ahead Horizon LAH(T)	Operating Period T
Distribution System	**Day D:** IDSO can submit demand bids and supply offers to DAM(D+1) for period T.	**Step 1:** GER data collection	**Step 2:** Edge LISA for each GER R forms & sends Bid(R) to IDSO for period T.	**Step 3:** IDSO forms AggBid(T) IDSO can submit demand bids and supply offers to RTM(T) for period T IDSO submits AggBid(T) to ITSO to facilitate ITSO's dispatch of bids & offers cleared in DAM(D+1) and RTM(T) for period T	**Step 4:** IDSO sets retail prices for GERs and sends retail price signals to edge LISAs, given its info, objectives, & constraints	**Step 5:** Edge LISA for each GER R inserts price signals into Bid(R) that trigger period-T power control actions for R's smart devices
Transmission System	ITSO conducts DAM(D+1) and posts demand bids and supply offers cleared for day D+1			ITSO conducts RTM(T) and posts demand bids and supply offers cleared for period T	ITSO dispatches demand bids and supply offers cleared in DAM(D+1) and RTM(T) for period T	

Fig. 5. Timing coordination between transmission and distribution operations

ITD Timing Coordination: Multiple Forward Markets



M(OP)

LAH(OP)

OP

M^s M^e t^s t^e

time

Market

Look-Ahead Horizon

Operating Period

Multiple shorter-term forward markets

SM1(T') LAH(T') T'

SM1^s SM1^e $t^{s'}$ T $t^{e'}$

SM1(T") LAH(T") T"

SM2^s SM2^e $t^{s''}$ $t^{e''}$

time

Real-Time Operations

Step 1

Step 2

RTM(T)

Step 3

LAH(T)

Step 4

Operating Period T

Step 5

Fig. 6. Timing coordination of multiple forward markets with real-time market operations

Research Completed … Continued

Development of the ITD TES Platform V2.0 for test-case study of the proposed ITD TES design

ITD TES Platform V2.0

- Developed the ITD TES Platform V2.0 to evaluate the proposed ITD TES design

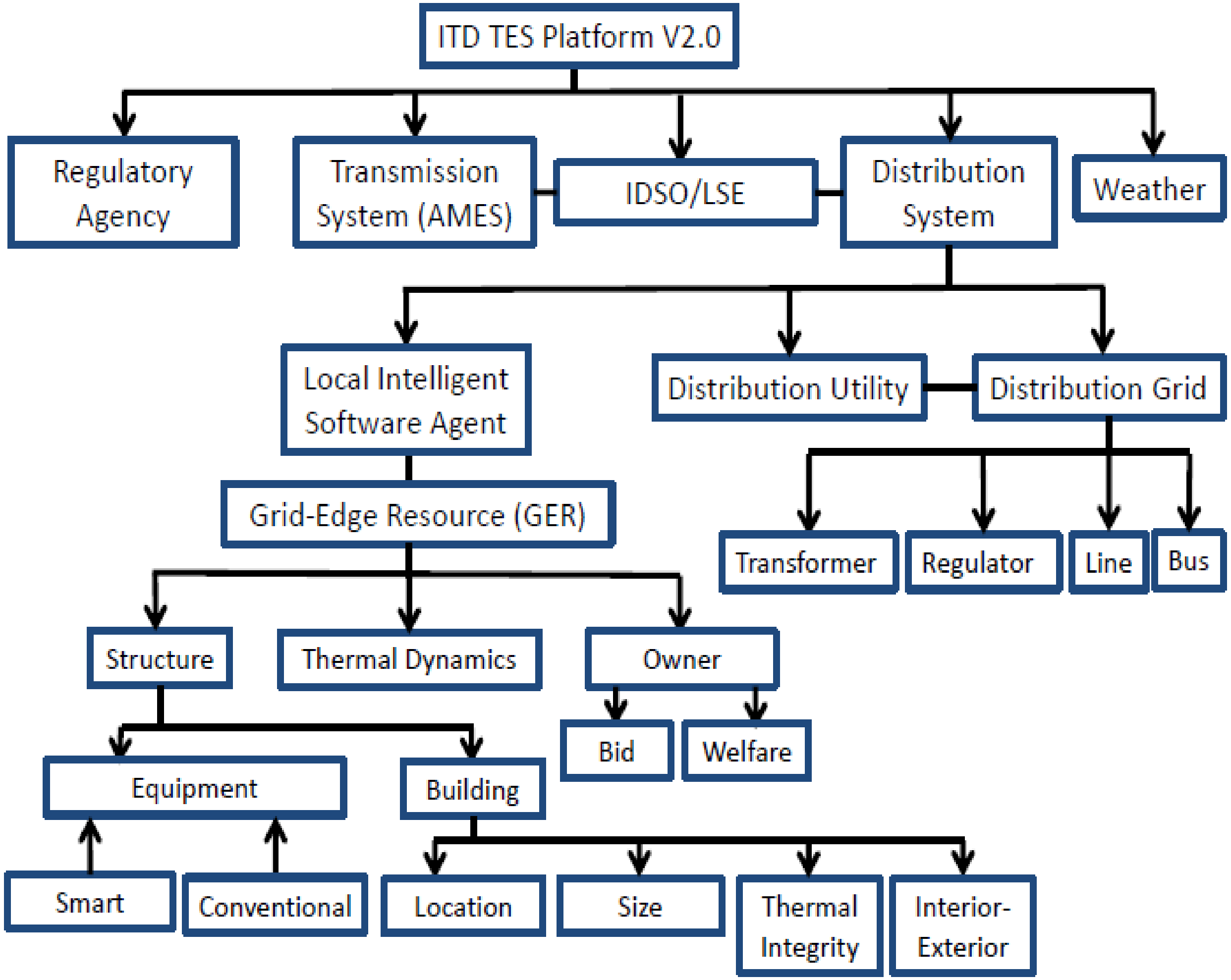


Fig. 7. Partial agent hierarchy for the ITD TES Platform V2.0

Key Software Components

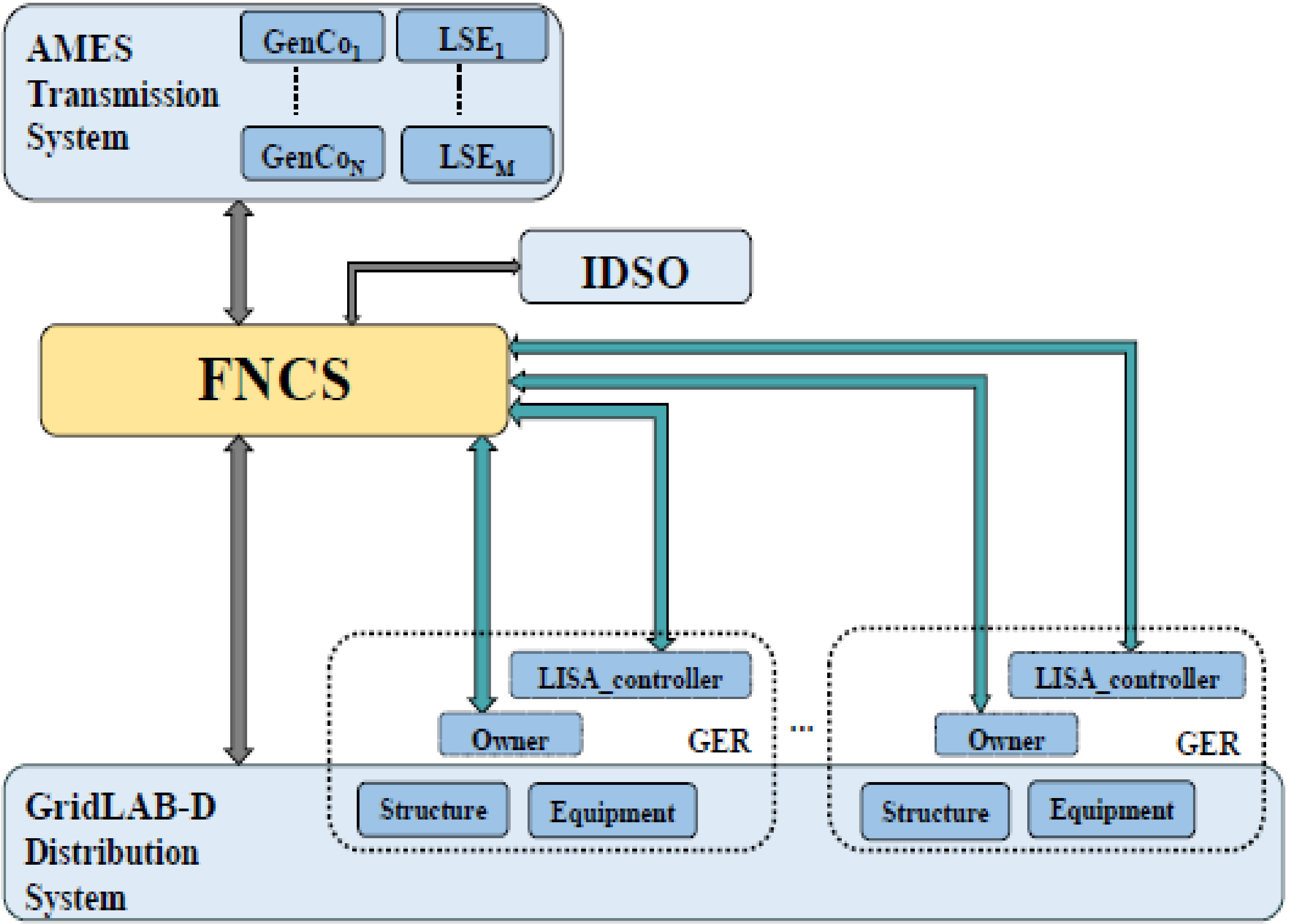


Fig. 8: Key software components for the ITD TES Platform V2.0

Research Completed … Continued

Development of the ERCOT Test System

A specialization of AMES V5.0 used as the transmission system component for the ITD TES Platform V2.0 in test-case studies of the proposed ITD TES design

AMES V5.0 Transmission System: Specialized to ERCOT

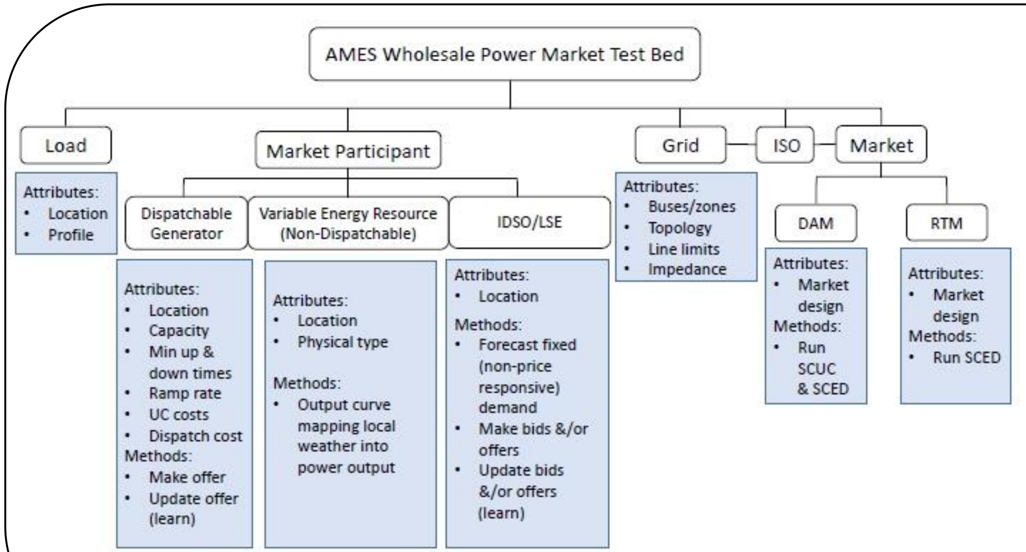


Fig. 9. Partial agent hierarchy for AMES V5.0, from Tesfatsion/Battula [5]

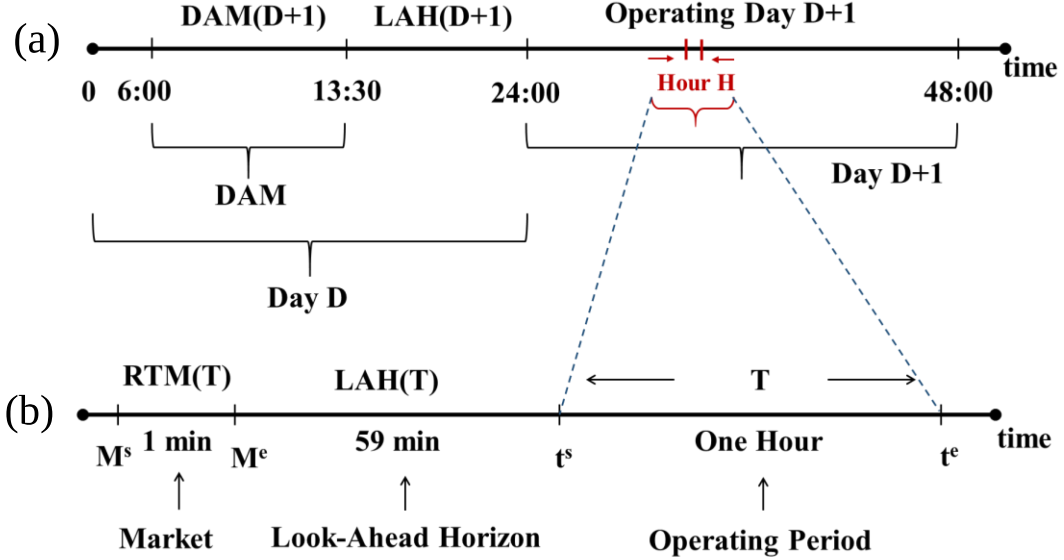
System constraints for SCUC/SCED in DAM & RTM

