Iowa State University

Department of Economics, Department of Electrical & Computer Engineering

Q15 Report: Project DE-OE 0000839

Project Start: 1/1/2017

Project End (With No-Cost Extension): 9/30/2020

Flexible Service Contracting for Risk Management within Integrated Transmission and Distribution Systems

Iowa State University Project Team

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DOE WebEx Meeting

25 November 2020

Presentation Outline

- Overview of our four completed project goals
- Project pubs, reports, & software releases (2020)
- Project-related presentations (2020)
- Q15 project task & activities: Summary
- Q15 project task & activities: Details
- Conclusion

Project Goal 1 (Done)

- Develop a bid-based *Transactive Energy System (TES)* design managed by an *Independent Distribution System Operator (IDSO)*

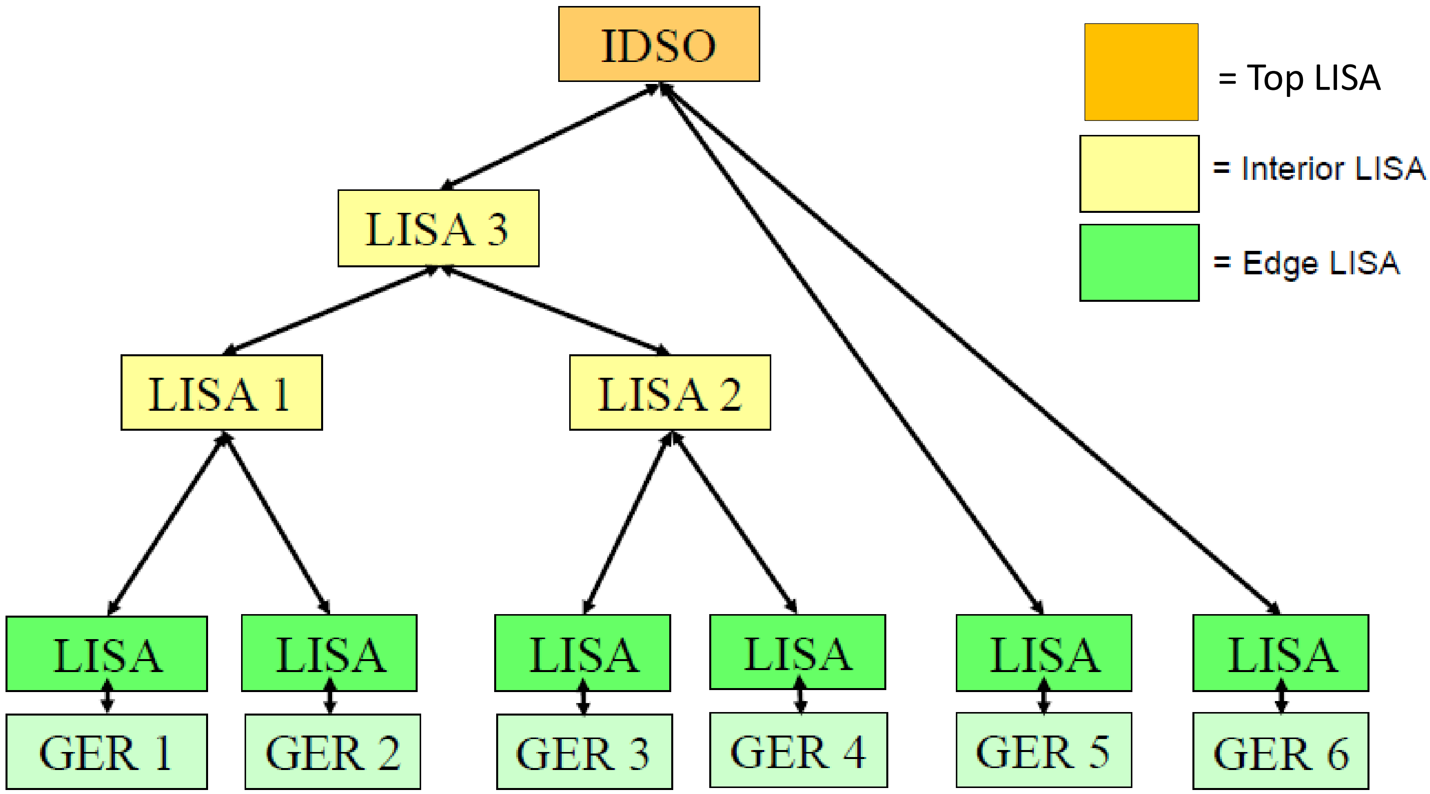


Fig. 1: Illustrative two-way communication network of Local Intelligent Software Agents (LISAs) for an IDSO-managed bid-based TES design with Grid-Edge Resource (GER) participants

Project Goal 2 (Done)

- Develop swing contracts permitting IDSOs to offer flexible reserve (dispatchable down/up power paths) into ISO-managed wholesale power markets

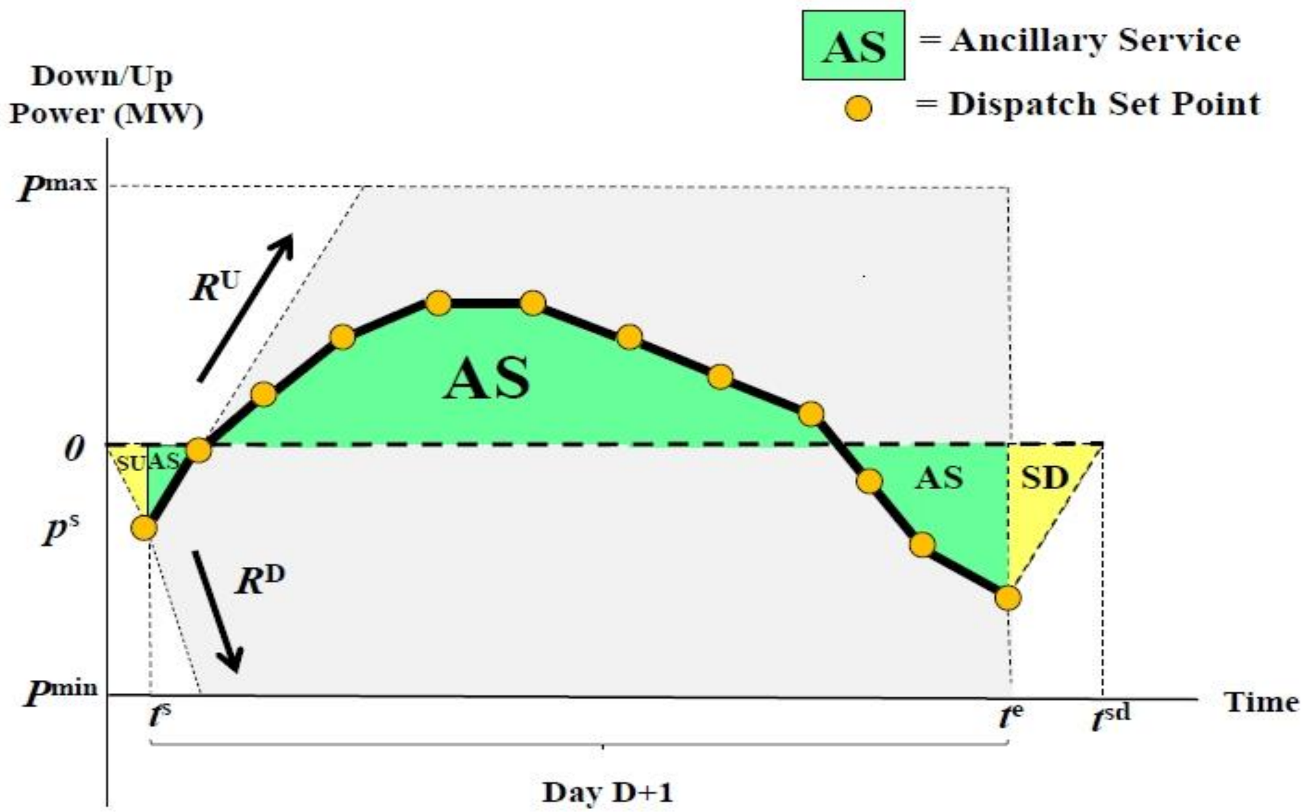


Fig. 2: One among many possible power paths an IDSO could be dispatched to deliver during day D+1 if its swing contract offering flexible down/up power & ramp is cleared in a day-D DAM

Project Goal 3 (Done)

- Develop a platform permitting evaluation of our proposed IDSO-managed bid-based TES design within an *Integrated Transmission and Distribution (ITD)* system

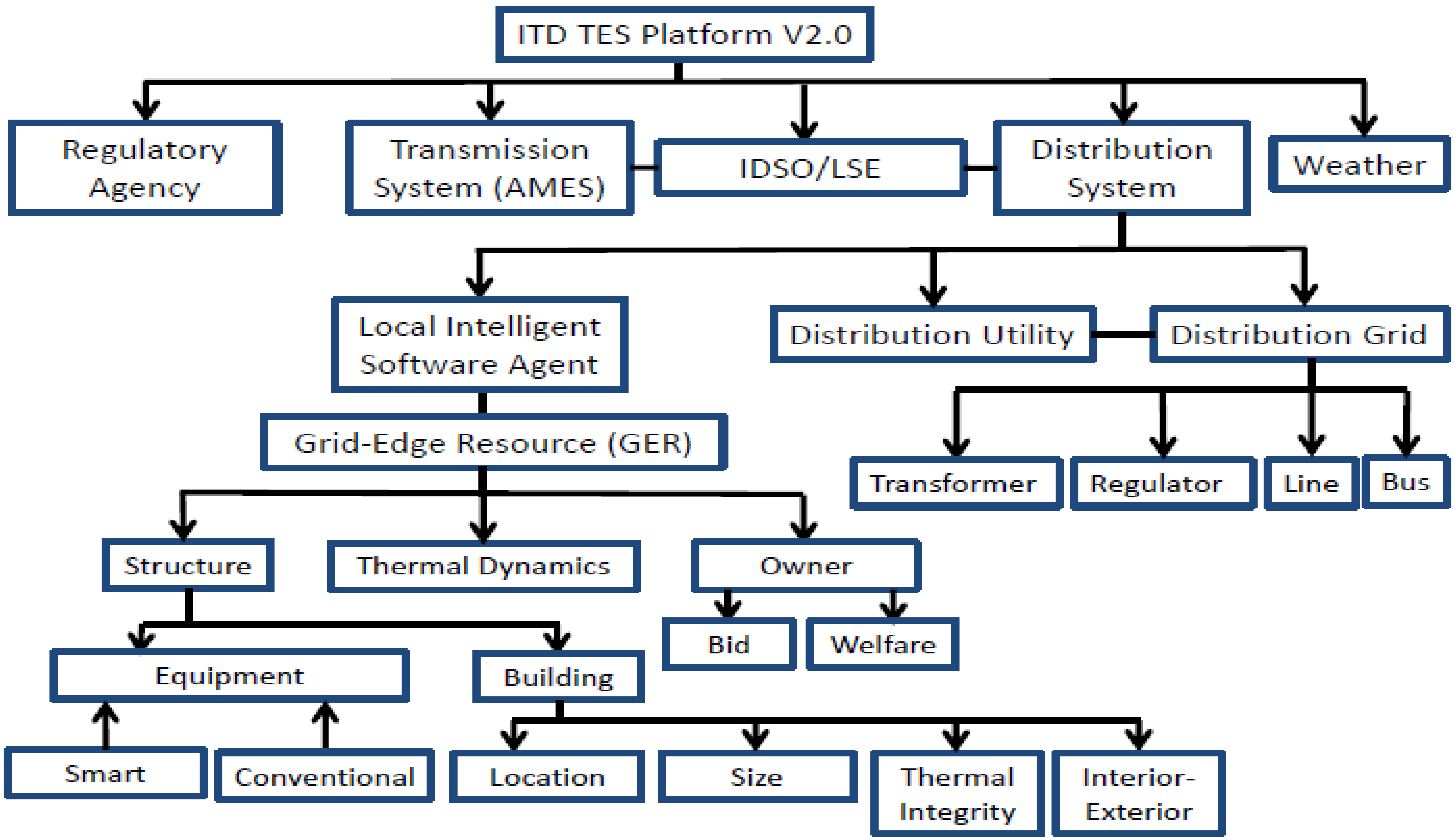


Fig. 3: Partial agent hierarchy for the ITD TES Platform V2.0

Project Goal 3 (Done) … Continued

- *Transmission component for the ITD TES Platform V2.0*
  — *AMES V5.0* **https://github.com/ames-market/AMES-V5.0**

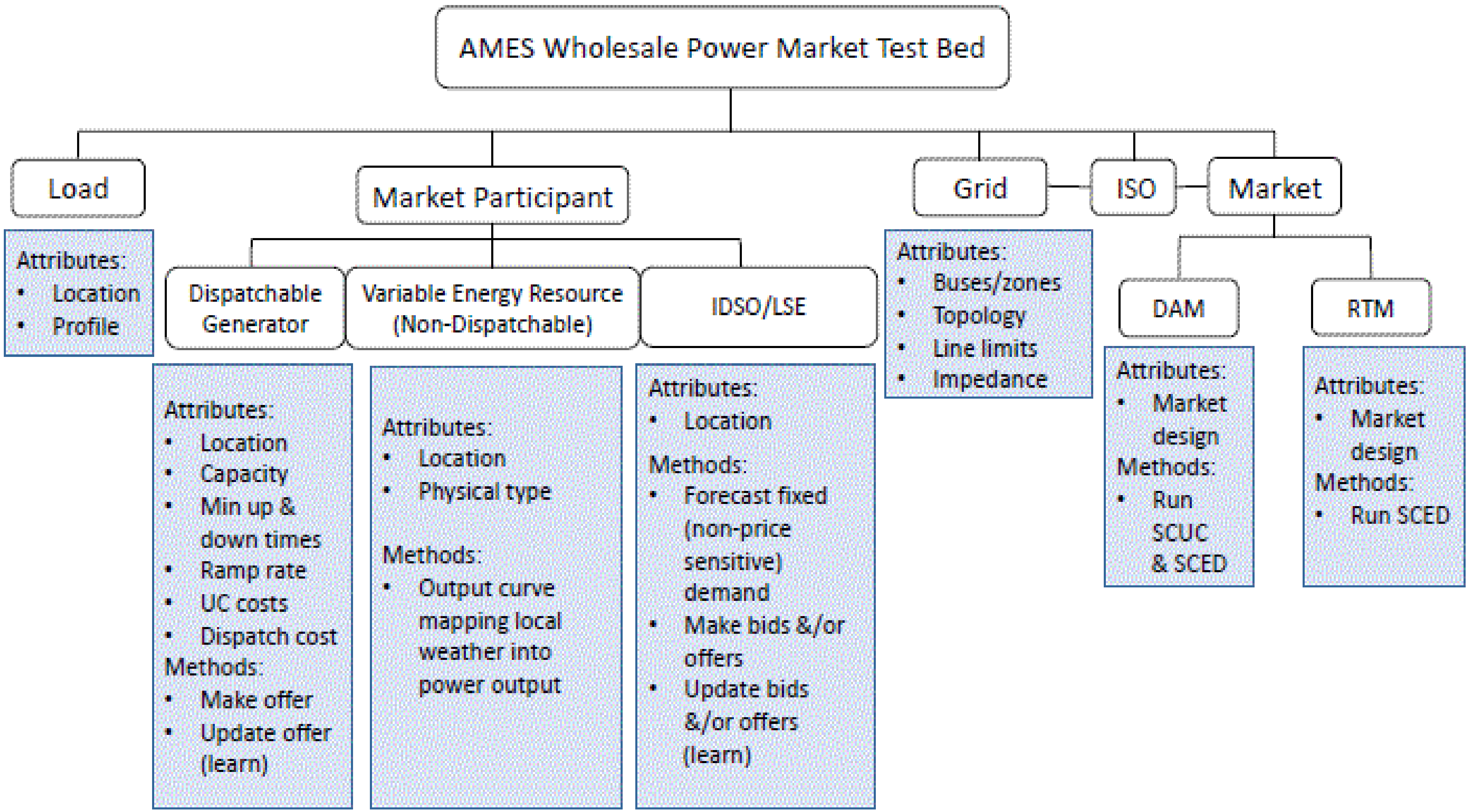


Fig. 4: Partial agent hierarchy for AMES V5.0

Project Goal 3 (Done) … Continued

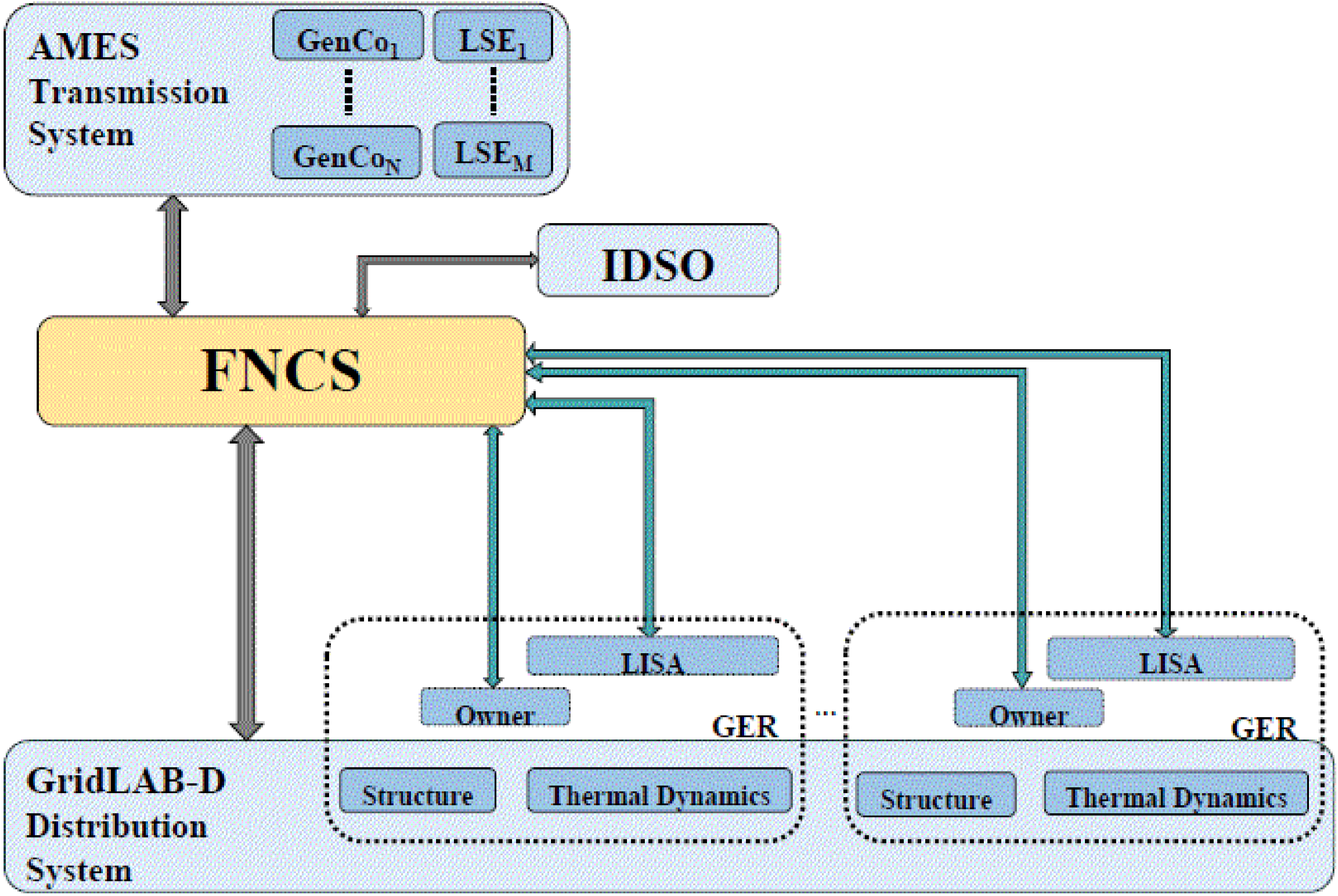


Fig. 5: Key software components for the ITD TES Platform V2.0

Project Goal 4 (Done)

- Use our ITD TES Platform V2.0 to evaluate our proposed IDSO-managed bid-based TES design

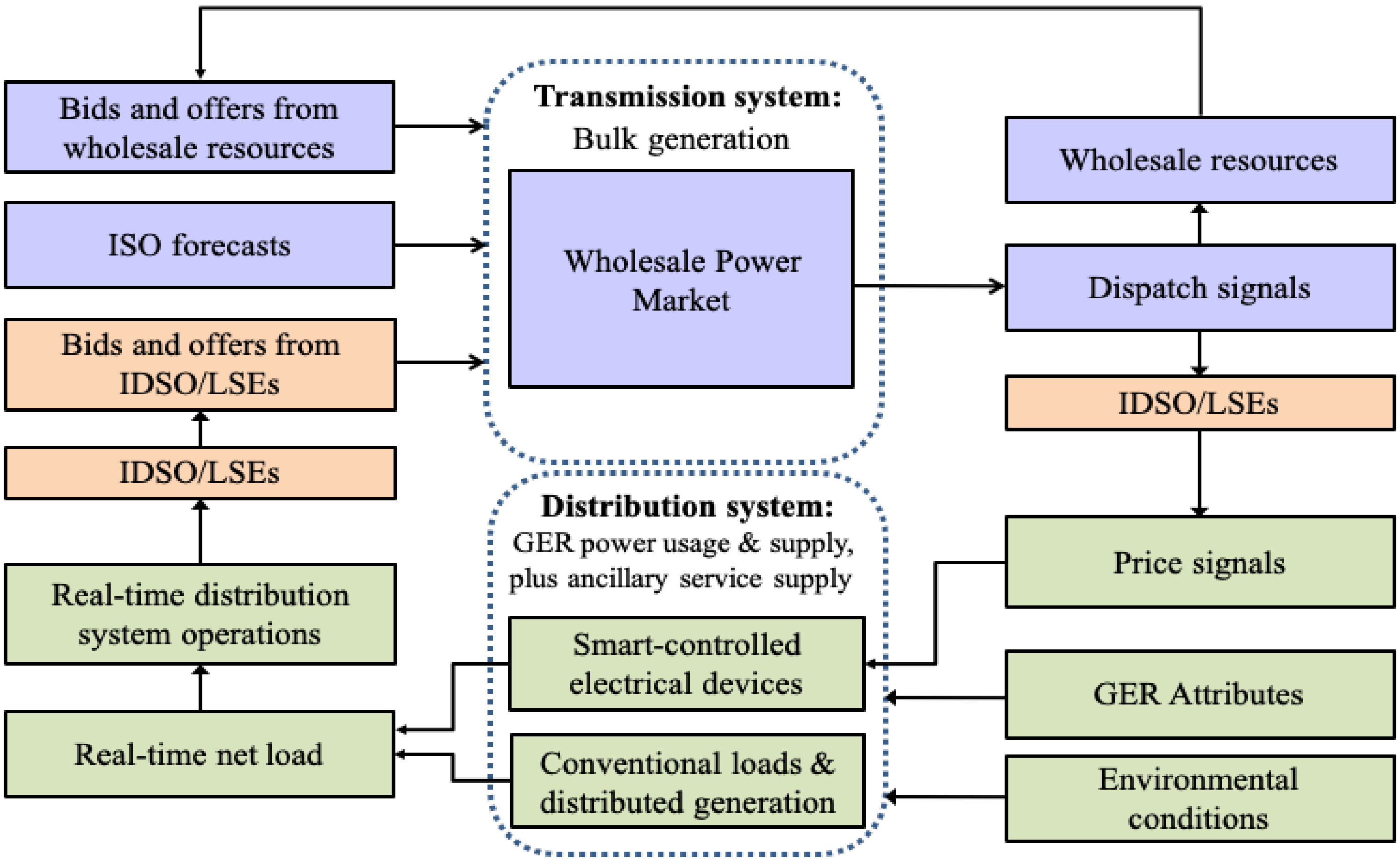


Fig 6: ITD TES Platform V2.0 modeling of an IDSO-managed bid-based TES design

Project Publications and Reports (2020)

[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] L. Tesfatsion (2020). *A New Swing-Contract Design for Wholesale Power Markets*, 21 Chapters, 272pp., Wiley/IEEE Press, scheduled December 20 release.

[4] 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.