- Transmission line power flow limits
- Power balance constraints
- Generator capacity constraints
- Dispatchable generator ramp constraints for start-up, normal, and shutdown operating conditions
- Dispatchable generator min up/down-time constraints
- Dispatchable generator hot-start constraints
- System-wide reserve requirement constraints
- Zonal reserve requirement constraints

Fig. 10. AMES market timing specialized to ERCOT.

a) ERCOT Test System timing configuration for a DAM conducted on day D to facilitate net load balancing during the following day D+1

b) ERCOT Test System default timing configuration for an RTM whose purpose is to facilitate net load balancing for a near-term operating hour T



AMES V5.0 Transmission Grid: Specialized to ERCOT

Data

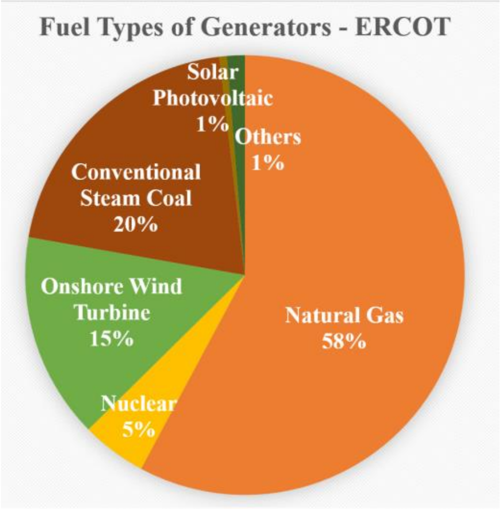


Fig. 11. ERCOT 2016 generation proportions by major fuel types

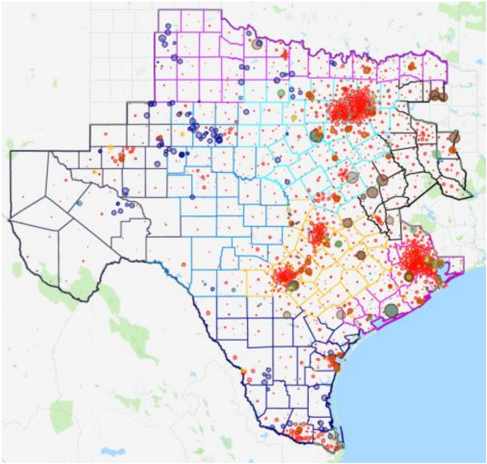


Fig. 12. Load and generation nodes

Grid Construction Method[1]

1. Specify the desired number of buses (NB)
2. Obtain ERCOT generation and load data
3. Use the ERCOT data to specify NN initial pure-generation and pure-load nodes, where NN ≥ NB
4. Use the hierarchical clustering algorithm developed by Johnson [35] to cluster these NN nodes into NB buses (node clusters).
5. Use Delaunay Triangulation [36] method plus ERCOT transmission line data to construct transmission lines connecting pairs of the NB buses formed in step 4.
6. Prune the resulting grid to achieve greater empirical realism for the application at hand, e.g., remove lines that traverse areas outside the energy region of interest.

[1] Based on synthetic grid construction method developed by Gegner, Birchfield, Xu, Shetye, & Overbye [34]

Grid Outcome

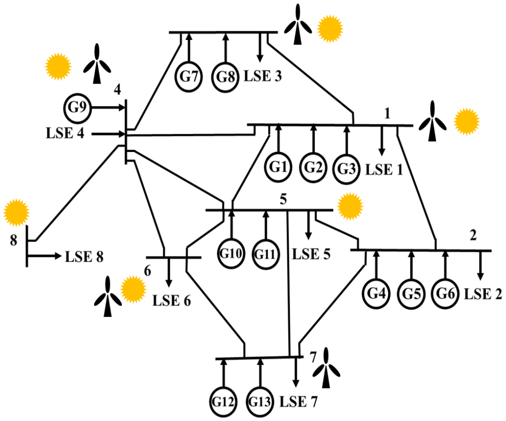


Fig. 13. 8-Bus ERCOT Test Grid

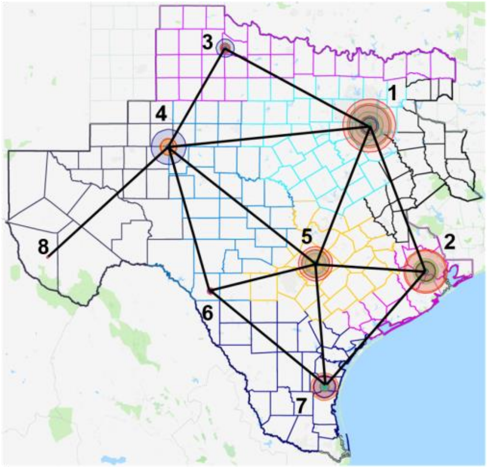


Fig. 14. 8-Bus ERCOT Test Grid superimposed on the ERCOT region

ERCOT Test System Verification Results

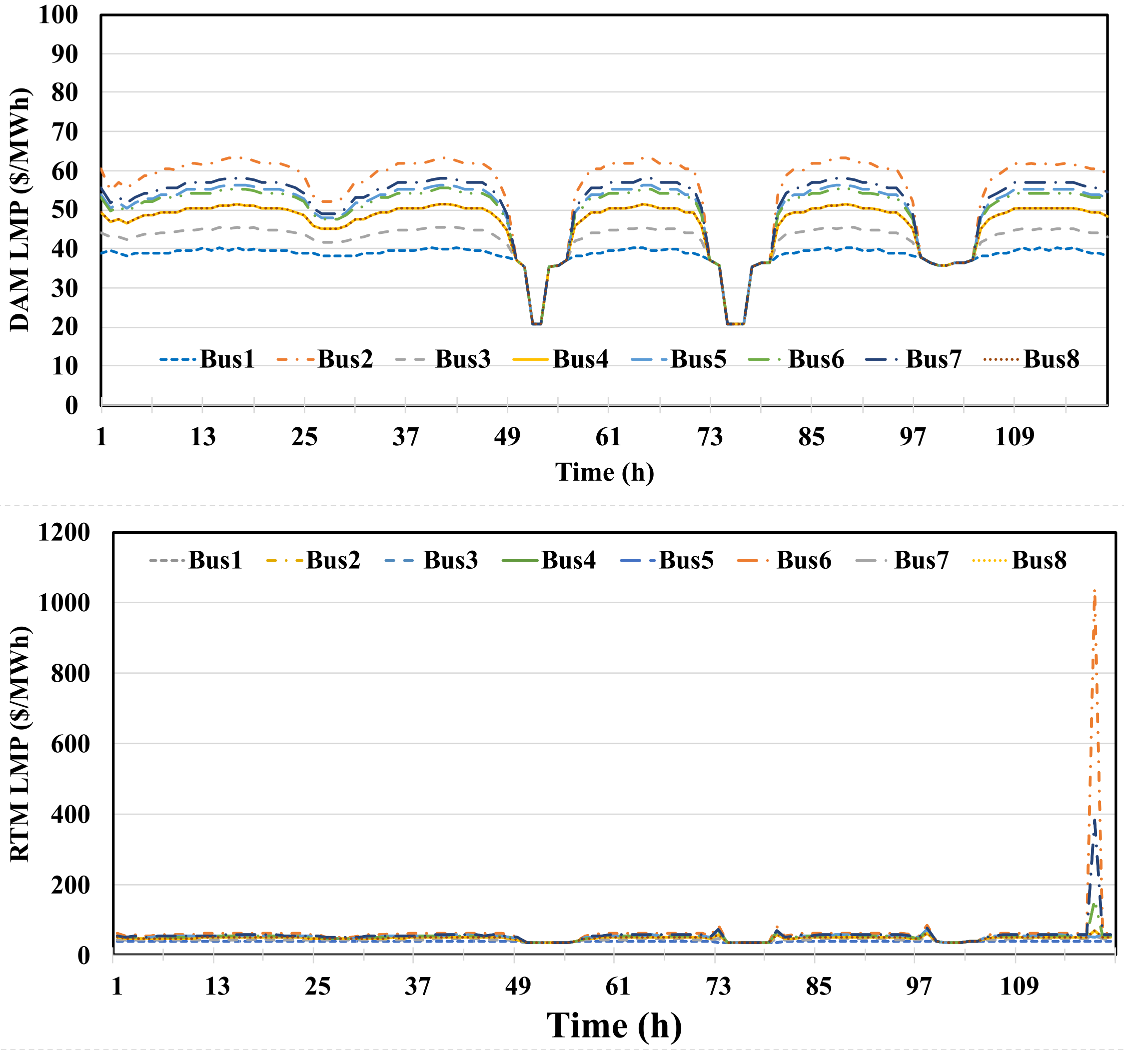


Fig. 15. Demonstration of DAM and RTM LMPs

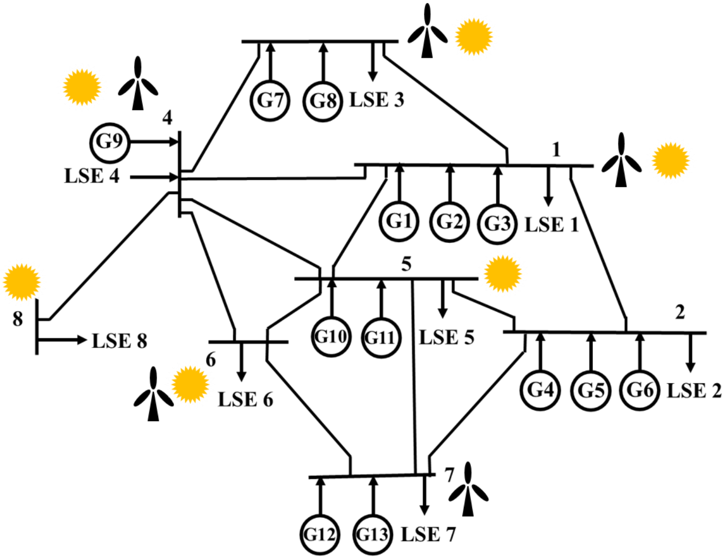
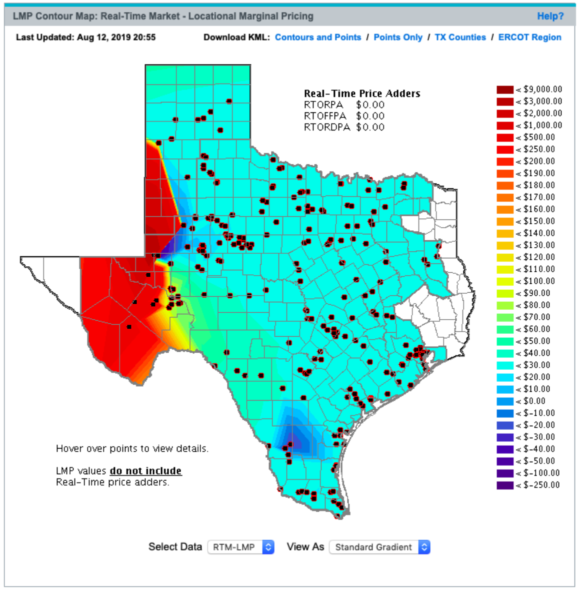


Fig. 16. 8-Bus ERCOT Test Grid


LMP Contour Map: Real-Time Market - Locational Marginal Pricing

Help?

Last Updated: Aug 12, 2019 20:55

Download KML: Contours and Points / Points Only / TX Counties / ERCOT Region

Real-Time Price Adders
RTORPA $0.00
RTOFFPA $0.00
RTORDPA $0.00

Hover over points to view details.

LMP values **do not include** Real-Time price adders.