[5] 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 (2020), *Transactive Energy System Design for Integrated Transmission and Distribution Systems*, PhD Thesis, Department of Electrical & Computer Engineering, Iowa State University, in progress.

Open-Source Software Releases (2020)

[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

Project-Related Presentations (2020)

- **Leigh Tesfatsion (2020)**. "A New Swing-Contract Design for Wholesale Power Markets," WebEx presentation, sponsored by the Electric Power Research Institute (EPRI), September 18.
  http://www2.econ.iastate.edu/tesfatsi/SlideSet.EPRIWebinar18Sept2020.Tesfatsion.FinalRev.pdf

- Rui Cheng, **Leigh Tesfatsion**, & **Zhaoyu Wang (2020)**. "Multi-Period Consensus-Based Transactive Control in an Unbalanced Distribution Network," Transactive Energy Systems Theory Workshop (WebEx), Pacific Northwest National Laboratory, September 14-17.
  http://www2.econ.iastate.edu/tesfatsi/MultiPeriodConsensusTC.RChengEtAl.TESWorkshop.17Sept2020.pdf

Q15 Project Task & Activities: Summary

			Q15 Activities	Comments on Q15 Activities
Q15 Task **Verify and evaluate the proposed flexible contracting system**	**9/30/2020**	**9/30/2020**	A1: Development of a bid-based *transactive energy system (TES)* design managed by an *independent distribution system operator (IDSO)* permitting the IDSO to function both as a power manager for a collection of *grid-edge resources (GERs)* at the distribution level and a DAM/RTM participant at the transmission level. A2: Use of the ITD TES Platform Version 2.0 to evaluate the performance of this TES design within an *integrated transmission and distribution (ITD)* system	**Activities A1 and A2 were undertaken to fulfill Goal 4, our final DOE project goal.**

Q15 Activities: Project Goal 4

- Suppose an IDSO operates at a T-D interface for an ITD system.
  - The IDSO can submit bids into the T-system wholesale power market for purchase/sale of power and ancillary service supply.
  - The IDSO manages a bid-based TES design for the D-system to service the power needs of *grid-edge resources (GERs).*

Challenge: Can T-system bids & a D-system bid-based TES design be formulated in a manner that permits the IDSO to align system goals/constraints with GER goals/constraints?

- Preliminary affirmative test cases, published in *IEEE TSG* (Ref. [1]), were discussed in our Q14 DOE project report

TES Design for IDSO-Managed Grid-Edge Resources

- The IDSO is the top-level ***Local Intelligent Software Agent (LISA)*** in a 2-way ***LISA communication network*** for ***grid-edge resources (GERs).***

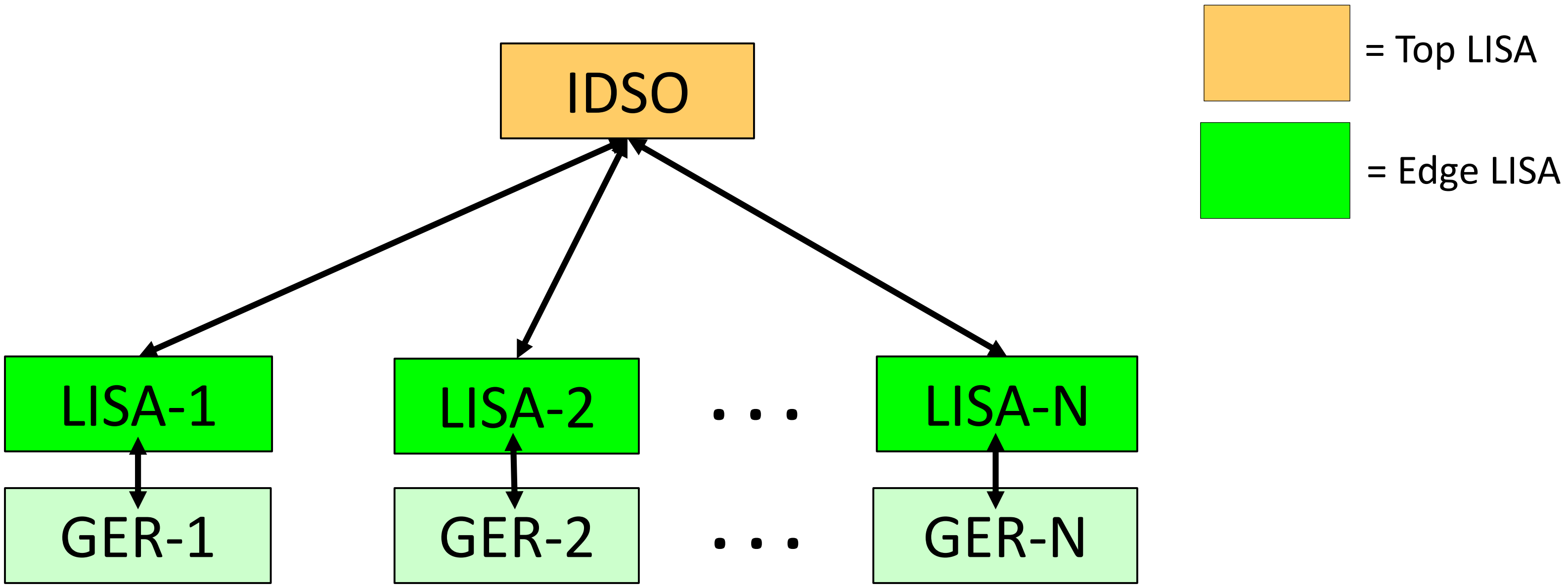


Fig. 7: LISA communication network for GERs with smart (price-sensitive) devices

Grid-Edge Resource: General Formulation

- Each GER in the LISA communication network is characterized by a hierarchy of attributes

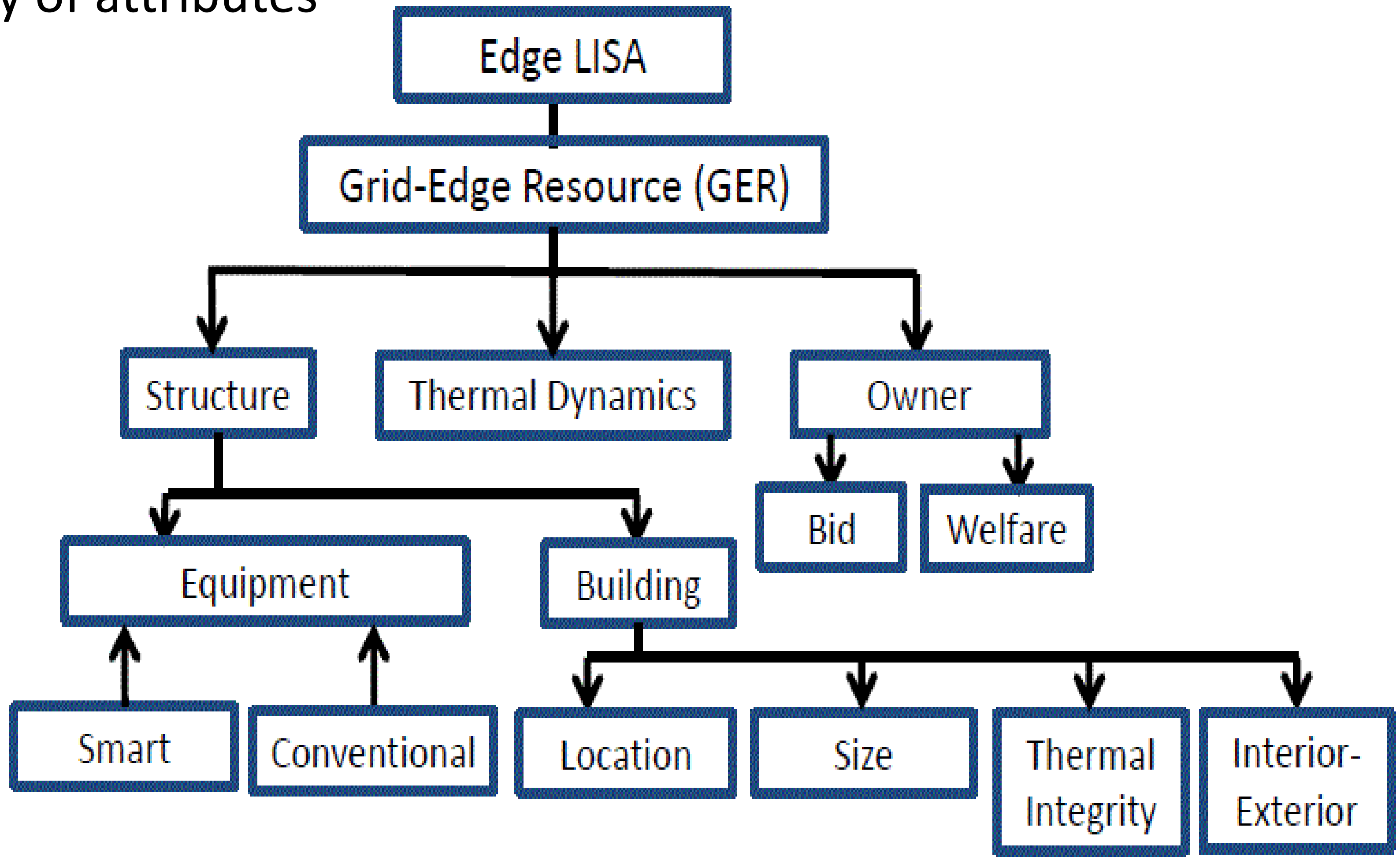


Fig. 8: Partial attribute hierarchy for a grid-edge resource (GER) managed by an edge local intelligent software agent (LISA)

Five-Step TES Design for IDSO-Managed GERs

Step 1: Edge LISA for each GER R collects data on state of R and each smart device v(R) owned by R at a *data check rate* and uses data to form state-conditioned device bid functions $Bid_v(R)$ for power demand, power supply and/or ancillary service supply.

Step 2: Edge LISA for each GER R uses the device bid functions $Bid_v(R)$ to form a state-conditioned vector **Bid**(R) consisting or one or more aggregate device bid functions, which it communicates to the IDSO at a *bid refresh rate*.

Step 3: IDSO uses latest vectors **Bid**(R) received from edge LISAs to form a vector **AggBid** of one or more aggregate bid functions at an *aggregate bid refresh rate*.

Step 4: IDSO uses **AggBid** to determine price signals that it communicates back to the edge LISAs at a *price signal rate*.

Step 5 (Control Step): Edge LISA for each GER R inserts its latest received price signals into its latest refreshed state-conditioned device bid functions $Bid_v(R)$ at a *power control rate*, which triggers a power response from each smart device v(R).

Five-Step TES Design: Timing

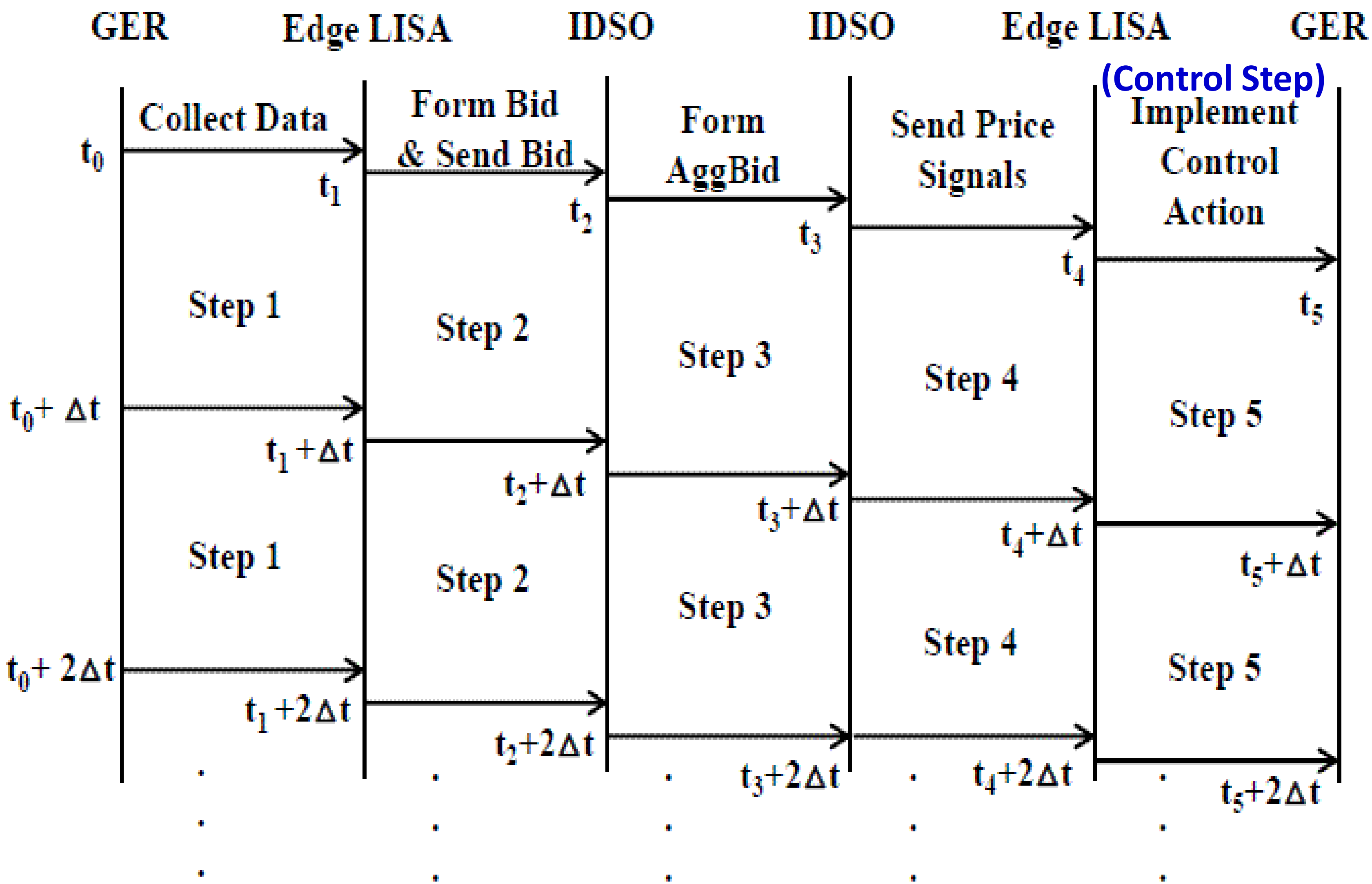
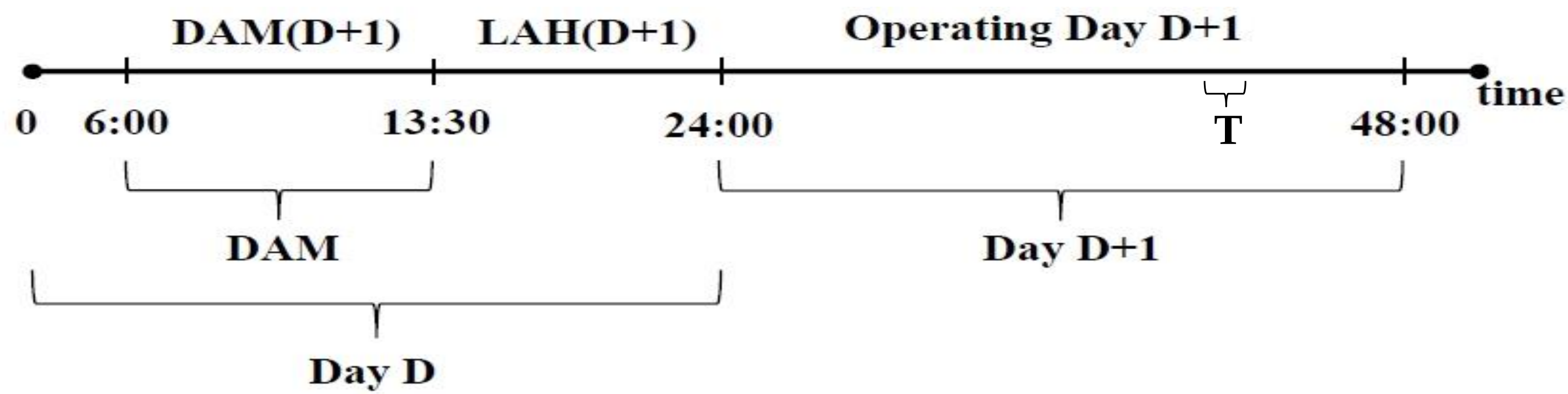


Fig. 9: Illustration of the staggered timing implementation for the Five-Step TES Design

Timing Coordination of TES Design for GERs with ***Day-Ahead Market (DAM)*** & ***Real-Time Market (RTM)*** operations at the transmission level



- An IDSO manages power needs for GERs via the Five-Step TES Design.
- Each operating day D+1 is partitioned into twenty-four *DAM operating hours H*, and finitely many *RTM operating periods T*.
- The IDSO on day D submits bids/offers into the ITSO-managed DAM(D+1) to service the power needs of its GERs during each RTM operating period T on day D+1.
- At the start of day D+1 the IDSO knows the DAM LMPs & dispatch schedule for each operating hour H on day D+1 as determined in the DAM(D+1) held on day D.

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)

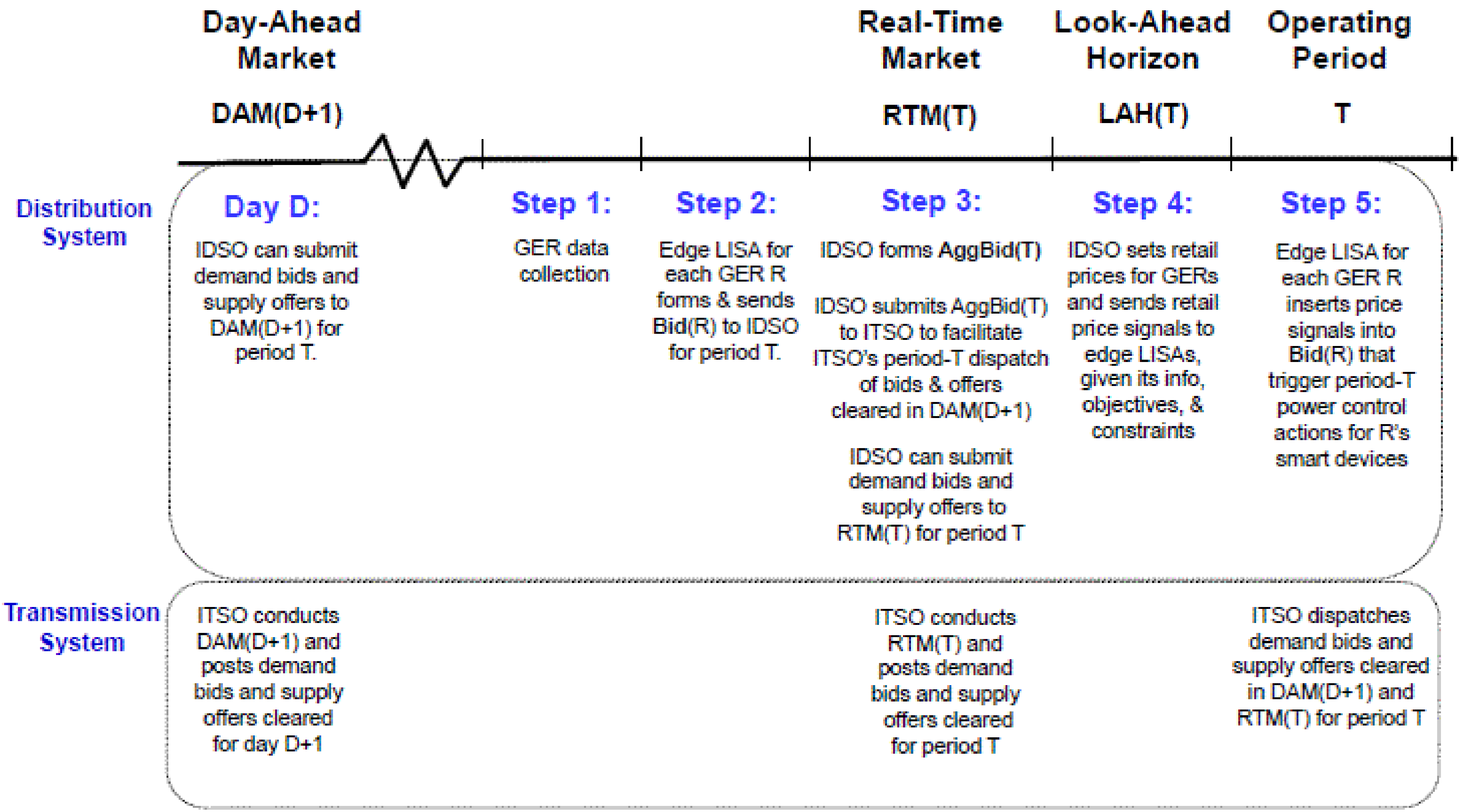


Fig. 11: Timing coordination

ITD Household Test Cases: Overview

- Each GER is a household that seeks to maximize its net benefit subject to local constraints
- Each household is characterized by attributes, as depicted below

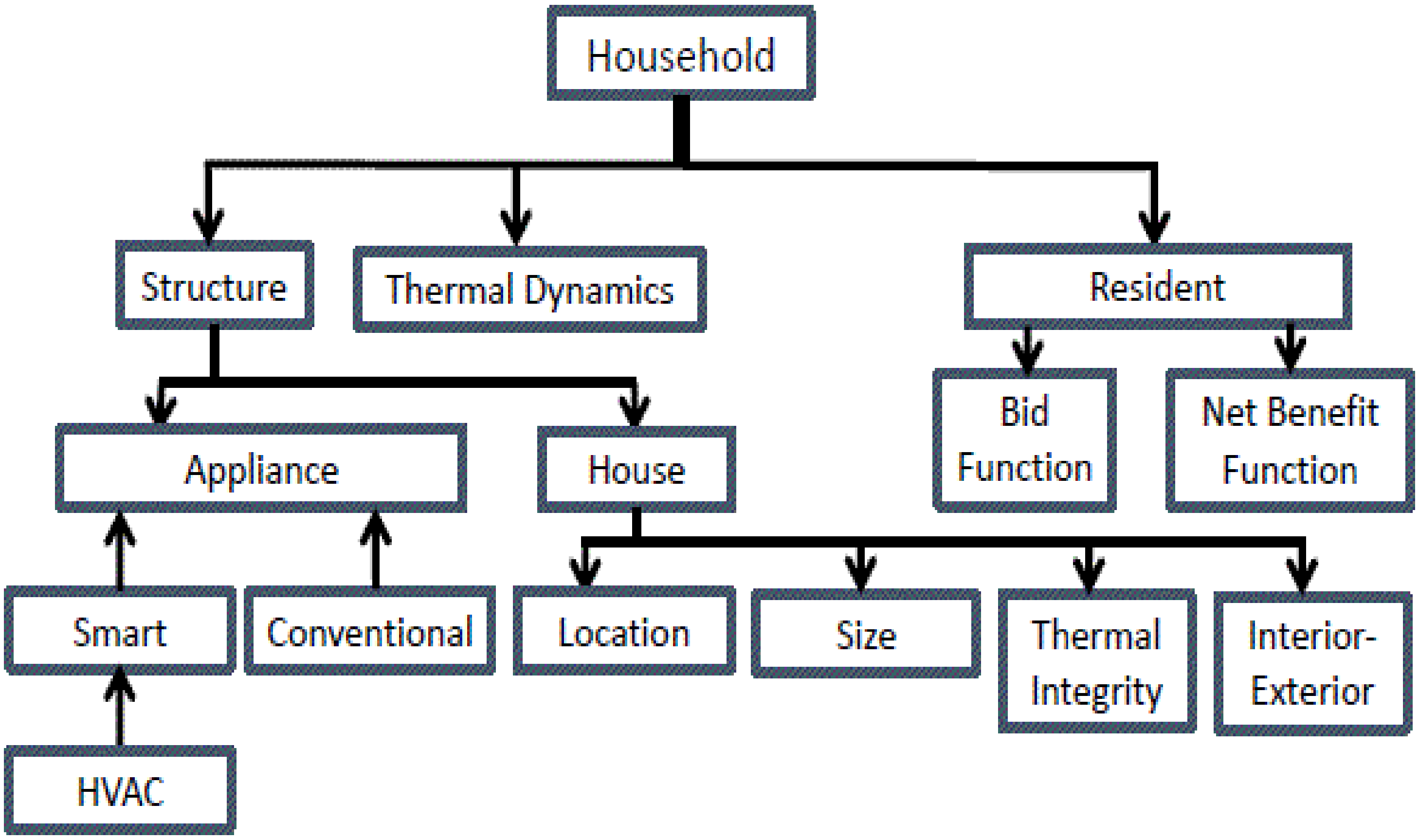


Fig. 12: Hierarchy of basic attributes characterizing a household

Household TES Design: Communication Network

❑ The IDSO is the top-level ***Local Intelligent Software Agent (LISA)*** in a two-way LISA communication network for D-system households