Select Data: RTM-LMP
View As: Standard Gradient

Fig. 17. Snapshot of ERCOT RTM LMPs dated 8/12/2019

Research Completed … Continued

Modeling of household GERs characterized by physical & preference attributes

Physical & Preference Attributes of a Household

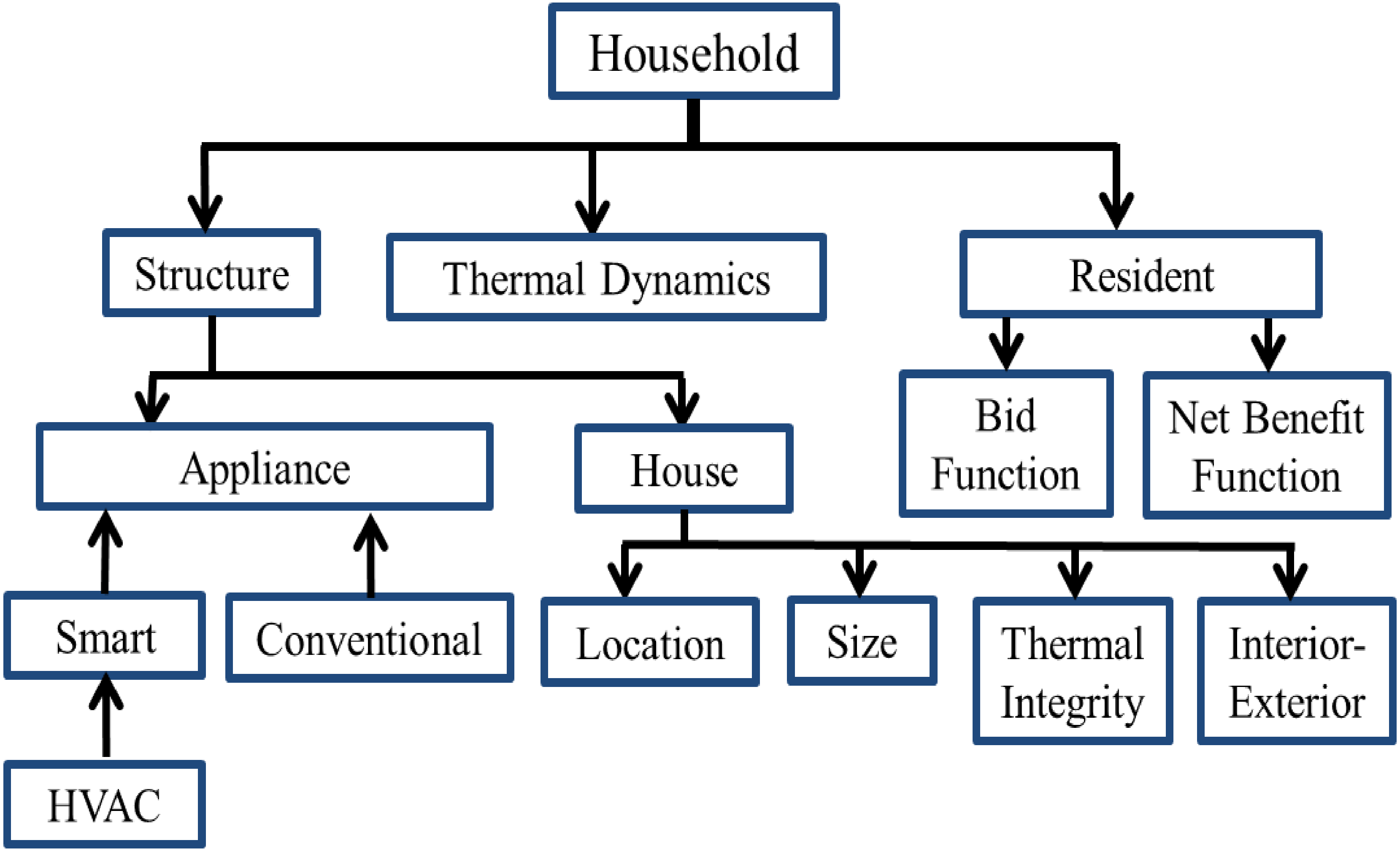
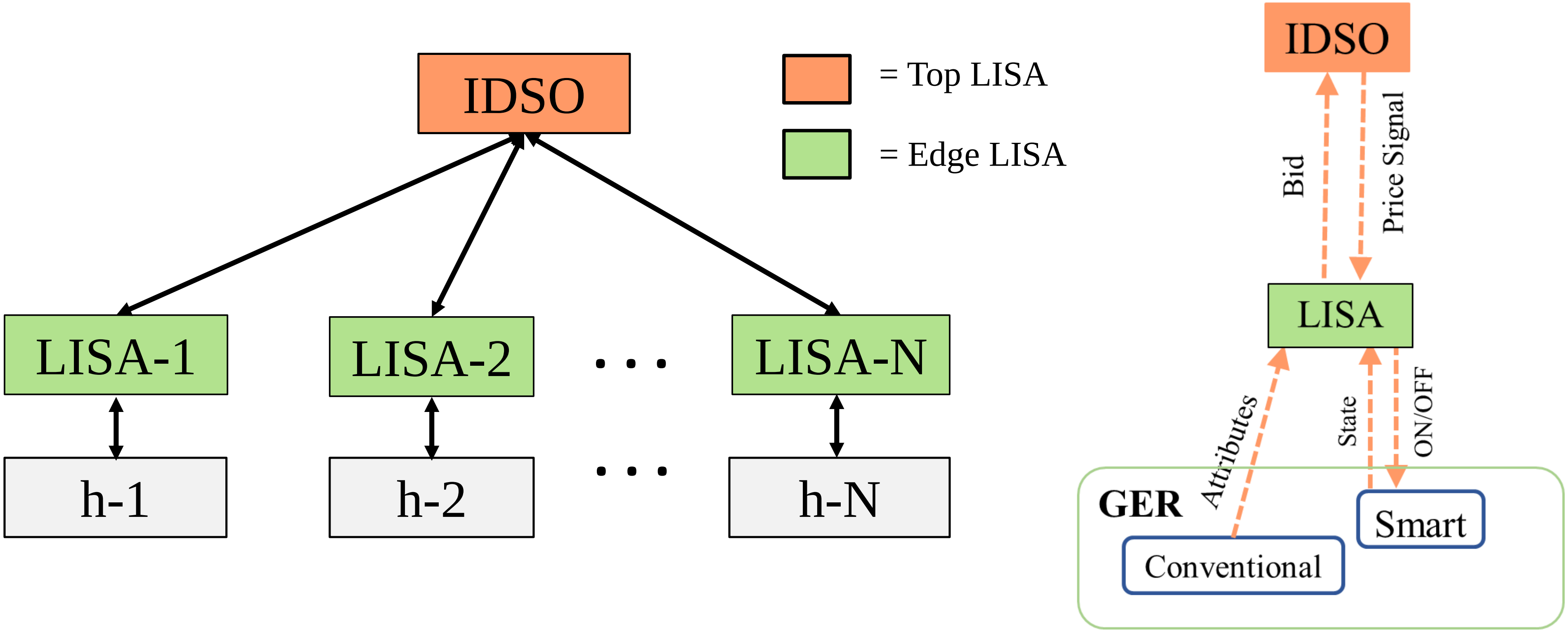


Fig. 18. Hierarchy of household attributes

LISA Communication Network for Households



(a) (b)

Fig. 19: LISA two-way communication network used in ITD household test cases. (a) Single-layer network for a collection of household GERs; and (b) communication links connecting the IDSO, an edge LISA for a household GER, and the household GER's smart (price-sensitive) and conventional appliances.

Modeling of Household Attributes: Details

- Derived the general optimal state-conditional bid form for a household with a smart TCL appliance, assuming household welfare is measured as comfort minus cost.

- This bid is either a demand for power usage or an offer to supply ancillary service (power absorption), depending on the state of the household.

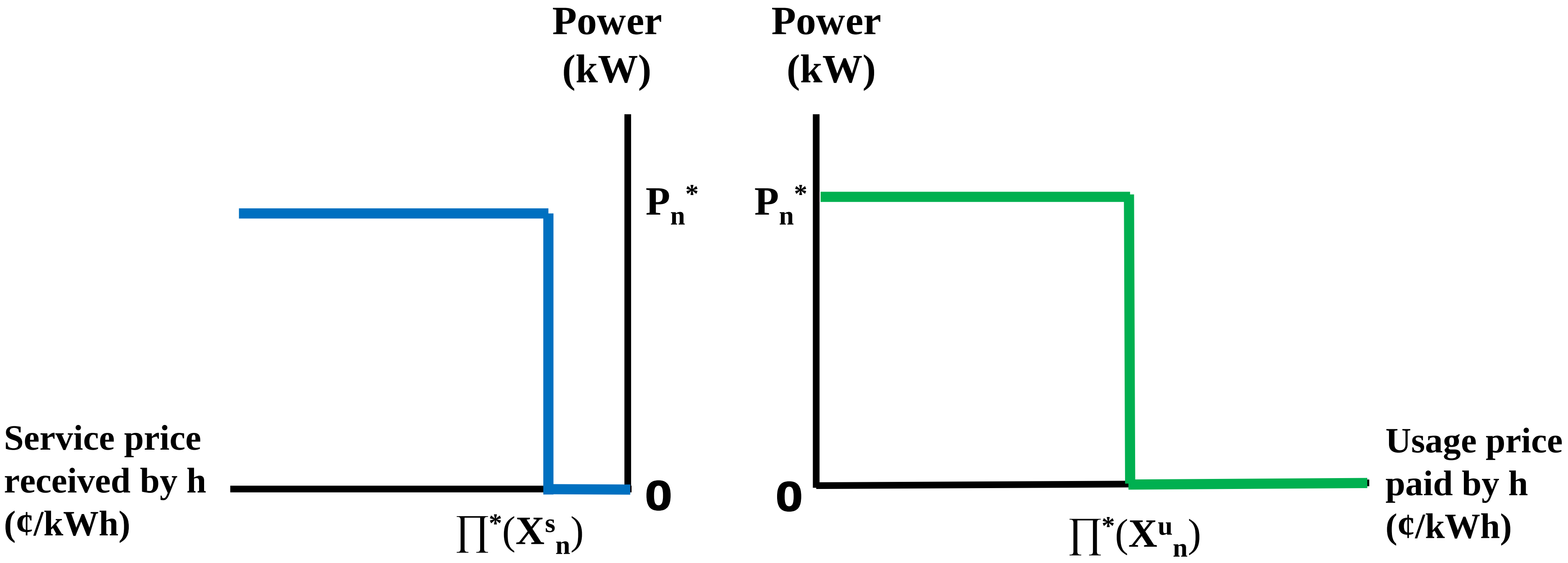
- Derived a quantitative representation for this bid form as a function of the base parameters characterizing the household's physical and preference attributes, assuming the household has a one-period look-ahead horizon.

- Developed a method for clustering households into representative types by means of their base parameter values

Key Differences in Relationship to Existing Literature

- Form of state-conditioned bid function is ***optimally derived*** based on an empirically meaningful parameterization for a household's physical and preference attributes
- Bid can be ***either*** a demand for power usage ***or*** a supply offer for ancillary service, depending on state
- The ON/OFF power mode of a household's smart TCL appliance during each control step is ***controlled by an IDSO price signal***, based on the household's latest TCL appliance bid.

Optimal price-sensitive bid form (Π^*, P^*) for a household h for each control-step n



(a) Bid form in ancillary service state **(b) Bid form in power usage state**

Fig. 20. Depending on its state at the start of a control-step n, household h either (a) is willing to **supply ancillary service (HVAC power absorption)** as a function of price received or (b) is willing to **demand power for HVAC usage** as a function of price paid. A **negative price** denotes a supply price received; a **positive price** denotes a demand price paid; & P* = HVAC ON power usage.

Illustration: Optimal Bid Derivation for a Household h

Simplifying assumptions:

(1) Household h’s only smart (price-sensitive) TCL appliance is a smart electric HVAC system.

(2) Season is summer, so this HVAC system is running in cooling mode.

(3) The look-ahead horizon for household h’s bids is a single control-step, i.e., should h’s HVAC system be turned (or kept) ON or OFF for the next control-step?

Illustration … Continued

- ***Comfort function (utils):*** Maximum thermal comfort (G_{max}) is achieved when discomfort is minimized, where discomfort is measured by the difference between actual inside air temp (T_a) and the household resident's bliss temp (TB):

$$G(t{:}\,t_o) = \int_{t_o}^{t} (GMax - h(s) \cdot [T_a(s) - TB]^2)\, ds$$

- ***Electricity cost (cents):*** $\pi_p(s)$ = price (cents/kWh) charged at time s for power P(s) (kW):

$$E(t{:}\,t_o) = \int_{t_o}^{t} \pi_p(s) \cdot P(s)\, ds$$

- ***Net Benefit (utils)*** is measured as (comfort – μ·cost). Here μ (utils/cent) = household's marginal utility of money, a standard economic welfare concept:

$$NB(t{:}\,t_o) = G(t{:}\,t_o) - \mu \cdot E(t{:}\,t_o)$$

Note: μ (utils/cent) denotes the Lagrange multiplier solution for the KKT first-order necessary conditions for a household optimization problem: Maximize utility of consumption subject to a budget constraint. It reflects the household's comfort-cost tradeoff preferences.