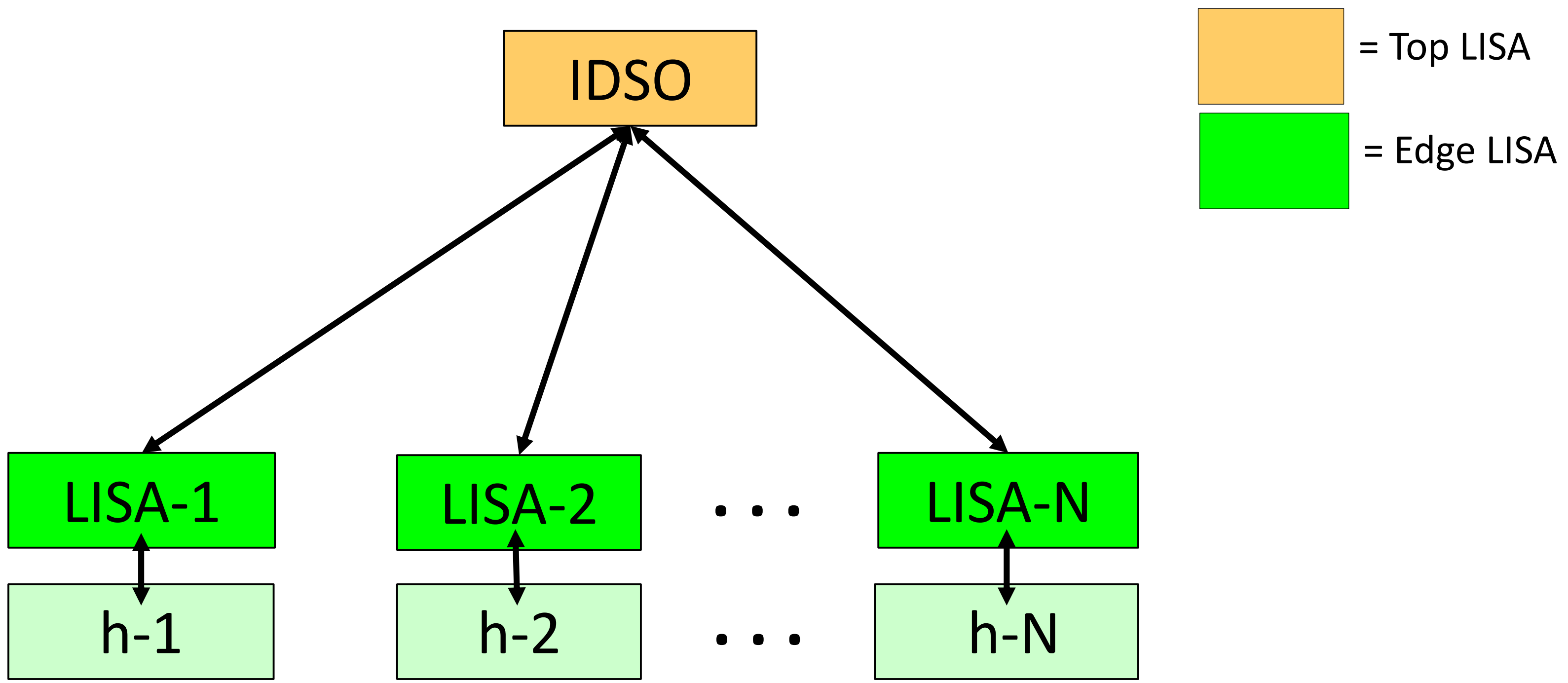


Fig. 13: Each household h has an HVAC system managed by a price-responsive HVAC controller (the edge LISA for h).

Household Five-Step TES Design

- The IDSO seeks to align/achieve D-system and household goals by iteratively implementing the following *Five-Step TES Design*:

STEP 1: HVAC controller for each household h collects data on h at a *data check rate* and uses these data to form a state-conditioned bid function Bid(h) for h's HVAC system. The bid function Bid(h) expresses either a demand schedule for HVAC power usage or a supply schedule for the HVAC provision of ancillary service (power absorption).

STEP 2: HVAC controller for each h communicates Bid(h) to IDSO at a *bid refresh rate*.

STEP 3: IDSO combines latest received household bid functions Bid(h) into a vector **AggBid** of one or more aggregate bid functions at an *aggregate bid refresh rate*.

STEP 4: IDSO uses **AggBid** to determine price signals that it communicates back to the household HVAC controllers at a *price signal rate.*

STEP 5 (Control-Step): HVAC controller for each household h inserts its latest received price signal into its latest refreshed state-conditioned bid function Bid(h) at a *power control rate*, which triggers an ON/OFF power control action for h's HVAC system.

Timing for Household Five-Step TES Design

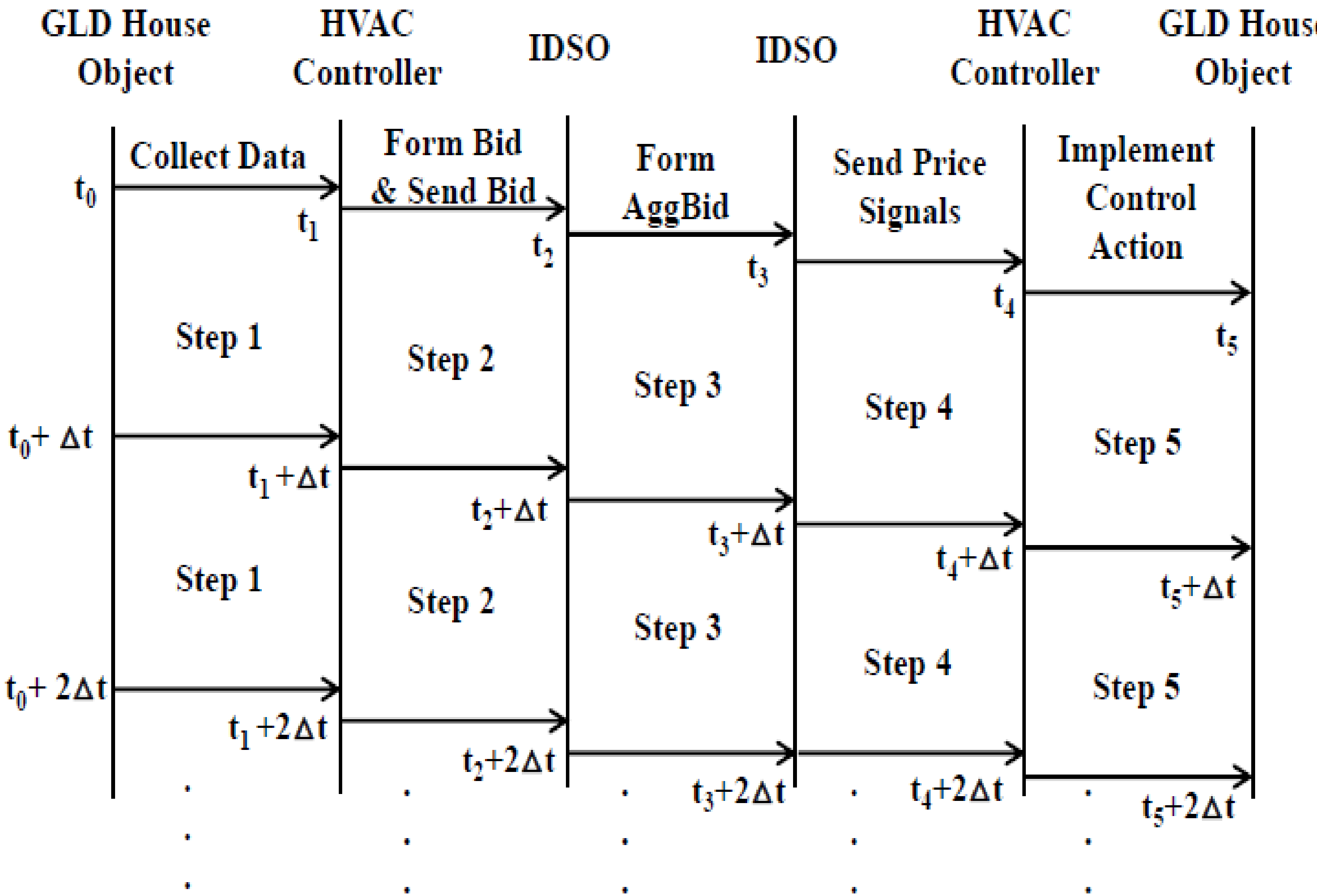


Fig. 14: Staggered implementation of the five steps comprising the Household Five-Step TES Design. Each action time-rate is commonly set equal to 1/Δt with time-step Δt = 300s for each of the Household ITD Test Cases reported below.

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

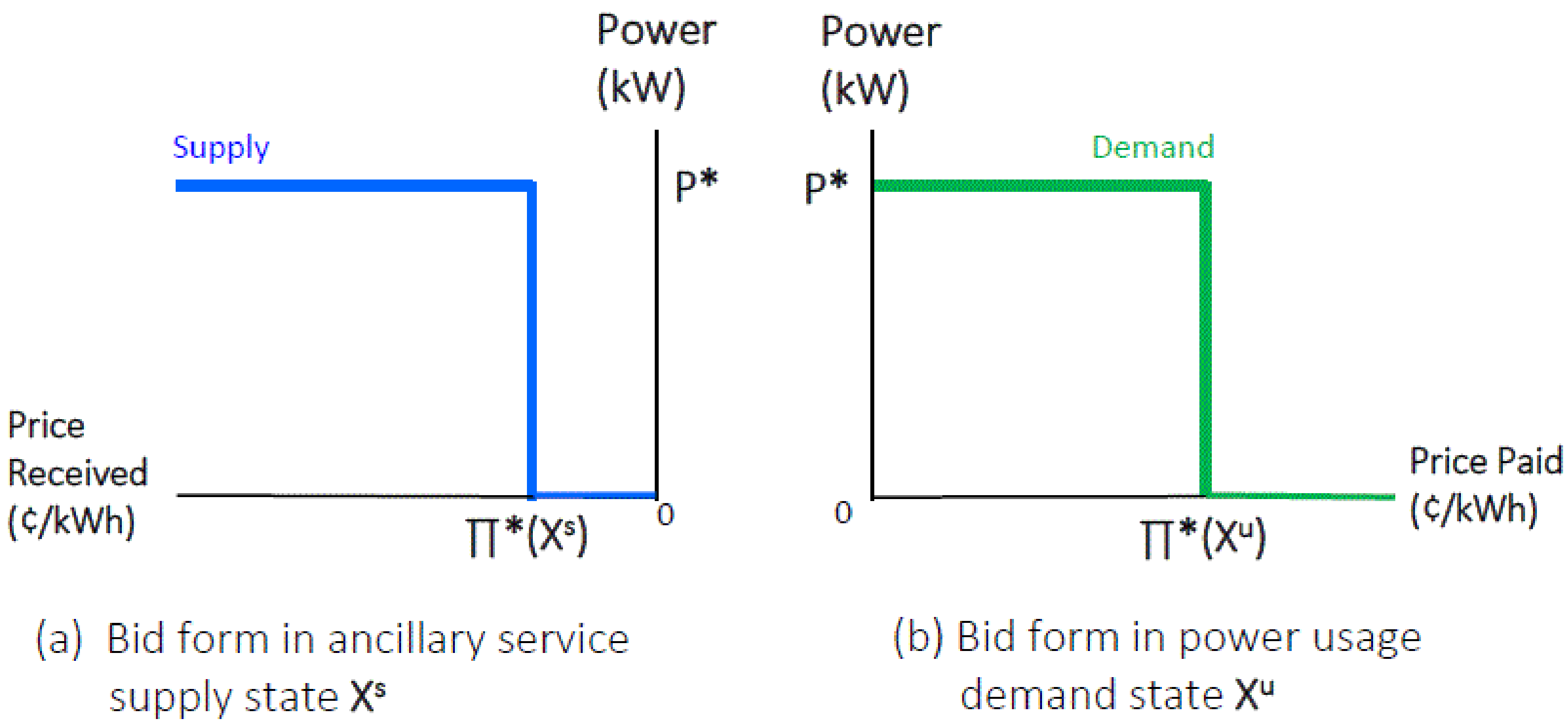


*Fig 15: Depending on its state at the start of a control-step n, a household h either (a) is willing to **supply ancillary service (HVAC power absorption)** as a function of price received or (b) is willing to **demand power for HVAC usage** as a function of price paid. A negative price denotes a supply price received; a positive price denotes a demand price paid; & P* = HVAC ON power usage.*