Illustration … Continued

Δt = Length of each control-step n

θ = Vector of ***base*** thermal dynamic (ETP model) parameters, where “base” means a parameter that is not expressible in terms of other parameters

λ = (G_{max}, h1, h2, TB, μ) = Vector of ***base*** welfare parameters

- Discretized form of household thermal comfort (utils) for control-step n

$$G(n{:}\,\theta,\lambda) = (G_{max} - \ (h1/2 \cdot (T_a(n,\theta) - TB)^2 + h2/2 \cdot (E[T_a(n+1,\theta)] - TB)^2)\ ) \cdot \Delta t$$

- Discretized form of household energy cost for control-step n: $P_T(n,\theta)$ (kW) = Total power usage of HVAC system, and $\pi_p(n)$ (cents/kWh) = price

$$E(n{:}\,\theta) = \pi_p(n) \cdot P_T(n,\theta) \cdot \Delta t$$

- Discretized form of household net benefit (utils) for control-step n

$$NB(n{:}\,\theta,\lambda) = G(n{:}\,\theta,\lambda) - \mu \cdot E(n{:}\,\theta)$$

Illustration … Continued

- Control Variable: $u(n) = 1$ or 0 (i.e., HVAC system *running in cooling mode* is ON or OFF)
- The household's bid function is the controller for this HVAC system
- **Problem:** Design this bid function so that the control signal u(n) sent to the HVAC system at the beginning of each control-step n maximizes household expected net benefit for n
- A signal u(n) = 1 switches (or leaves) the HVAC system ON for time-step n, whereas a signal u(n)=0 switches (or leaves) the HVAC system OFF for time-step n
- **OPTIMIZATION METHOD:**
  - Determine whether household is in bid-state X^u (may-run for usage) or X^s (may-run for ancillary service supply) at start of control-step n by checking whether ***comfort*** over n is higher with u(n)=1 or with u(n)=0
  - If higher with u(n)=1, household is willing to PAY to have HVAC ON (state X^u). Determine the ***maximum price*** the household is ***willing to pay*** to keep HVAC ON during control-step n
  - If higher with u(n)=0, household must be PAID to have HVAC ON (state X^s). Determine the ***minimum price*** the household is ***willing to accept*** in payment to keep HVAC ON during control-step n

Illustration…Continued: Derivation of Optimal Cut-Off Price

Let $\pi_p(n)$ denote a possible energy price (cents/kWh) for control-step n

- Case 0: Calculate household expected net benefit for control-step n with HVAC ‘OFF’ (u(n)=0)

$$NB^0(n\colon \theta,\lambda) = G_{max} \cdot \Delta t - \left(h1/2 \cdot (T_a(n,\theta) - TB)^2 + h2/2 \cdot (E[T_a(n+1\colon Case0,\theta)|n] - TB)^2\right) \cdot \Delta t$$

- Case 1: Calculate household expected net benefit for control-step n with HVAC ‘ON’ (u(n) = 1)

$$\begin{aligned} NB^1(n\colon \theta,\lambda) = {} & G_{max} \cdot \Delta t - \left(h1/2 \cdot (T_a(n,\theta) - TB)^2 + h2/2 \cdot (E[T_a(n+1\colon Case1,\theta)|n] - TB)^2\right) \cdot \Delta t \\ & -\mu \cdot \pi_p(n) \cdot P_T^*(n,\theta) \cdot \Delta t \end{aligned}$$

- Calculate the optimal cut-off price $\prod^*$ (positive or negative) for control-step n to be the maximum value of $\pi_p(n)$ for which $NB^0 \leq NB^1$

$$\pi_p(n) \leq \frac{h_2}{2 \cdot \mu \cdot P_T^*(n,\theta)} \left((E[T_a(n+1\colon Case0,\theta)|n] - TB)^2 - (E[T_a(n+1\colon Case1,\theta)|n] - TB)^2\right)$$

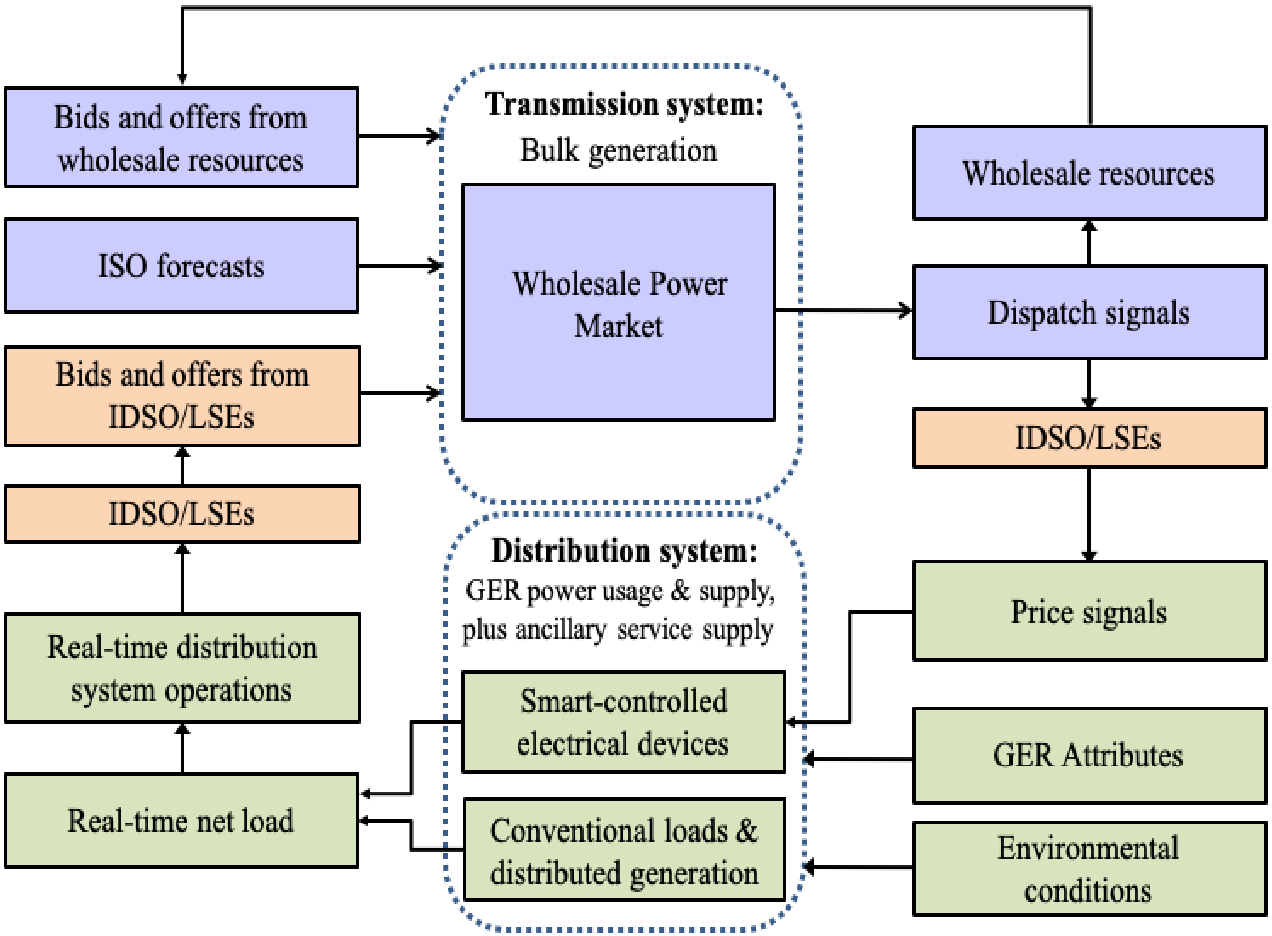
- Right-hand side of the above expression is the optimal cut-off price $\prod^*$, which can be positive or negative in value.

NOTE: $E[T_a(n+1\colon Case0,\theta)|n]$, $E[T_a(n+1\colon Case1,\theta)|n]$ denote the expected inside air temp of the house at the start of control-step n+1, given Case 0 and Case 1 respectively.

Research Completed … Continued

Modeling of an IDSO as a
Linkage Entity in an ITD System

ITD System with IDSO Linkage Agent: General Feedback Loop



Transmission system:
Bulk generation

Wholesale Power Market

Bids and offers from wholesale resources

ISO forecasts

Bids and offers from IDSO/LSEs

IDSO/LSEs

Real-time distribution system operations

Real-time net load

Wholesale resources

Dispatch signals

IDSO/LSEs

Price signals

GER Attributes

Environmental conditions

Distribution system:
GER power usage & supply, plus ancillary service supply

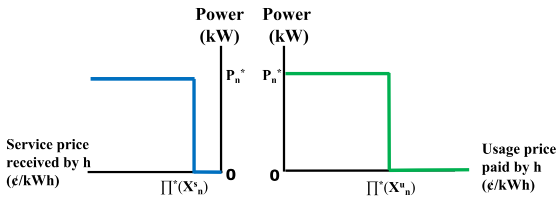
Smart-controlled electrical devices

Conventional loads & distributed generation

Fig. 21: Illustration of an ITD system with an IDSO operating as a linkage agent

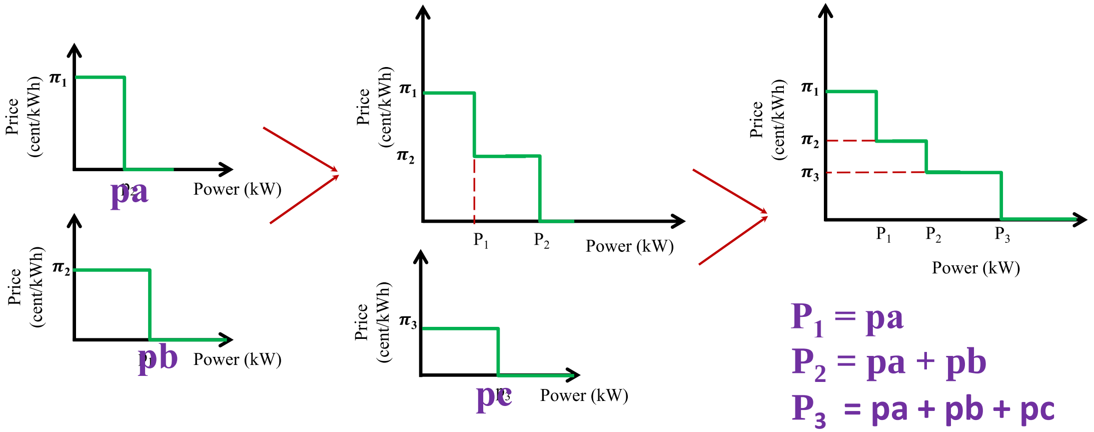
IDSO as a GER Aggregator

- Operates in wholesale power market as a Load-Serving Entity (LSE) and Ancillary Service Provider
  - Submits bids for procurement of power to meet GER power usage demands
  - Submits bids offering to supply ancillary services harnessed from GERs
- Operates in distribution system as a GER aggregator that manages GER bids via price signals