Household Classification Into Types

- Classification is based on correlated physical attributes

- *Low Structure Quality:*
  - HVAC system with a relatively poor performance rating
  - House that has a relatively small size
  - House that has relatively poor thermal insulation

- *Medium Structure Quality:*
  - HVAC system with an average performance rating
  - House that has an average size
  - House that has average thermal insulation

- *High Structure Quality:*
  - HVAC system with a relatively good performance rating
  - House that has a relatively large size
  - House that has relatively good thermal insulation

ITD Household Test Cases: Feedback Loop

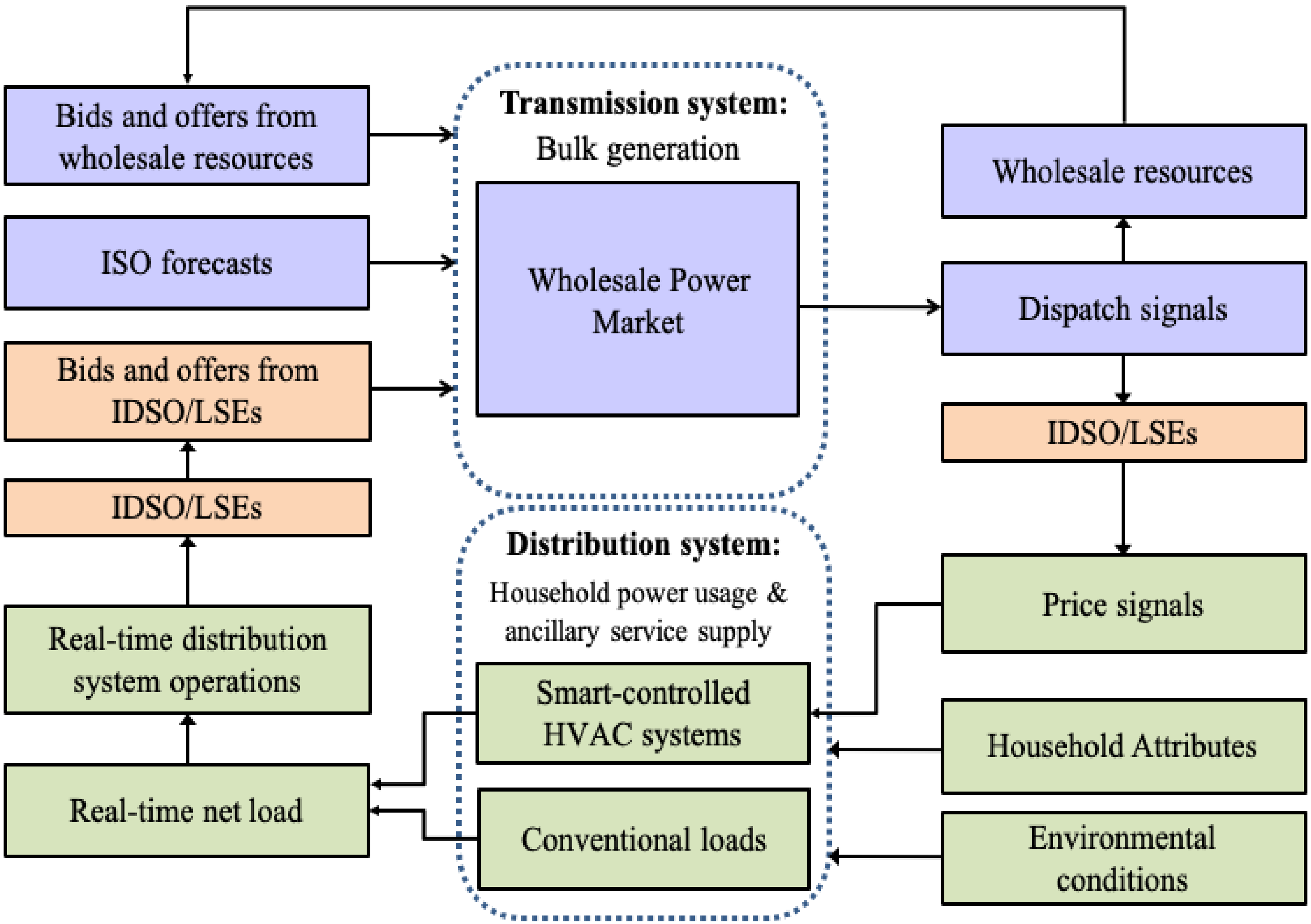


Fig. 16: ITD Feedback loop for each household test case

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 $\mu(h)$ (utils/$) denotes household h's comfort-cost trade-off parameter.

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

- The net benefit outcomes reported below are average net benefit attained by households for a particular operating day D

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: The two basic types of ITD Household Test Cases discussed in this report

TC1: Bid Function Comparison

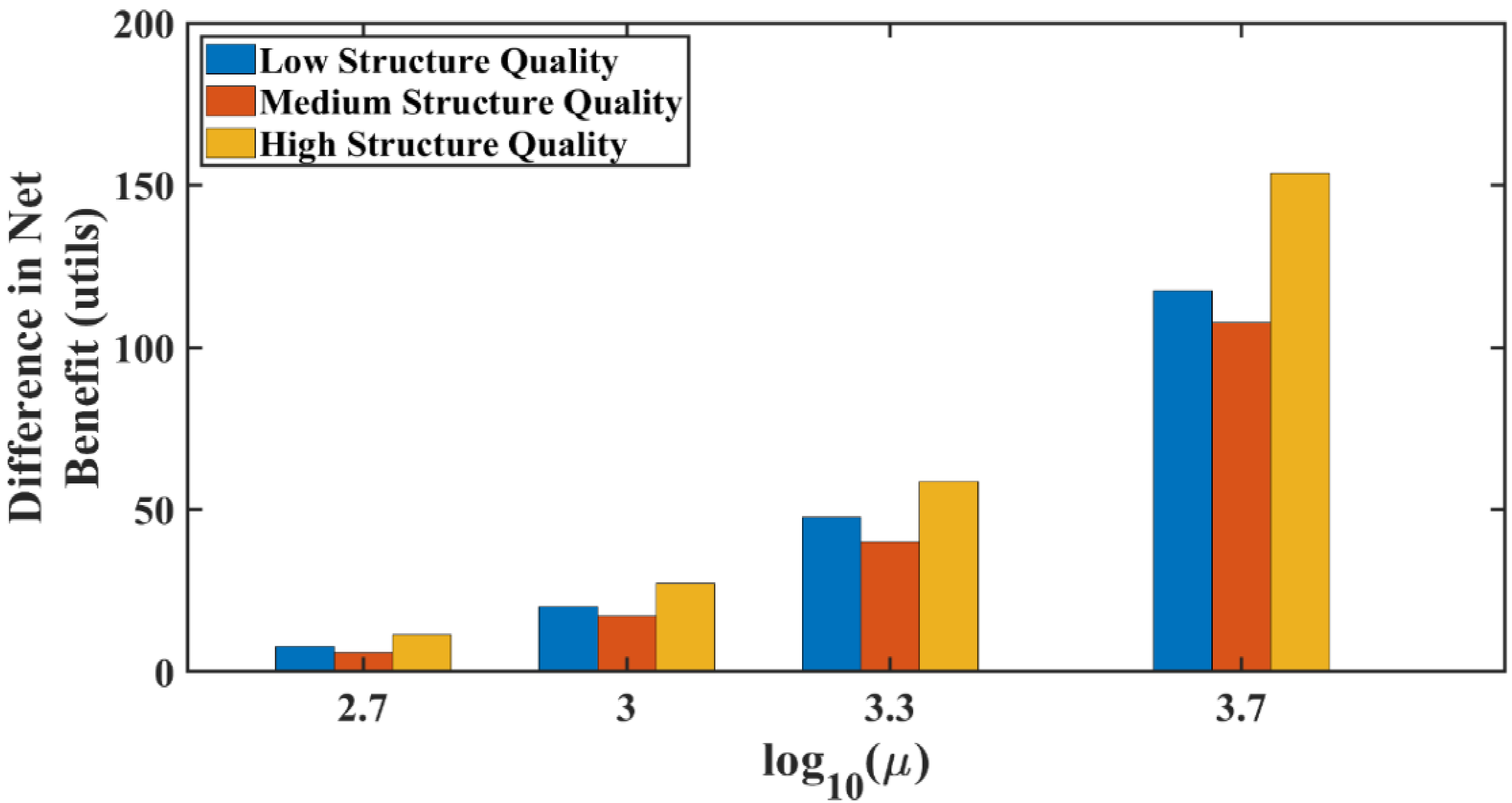


Fig. 17. Increase in net benefit resulting when a household switches from the heuristic bid function developed in Nguyen et al. (2019) to our optimal bid function form depicted in Fig. 15, under varied settings for household marginal utility of money μ (utils/$) & structure quality type.

TC1: IDSO Peak-Load Reduction Capabilities

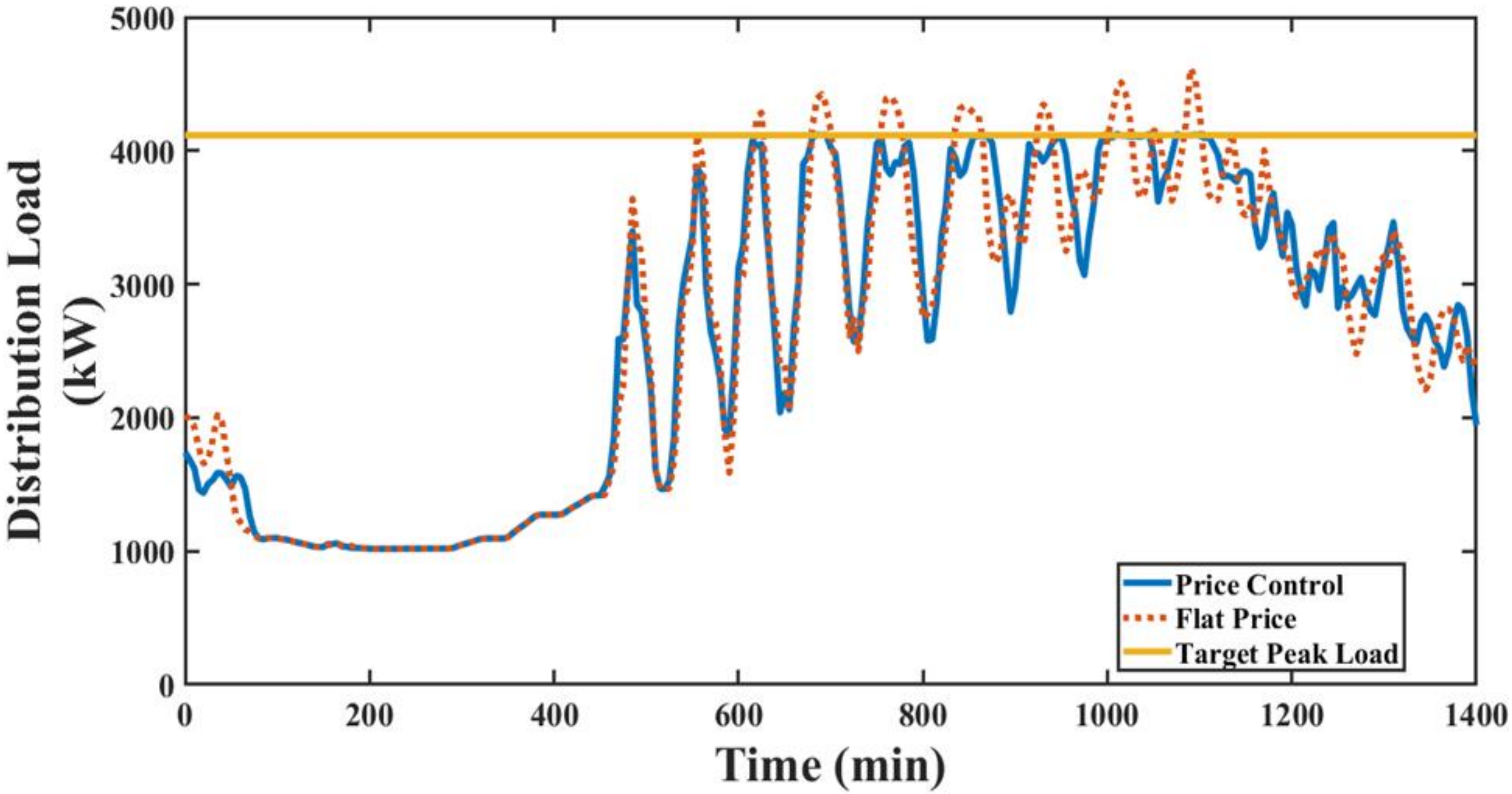


Fig. 18. Low Structure Quality Type (SQT) Case: Load outcomes on day D+1 when the IDSO controls retail prices to achieve a 0.5MW target peak load reduction with all Low SQT households.

TC1: IDSO Peak-Load Reduction Capabilities … Continued

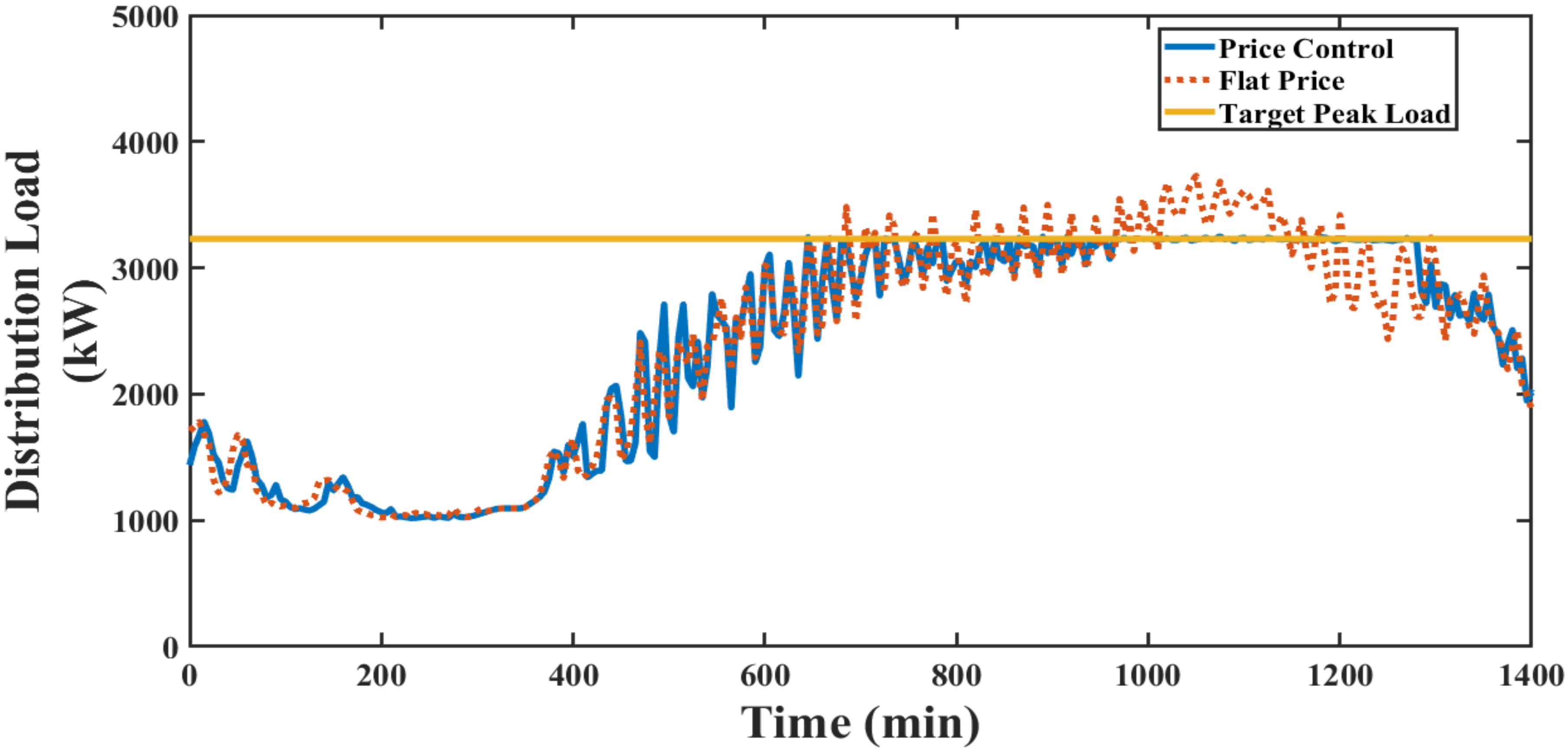


Fig. 19. Medium Structure Quality Type (SQT) Case: Load outcomes on day D+1 when the IDSO controls retail prices to achieve a 0.5MW target peak load reduction with all Medium SQT households.

TC1: IDSO Peak-Load Reduction Capabilities … Continued

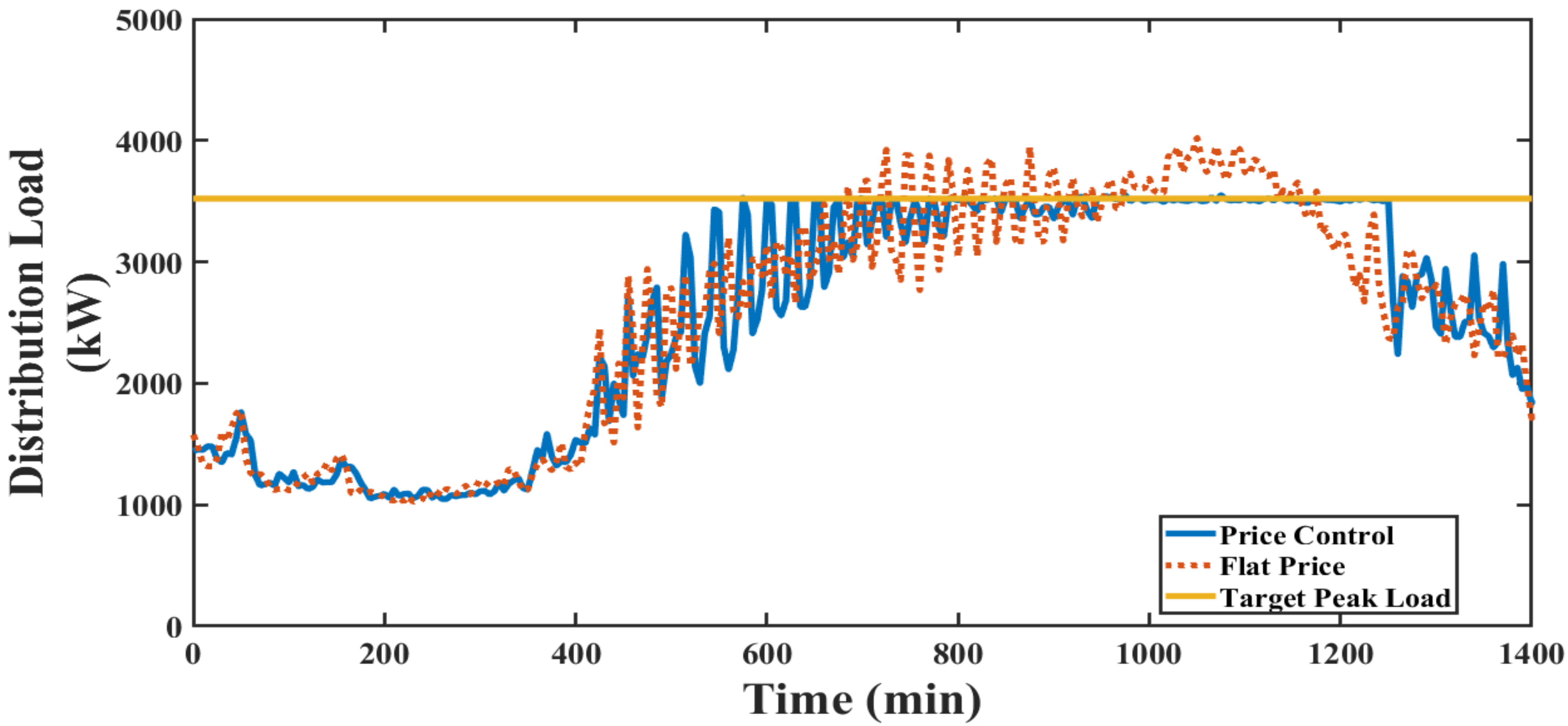


Fig. 20. High Structure Quality Type (SQT) Case: Load outcomes on day D+1 when the IDSO controls retail prices to achieve a 0.5MW target peak load reduction with all High SQT households.

TC1: IDSO Peak-Load Reduction Capabilities … Continued

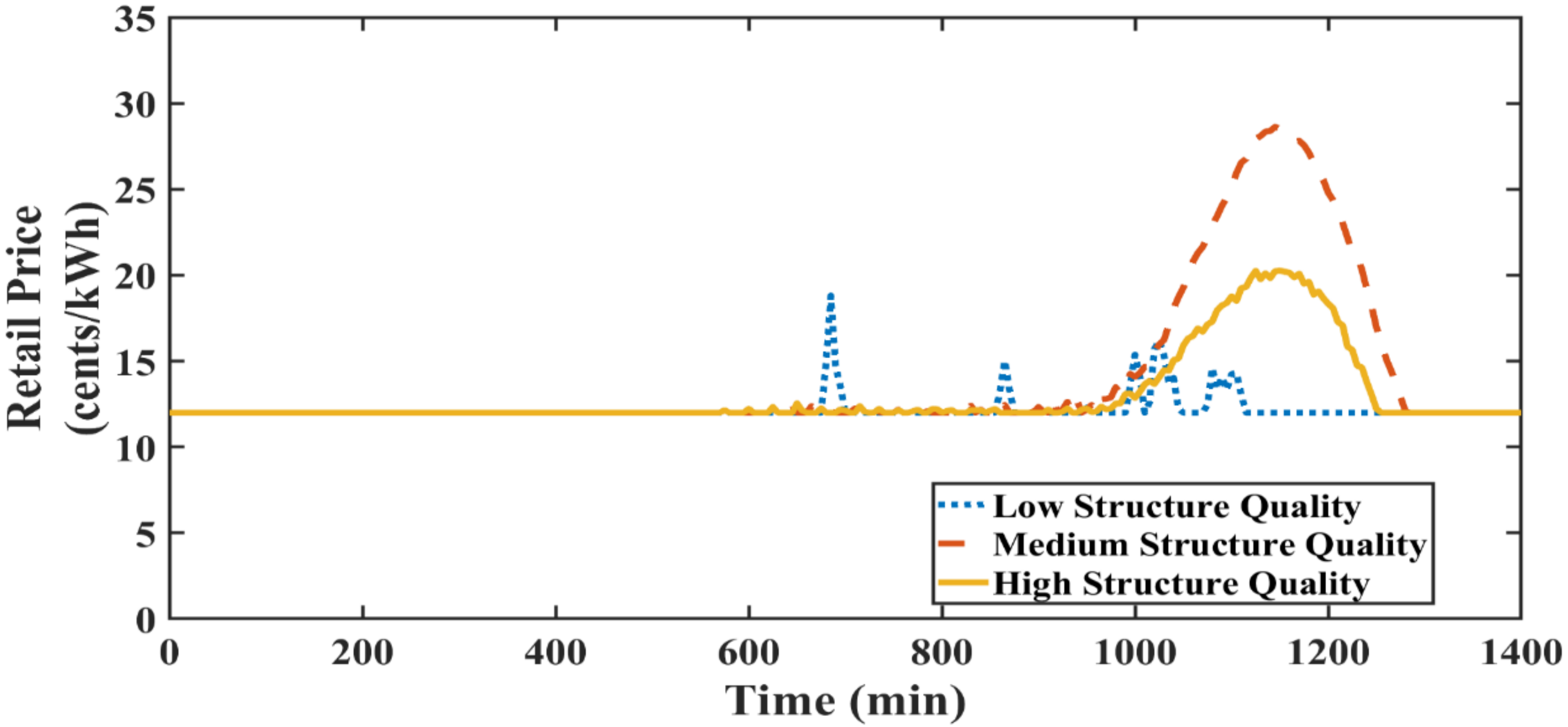


Fig. 21: IDSO-controlled retail price signals used by the IDSO on day D+1 to achieve a 0.5MW target peak load reduction under three different household structure quality type treatments: all Low; all Medium; or all High.