(a)Bid form in ancillary service state

(b) Bid form in power usage state



$P_1 = pa$

$P_2 = pa + pb$

$P_3 = pa + pb + pc$

Fig. 22. Illustration of the IDSO's GER bid aggregation method

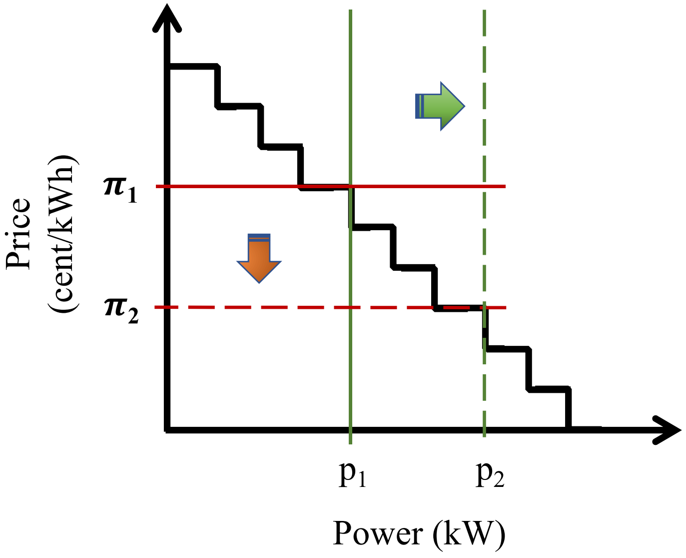


Fig. 23. Example of a GER aggregated bid function formed by IDSO

Research Completed … Continued

Formulation of ITD Household Test Cases

ITD Household Test Cases: Feedback Loop

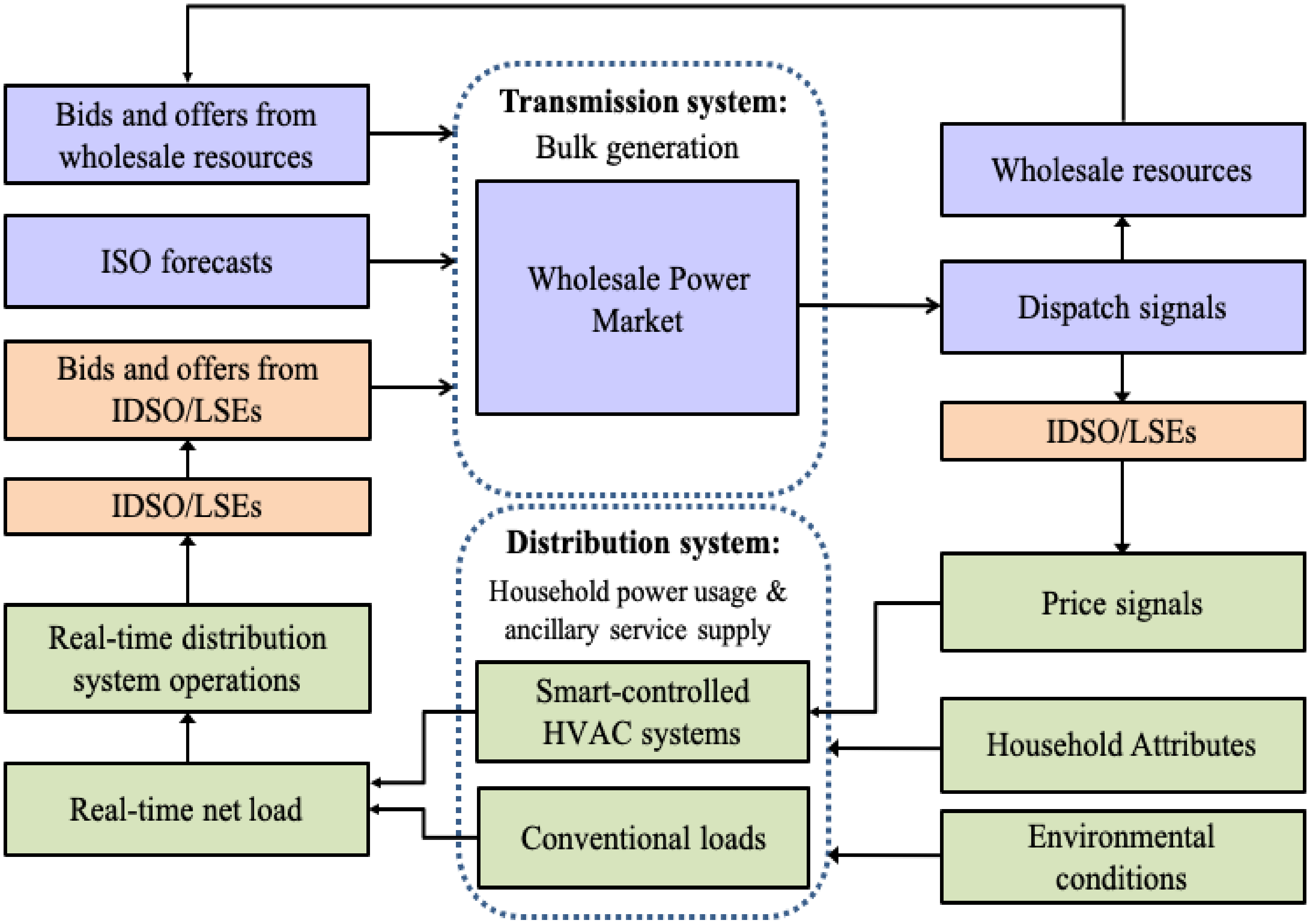


Fig. 24. ITD Feedback loop for each ITD household test case

ITD Household Test Cases: Two Basic Types

Test Case	GER Role	IDSO Role	GER Mix of Appliances
TC1	Each household submits a state-conditioned price-sensitive bid to the IDSO expressing either HVAC demand for power usage or HVAC supply of ancillary service (power absorption).	IDSO submits a fixed demand bid into each day-D DAM to cover forecasted total household power usage for day D+1. In real-time operations on each day D+1, the IDSO sets prices for household price-sensitive bids to meet IDSO system goals and constraints.	Each household has conventional (fixed load) appliances plus a smart (price-sensitive) HVAC system
TC2	Same as TC1	IDSO submits a fixed demand bid into each day-D DAM to cover total forecasted household power usage for day D+1. + IDSO submits ancillary service offer(s) into each day-D DAM for provision of ancillary services during day D+1. In real-time operations on each day D+1, the IDSO sets prices for household price-sensitive bids to meet IDSO system goals and constraints, conditional on the IDSO's obligation to satisfy any ITSO-instructed dispatch set points for ancillary service resulting from DAM-cleared IDSO ancillary service offers.	Same as TC1

Table 1: Types of ITD Household Test Cases

ITD Household Test Cases: Grid

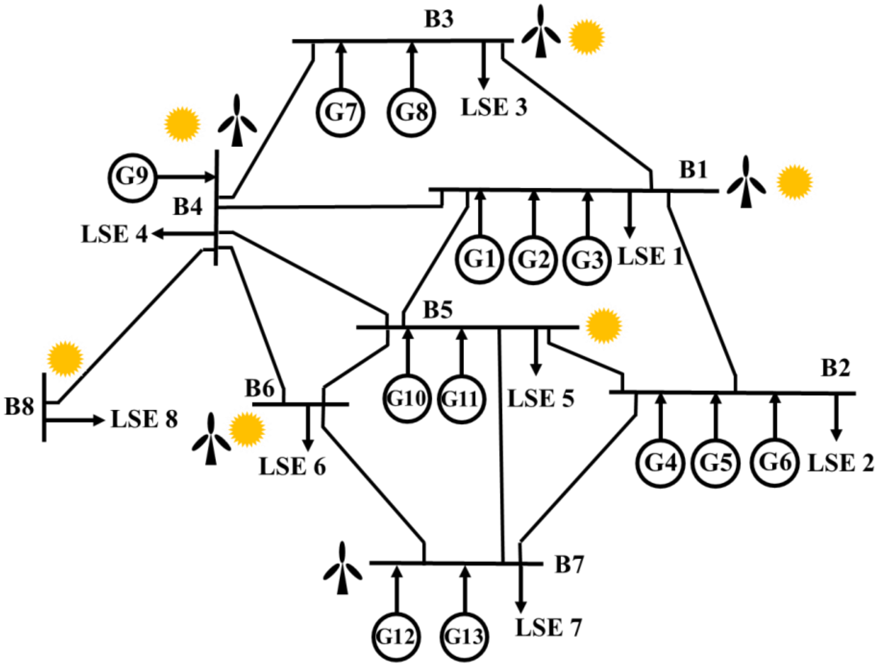


Fig. 25. 8-Bus ERCOT transmission test grid with distributed wind, solar, and thermal generation [2]

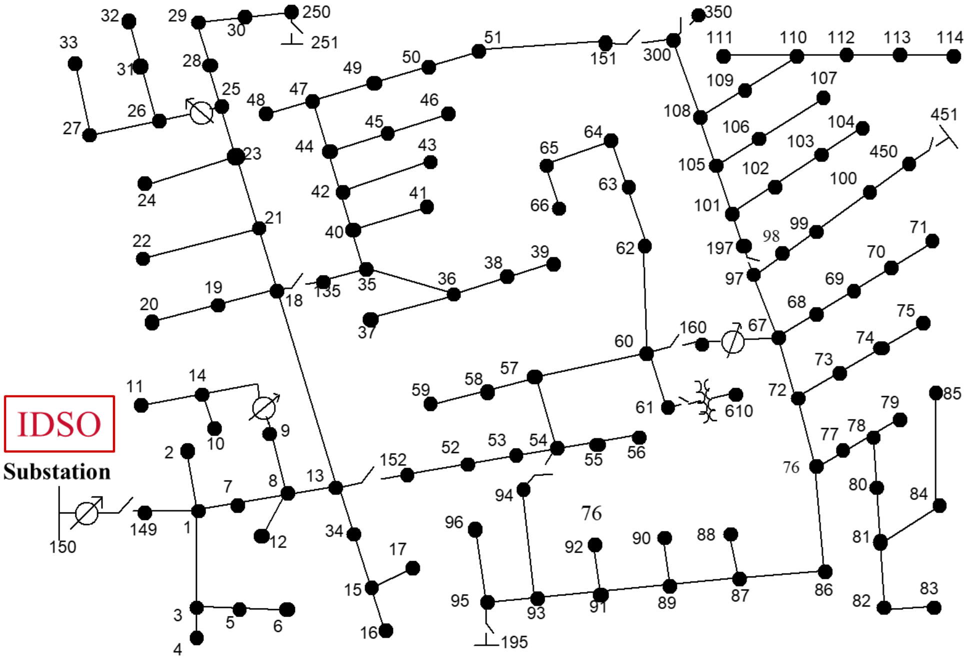


Fig. 26. The IDSO-managed modified IEEE 123-bus distribution grid used for test cases [1]

- Linkage bus B* for transmission and distribution grids is implemented as transmission bus B2; this is the bus where the IDSO operates as a linkage agent.
- The load connected at each bus of the standard IEEE 123-bus distribution grid is replaced with household load.
- 927 households are distributed across the 123 buses of the distribution grid in proportion to the original loads, which are then omitted.

ITD Household Test Cases: Market Timing

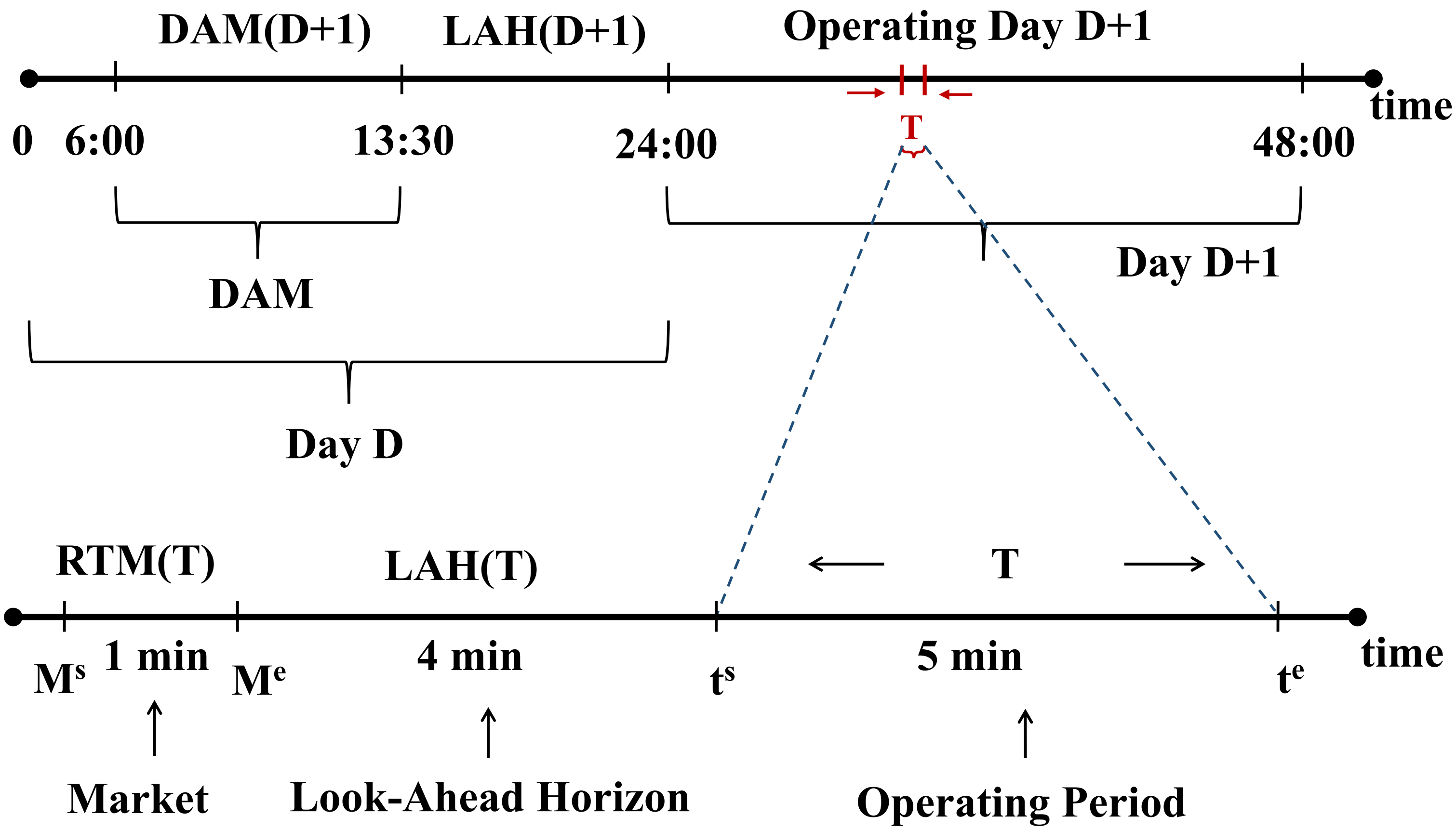


Fig. 27. Specific ERCOT market timings used to implement DAM and RTM operations for ITD household test cases

ITD Household Test Cases: Net Benefit Calculation

- The net benefit of each household h is calculated as

$$\text{Net Benefit}(h) \;=\; \text{Comfort}(h) - \mu(h) \bullet \text{Electricity Cost}(h)$$

where comfort expresses thermal benefit, and μ(h) (utils/$) denotes household h's ***marginal utility of money***, here functioning as a comfort-cost trade-off parameter.

- The parameter μ(h) measures the benefit (utility) that would be attained by household h if its electricity cost were reduced by $1.

- Net benefit outcomes in all reported ITD household test cases are average household net benefit attained for a particular operating day D

Research Completed … Continued

Illustrative ITD household test case outcomes obtained using the ITD TES Platform V2.0

TC1: Bid Function Comparison

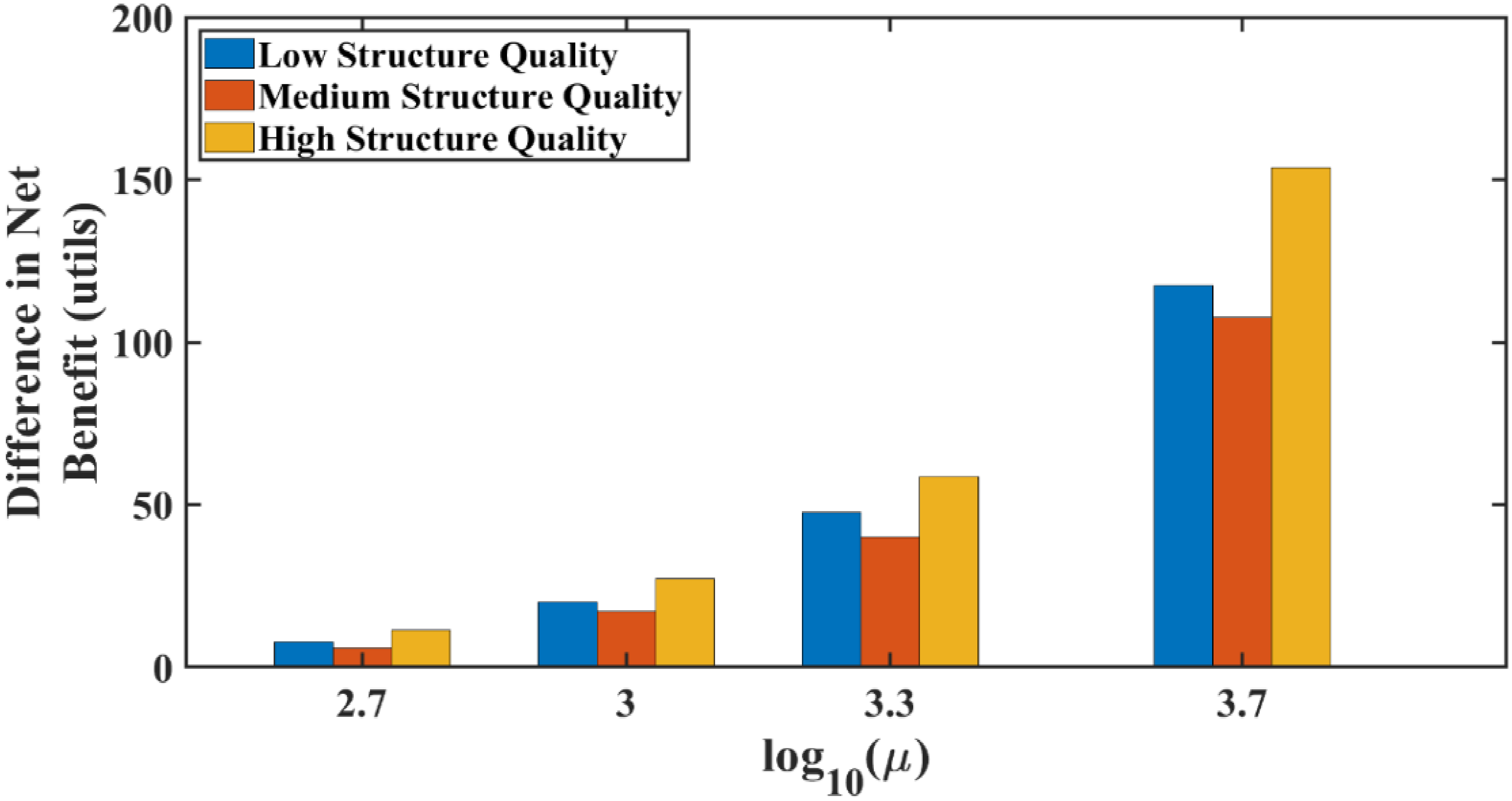
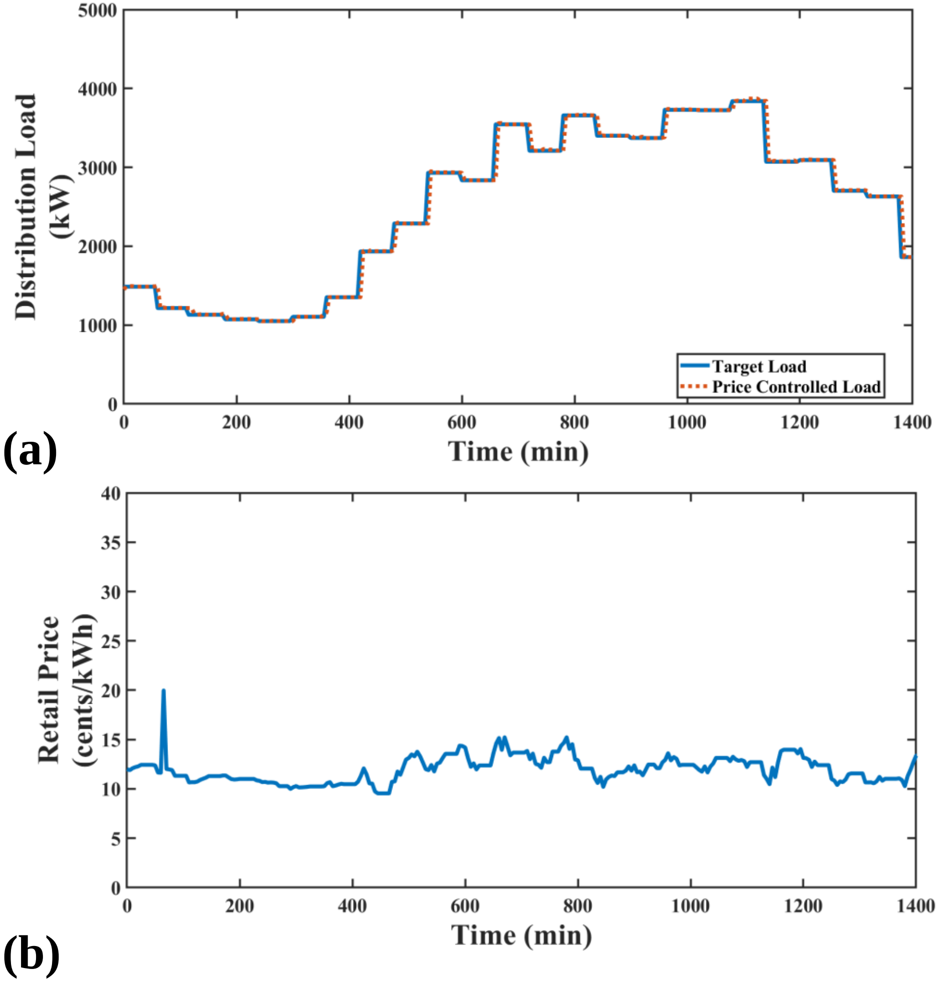


Fig. 28. Increased net benefit resulting when a household switches from the heuristic bid function developed by Nguyen, Battula et al. [3] to the optimal bid function form (Fig. 20) developed by Battula et al. [1], under varied settings for household marginal utility of money μ (utils/$) & structure quality.

TC1: IDSO’s Load Matching Capability



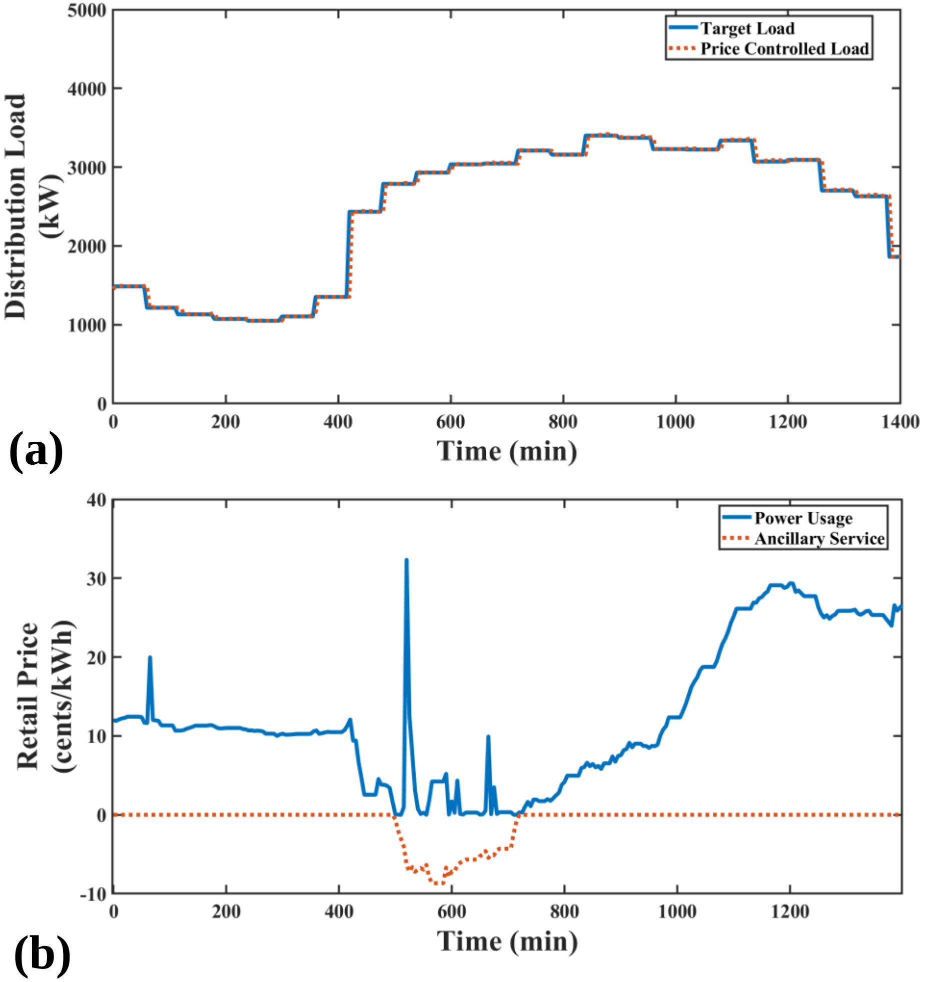


Fig. 29. (a) IDSO’s ability to use controlled retail prices to match total household load on day D+1 to a target load profile, given by the IDSO’s fixed demand bid submitted into the DAM on day D.
(b) The retail price signals sent by the IDSO to households on D+1.

Fig. 30. (a) IDSO’s ability to use controlled retail prices to match total household load on day D+1 to a different target load profile, i.e., a different fixed demand bid submitted into the day-D DAM.
(b) The positive and negative retail price signals sent by the IDSO to households on day D+1

TC2: IDSO Participation in a Day-D DAM

- Fixed Demand Bid for Hour H of day D+1

$$P^{DA}_{FD}(B^*,H,D+1) \;=\; PAvg_{TD}(B^*,H,D-1)\,,$$
$$H \in \{1,2,\ldots,24\}$$

$PAvg_{TD}(B^*,H,D-1)$ = average household total power usage (MW) realized at the linkage bus B* during each hour H of the previous day D-1

$P^{DA}_{FD}(B^*,H,D+1)$ = power level (MW) submitted by the IDSO into the day-D DAM as its fixed (non-price-sensitive) demand at the linkage bus B* during hour H of day D+1

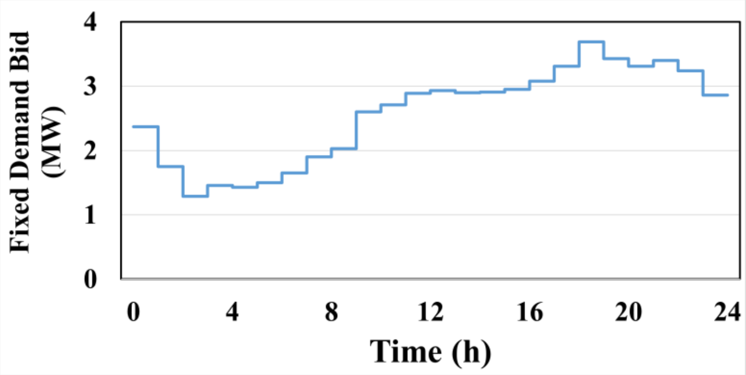


Fig. 31. Example of a fixed demand bid (load profile) submitted into a day-D DAM

- Swing-Contract Offer for Hour H of day D+1

$$SC = (\alpha, PP(H), \varphi(H))$$

$\alpha =$ Offer price

$PP(H) =$ Power-path set = (B^*, t^s, t^e, P, RR)

$B^* =$ Power-path delivery location (linkage bus);

$t^s =$ Start-time of each offered power-path;

$t^e =$ End-time of each offered power-path;

$P = [P^{min}, P^{max}]$ = Feasible down/up power range for H;

$RR = [-R^D, R^U]$ = Feasible ramp-rate range for H.

$\varphi(H) =$ Performance payment method for H

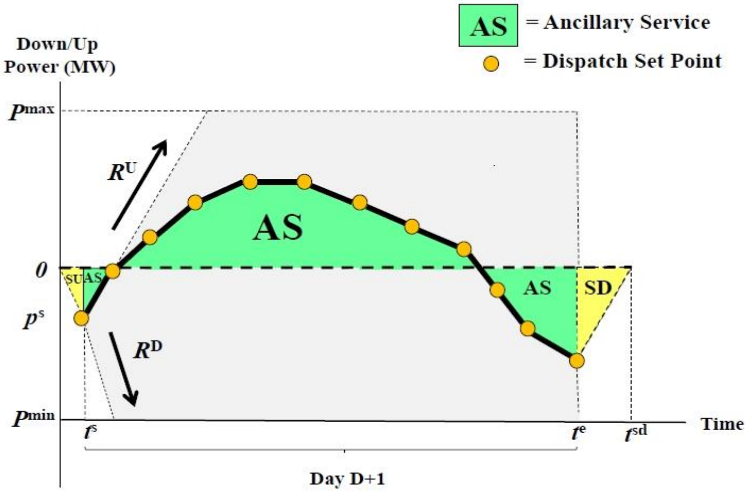


Fig. 32. Example of a swing-contract offer submitted into a day-D DAM. Source: [35]

TC2: IDSO’s Participation in a Day-D DAM ..Continued

- On day D the IDSO submits the swing-contract $SC = (\alpha, PP(H), \varphi(H))$ into an ITSO-managed DAM for day D+1, where SC offers the provision of ancillary service during hour H of day D+1.

- α = Amount ($) that must be paid to the IDSO if the ITSO clears SC

- $[P^{\min}, P^{\max}]$ = Range of feasible down/up power levels that the IDSO indicates it can provide during hour H in response to ITSO dispatch signals.

  NOTE: Suppose the ITSO clears SC in the day-D DAM for hour H of day D+1, and later dispatches the IDSO at a feasible down/up power level p*(I) at bus B* during sub-interval I of hour H. The IDSO must then send price signals to its managed households before the start of I that adjust their total price-sensitive HVAC load for I by an appropriate amount. The metric used to verify this adjustment is the deviation [L(I) – L*(I)], where L(I) is the total household load for I implied by the IDSO’s fixed demand bid submitted into the day-D DAM for hour H, and L*(I) is the actual total household load during I. This deviation should equal p*(I), implying the IDSO has provided a load reduction (if p*(I) > 0) or a load increase (if p*(I) < 0) relative to the originally anticipated total household load L(I) for I.

- $\varphi(H)$ = Performance payment method for any actual ancillary service provision during hour H.

  NOTE: For all reported TC2 test cases, $\varphi(H)$ is specified as follows. If the ITSO clears SC and ultimately dispatches the IDSO to maintain a feasible down/up power level p(I) at bus B* during an RTM SCED sub-interval I of hour H, the IDSO is to be compensated for |p(I)| (MWh) in accordance with the RTM LMP ($/MWh) determined for interval I of hour H at the linkage bus B*.

- The IDSO must ensure that its SC offer is physically feasible and can be met without violating distribution reliability constraints.

TC1 vs. TC2 Comparative Studies: Specific Design Features

- Fixed Demand Bid Submitted into DAM by IDSO:

  Fixed demand bid submitted by IDSO into the DAM for both TC1 and TC2 are the same, given as in Fig. 31 (Slide 44) .

- Swing Contract Offer Submitted Into DAM by IDSO:

  For TC2, additionally, the swing contract offer submitted by the IDSO into the DAM for each hour H is given by

$$SC = (\alpha, PP(H), \varphi(H))$$

where:

$\alpha = 0$

$PP(H) =$ Power-path set = $(B^*, t^s(H), t^e(H), P(H))$

$B^* =$ Power-path delivery location (linkage bus) = Bus 2

$t^s(H) =$ Start-time of hour H

$t^e(H) =$ End-time of hour H

$P(H) = [P^{min}, P^{max}] =$ Feasible power range for H = [0MW, 0.5MW]

$\varphi(H) =$ Performance payment method for hour H is as explained on Slide 45

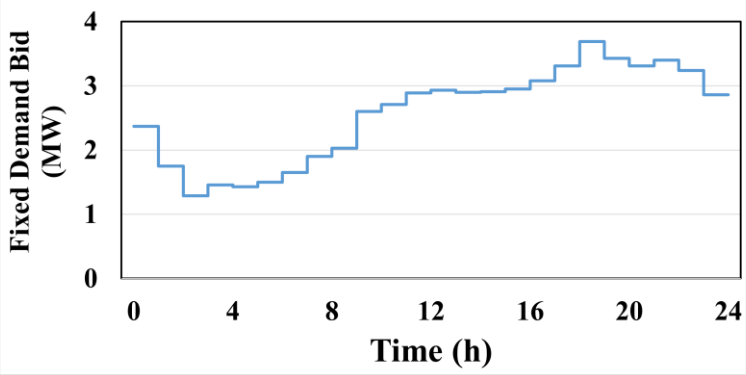


Fig. 31 (from Slide 44): Fixed demand bid submitted for TC1 and TC2

Note 1: ITSO uses the above IDSO fixed demand bid and SC offer in addition to offers it receives from other market participants, such as GenCos and other IDSOs, in determining its DAM SCUC and RTM SCED outcomes.

Note 2: The key difference between this proposed ancillary service provision method and existing demand response methods is that the IDSO's compensation for real-time ancillary service provision is determined in accordance with the IDSO's SC offer submitted into the DAM, not by means of an historically determined "base line" IDSO power procurement profile.

TC1 vs. TC2 Comparative Studies: Data Inputs

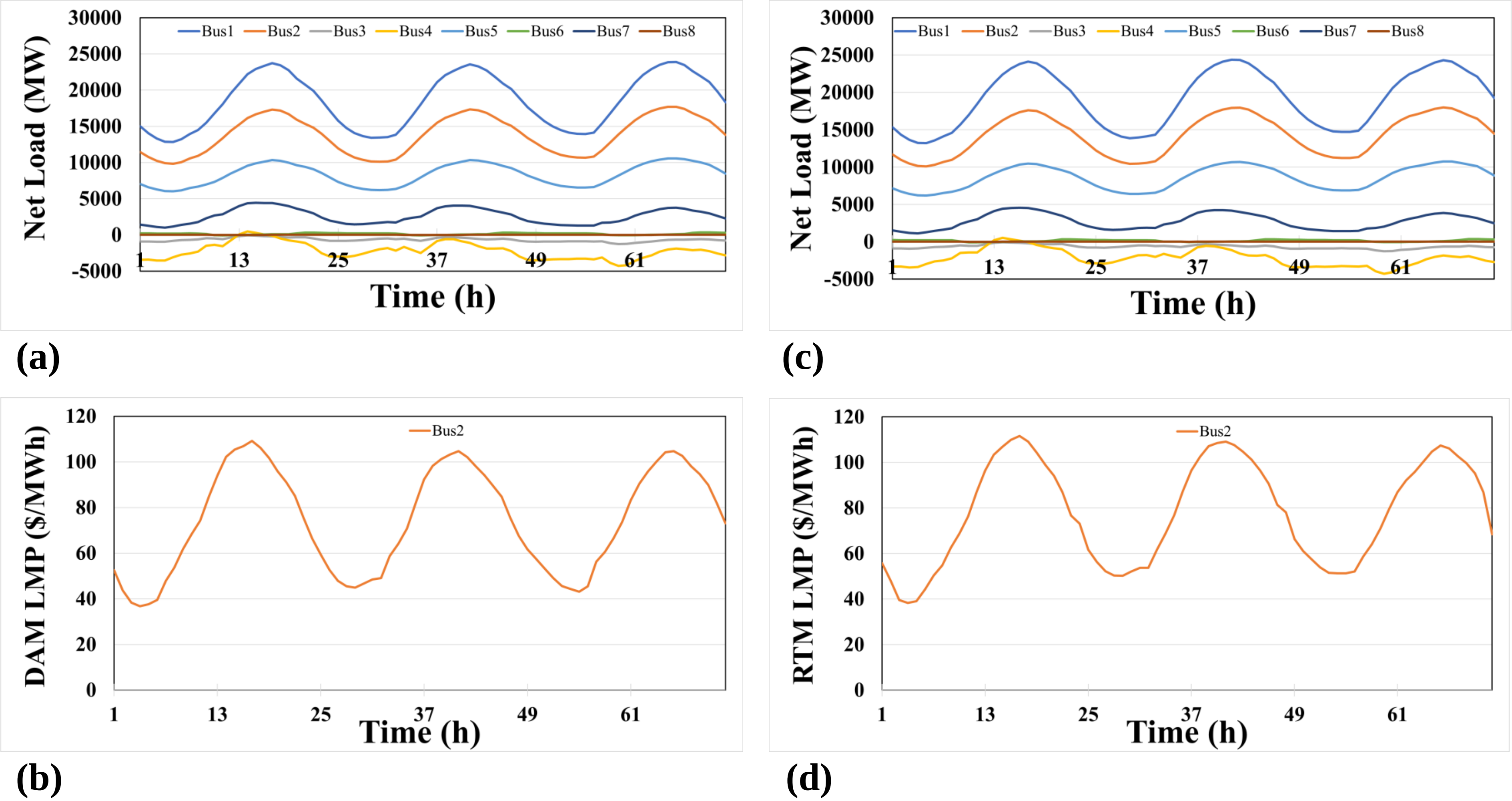
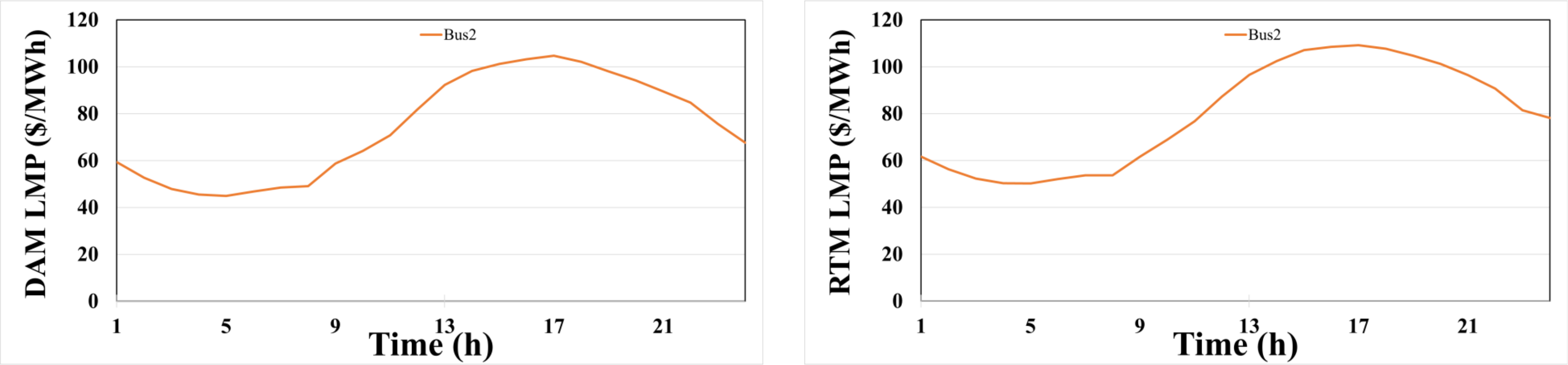
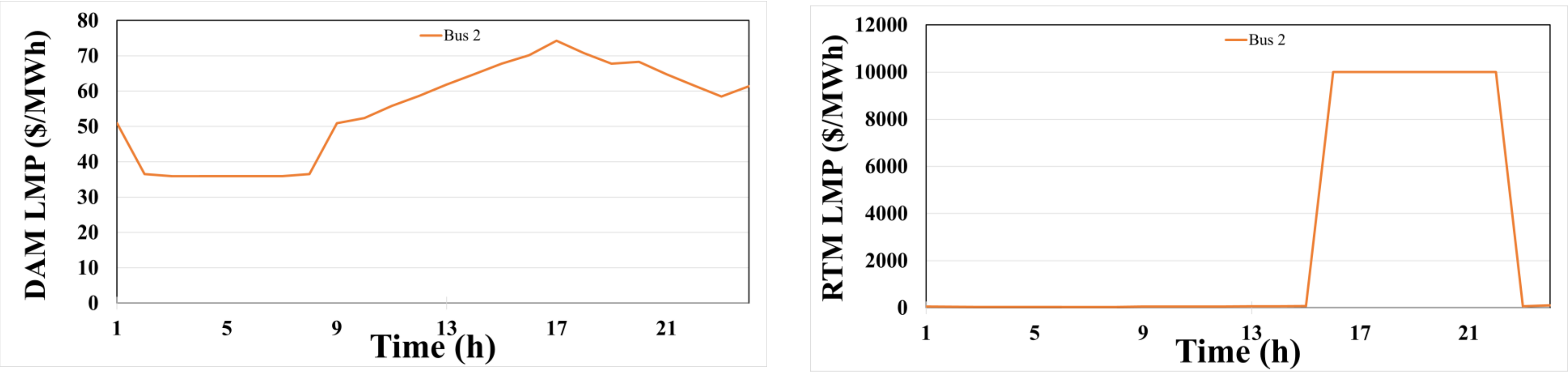


Fig. 33. (a) Day-ahead forecasted hourly net load for three consecutive simulated days
(b) Corresponding DAM LMPs for the DAM profile given in (a)
(c) Realized hourly net load for three consecutive simulated days
(d) Corresponding RTM LMPs for the RTM profile given in (c)

TC1 vs. TC2 Comparative Studies: Data Inputs … Continued



(a) DAM LMP Scenario 1 (b) RTM LMP Scenario 1



(c) DAM LMP Scenario 2 (d) RTM LMP Scenario 2

Fig. 34. Price scenarios for TC1 vs. TC2 comparative studies

TC1 vs. TC2 Comparative Studies: Metrics & Cases

Metrics for Comparison: For each household h,

Benefit : $\text{Benefit}^h(H, D+1) = \text{Comfort}^h(H, D+1) + \mu^h\,[\text{ASRev}^h(H, D+1)]$

Cost : $\text{Cost}^h(H, D+1) = \mu^h\,[\text{ElectricityCost}^h(H, D+1)]$

Net Benefit : $\text{NetBenefit}^h(H, D+1) = \text{Benefit}^h(H, D+1) - \text{Cost}^h(H, D+1)$

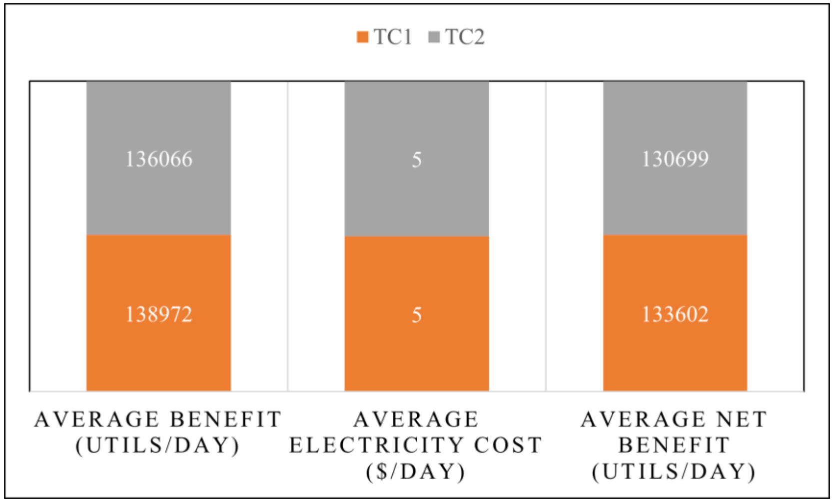
where μ^h (utils/¢) = marginal utility of money for household h

Three Cases:

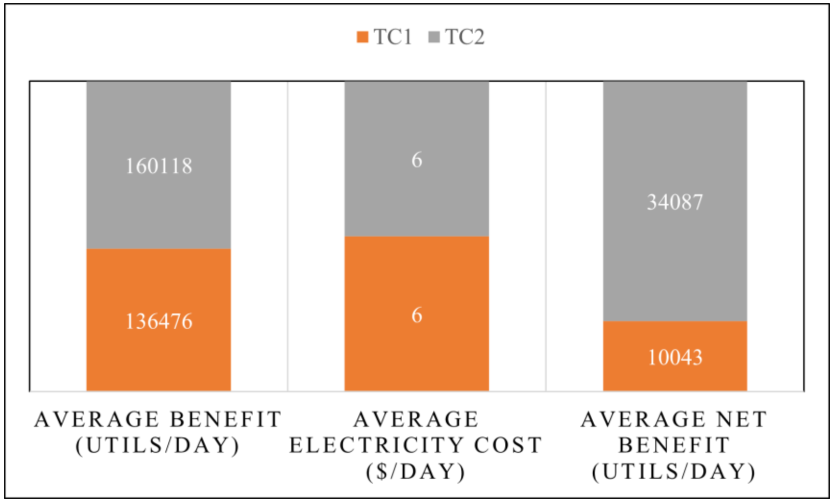
Comparison of TC1 and TC2 is performed for the following three cases:

- Case (C1): $\mu = 10$ for all h; DAM and RTM LMPs set as in Fig. 34 (a) & (b)
- Case (C2): $\mu = 200$ for all h; DAM and RTM LMPs set as in Fig. 34 (a) & (b)
- Case (C3): $\mu = 10$ for all h; DAM and RTM LMPs set as in Fig. 34 (c) & (d)

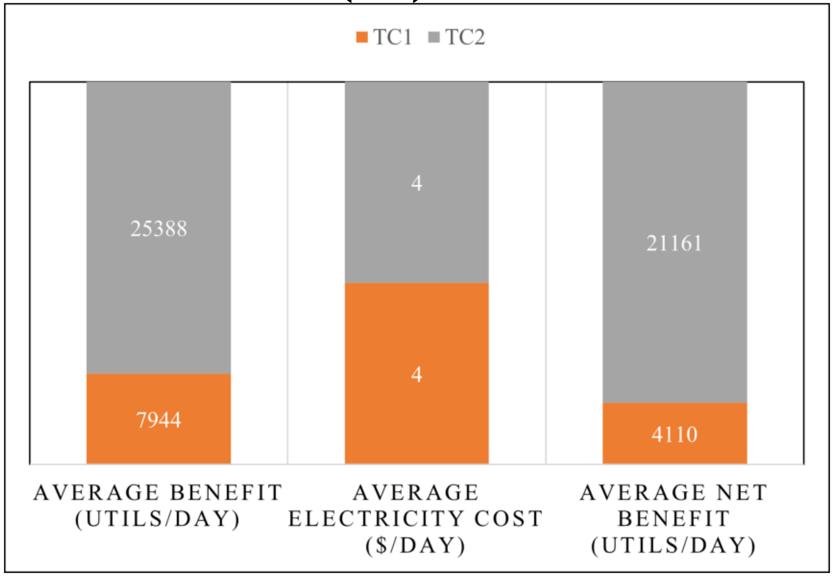
Benefit, Cost, and Net Benefit Outcome Comparisons



(C1)



(C2)

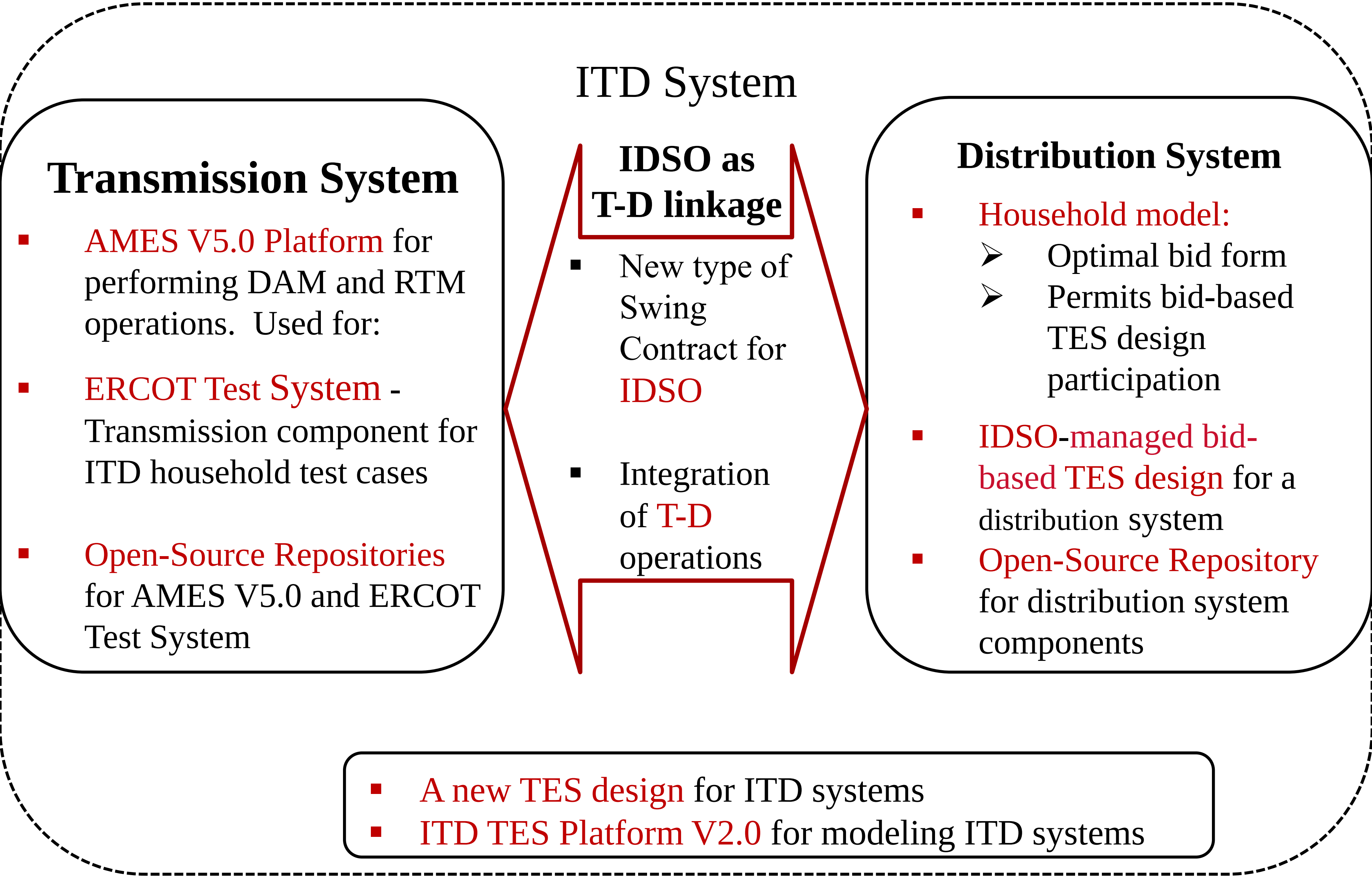


(C3)

Fig. 36. Stacked column charts reporting percentage comparisons of household average benefit, cost, and net benefit outcomes with (TC2) and without (TC1) the IDSO submission of DAM swing-contract ancillary service offers. Comparative outcomes are separately reported for each of the three cases (C1), (C2), and (C3) described on Slide 48.

Observation: Average net benefit of households is sharply higher for TC2 in cases (C2) and (C3).

Research Contribution: Summary



ITD System

Transmission System

- AMES V5.0 Platform for performing DAM and RTM operations. Used for:
- ERCOT Test System - Transmission component for ITD household test cases
- Open-Source Repositories for AMES V5.0 and ERCOT Test System

IDSO as T-D linkage

- New type of Swing Contract for IDSO
- Integration of T-D operations

Distribution System

- Household model:
  - Optimal bid form
  - Permits bid-based TES design participation
- IDSO-managed bid-based TES design for a distribution system
- Open-Source Repository for distribution system components

- A new TES design for ITD systems
- ITD TES Platform V2.0 for modeling ITD systems

Conclusion: Overview

- The proposed TES design for ITD systems includes:
  - An IDSO-managed TES design for distribution systems that permits careful consideration of local customer goals, constraints, and privacy concerns
  - A state-conditioned bid form for GER-owned thermostatically controlled devices, such as HVACs, to permit their TES design participation
  - An IDSO modeled as a T-D linkage agent that can facilitate integration of transmission and distribution system operations
  - A new type of swing contract permitting IDSOs to participate in transmission system operations as providers of reserve

- The general efficacy of the proposed design for ITD participants is demonstrated by means of test-case simulations conducted using the ITD TES Platform V2.0.

- However, these test cases have also revealed that the implementation of an optimal bid form for GERs assuming a one-period look-ahead horizon has limitations. GER optimal bid forms based on look-ahead horizons that encompass multiple decision periods could potentially result in higher GER net benefit through consideration of sequentially correlated outcomes.

Conclusion: Topics for Future Study

- ❑ Extension of optimal bid form implementation to cases in which GERs have look-ahead horizons encompassing multiple decision periods
- ❑ Extension of the IDSO model to permit pursuit of more comprehensive objectives, such as the maximization of GER net benefit subject to explicitly imposed reliability constraints for distribution system operations
- ❑ Development of risk management strategies for the IDSO permitting it to harness ancillary services from different types of GERs for submission into multiple forward markets with different look-ahead horizons, without compromising distribution system reliability.

Conclusion: Publications, Reports and Software Releases

Peer-Reviewed Journal Articles:

[1] **S. Battula**, L. Tesfatsion, and Z. Wang (2020). "A Customer-Centric Approach to Bid-Based Transactive Energy System Design," *IEEE Transactions on Smart Grid*, 11(6), 4996-5008.

[2] **S. Battula**, L. Tesfatsion, and T.E. McDermott (2020). "An ERCOT Test System for Market Design Studies," *Applied Energy*, Vol. 275, October. DOI: 10.1016/j.apenergy.2020.115182

[3] H.T. Nguyen, **S. Battula**, R.R. Takkala, Z. Wang and L. Tesfatsion (2019). "An Integrated Transmission and Distribution Test System for Evaluation of Transactive Energy Designs," *Applied Energy*, Vol. 240, pp. 666-679.

Journal Article under Preparation:

[4] **S. Battula**, L. Tesfatsion, and Z. Wang (2020). "IDSO managed bid-based TES design for linked market operation of ITD systems," *in preparation*.

Documentation Reports:

[5] L. Tesfatsion and **S. Battula (2020).** "Analytical SCUC/SCED Optimization Formulation for AMES V5.0," AMES V5.0 Documentation, Econ Working Paper #20014, ISU Digital Repository.

[6] L. Tesfatsion and **S. Battula (2020).** "Notes on the GridLAB-D Household Equivalent Thermal Parameter Model," ITD TES Platform V2.0 Documentation, Econ Working Paper #19001, ISU Digital Rep., July revision.

Open-Source Software Releases:

[7] **S. Battula** and L. Tesfatsion (2020). *AMES V5.0 GitHub Code/Data Repository.* https://github.com/ames-market/AMES-V5.0

[8] **S. Battula**, L. Tesfatsion, and T.E. McDermott (2020). *ERCOT Test System Code/Data Repo.* https://github.com/ITDProject/ERCOTTestSystem

[9] **S. Battula** and L. Tesfatsion (2020). *ITD Project/Household Formulation (Python): Code/Data Repository.* https://github.com/ITDProject/HouseholdFormulationRepository

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Thank you