TC1: IDSO Load-Matching Capabilities

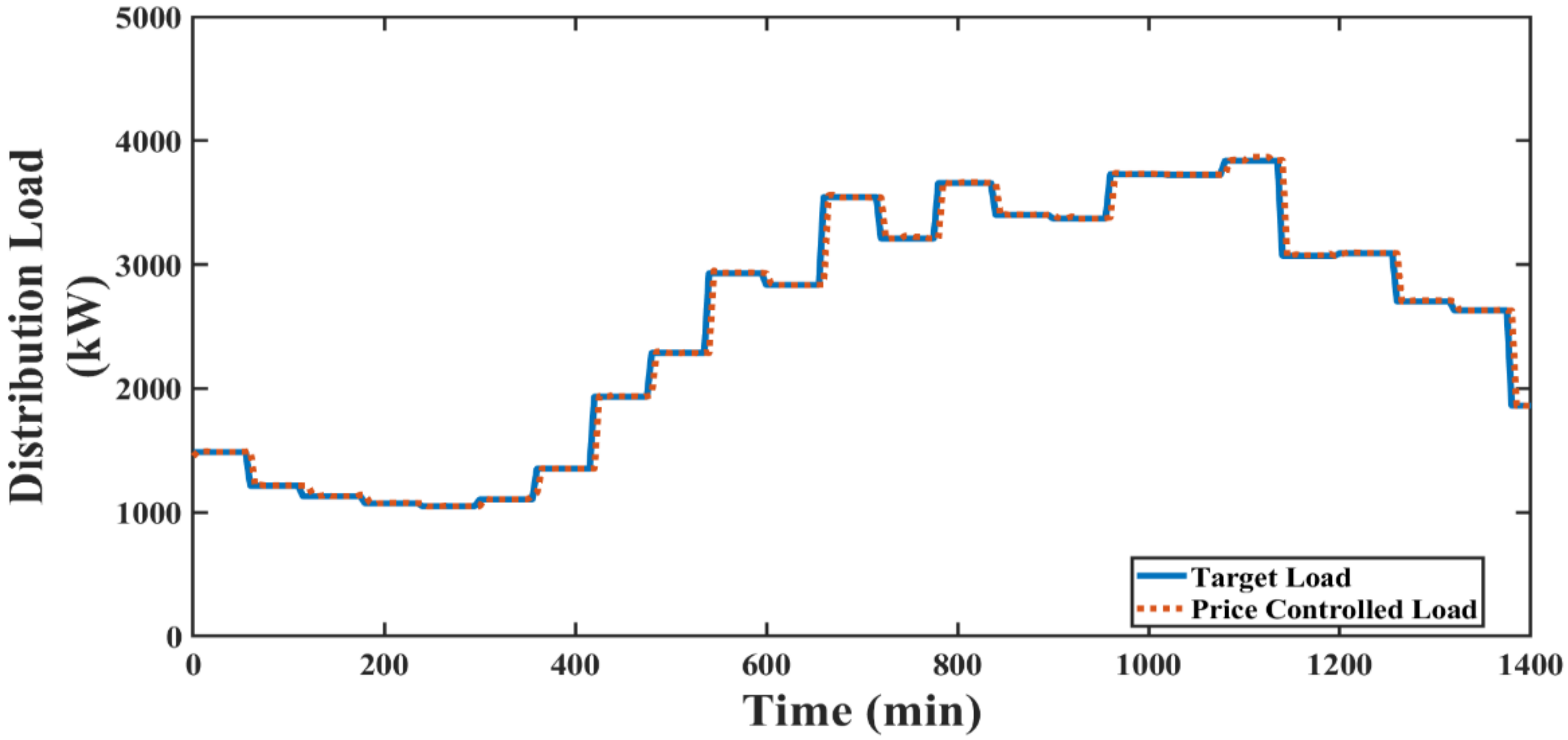


Fig. 22. IDSO's ability to use controlled retail prices to match total household load on day D+1 to a target load profile, given by the IDSO's fixed demand bid submitted into the DAM on day D.

TC1: IDSO Load-Matching Capabilities … Continued

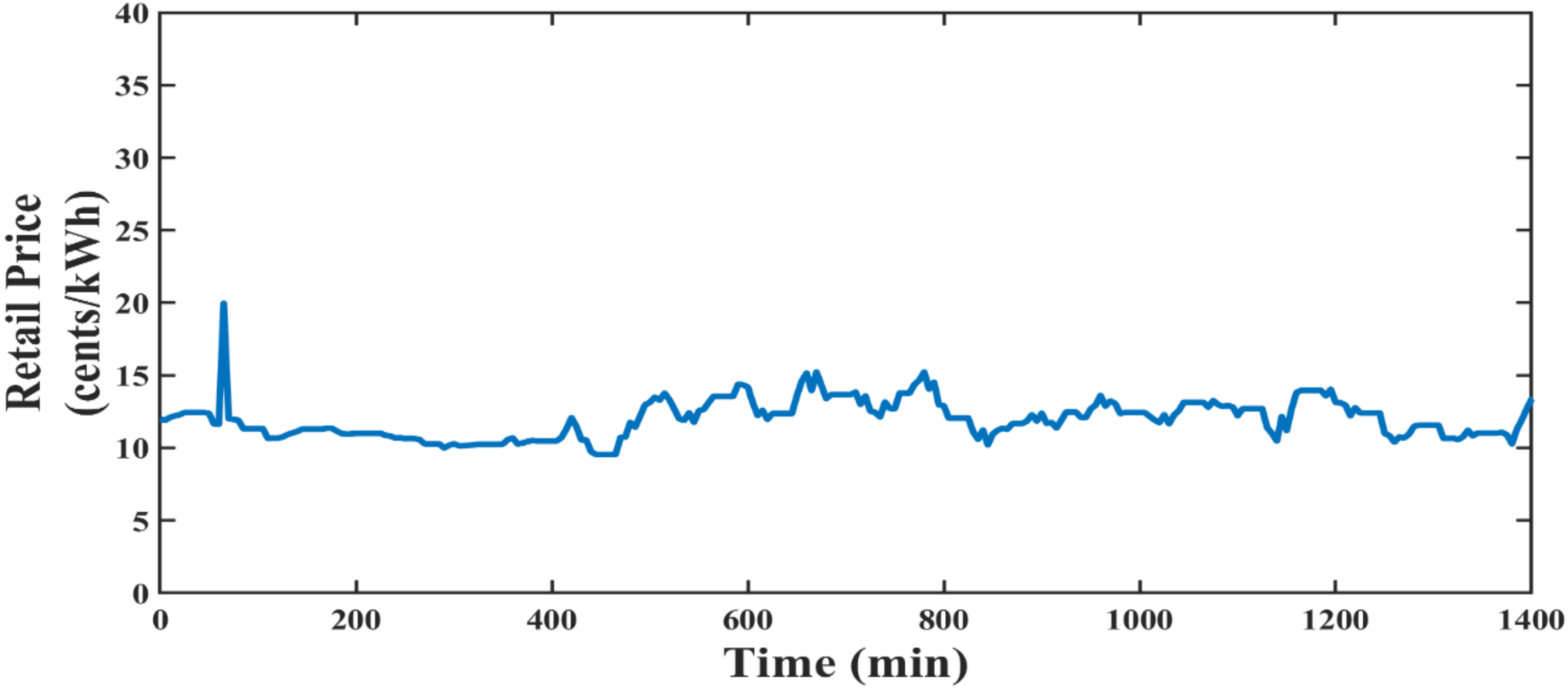


Fig. 23: The retail price signals sent by the IDSO on day D+1 to households in a power usage state to match total household load to the IDSO's day-D DAM fixed demand bid, depicted as the target load profile in Fig. 22.

TC1: IDSO Load-Matching Capabilities … Continued

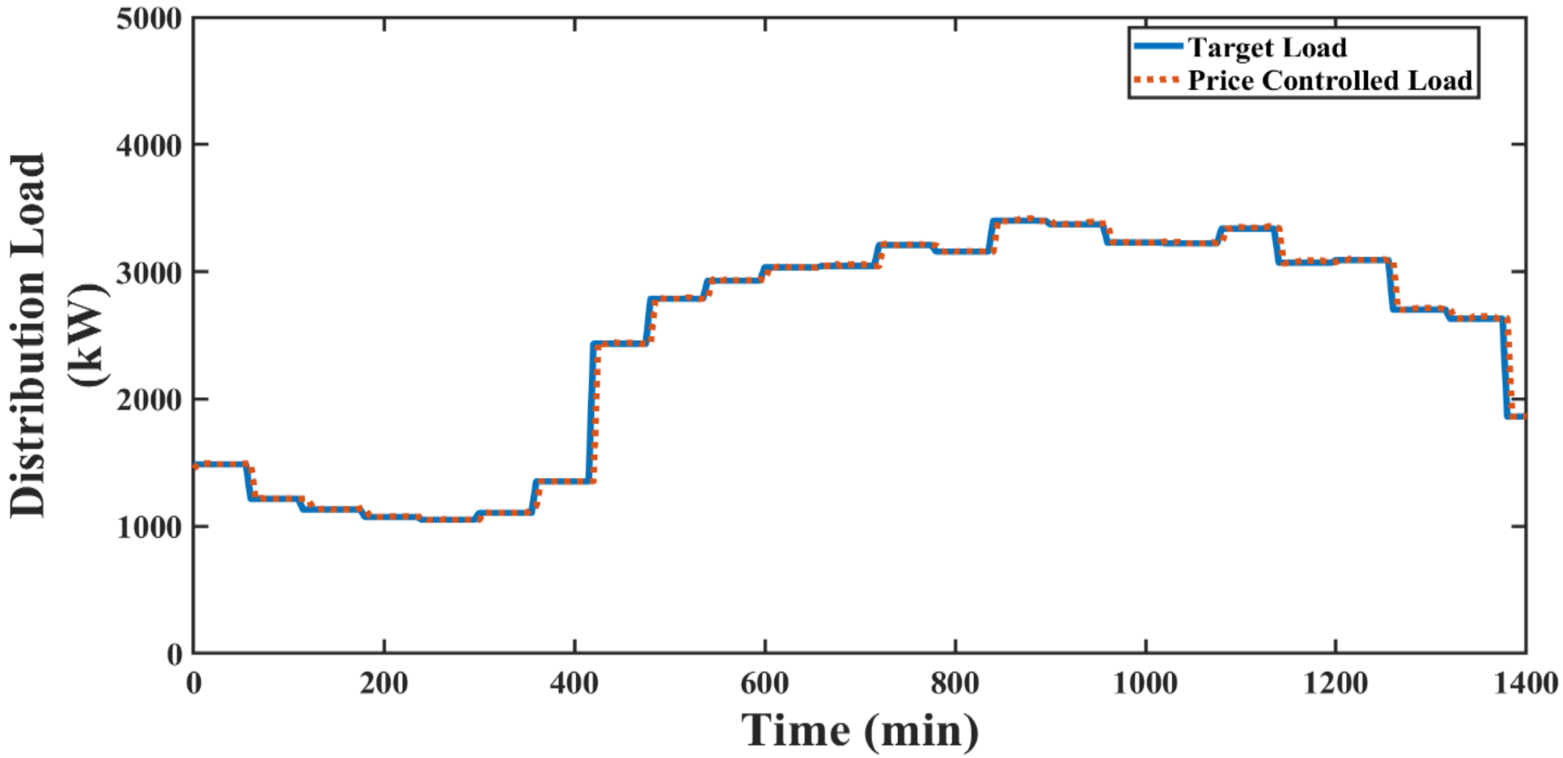


Fig. 23. IDSO's ability to use controlled retail prices to match total household load on day D+1 to a different target load profile, i.e., a different fixed demand bid submitted into the day-D DAM.

TC1: IDSO Load-Matching Capabilities … Continued

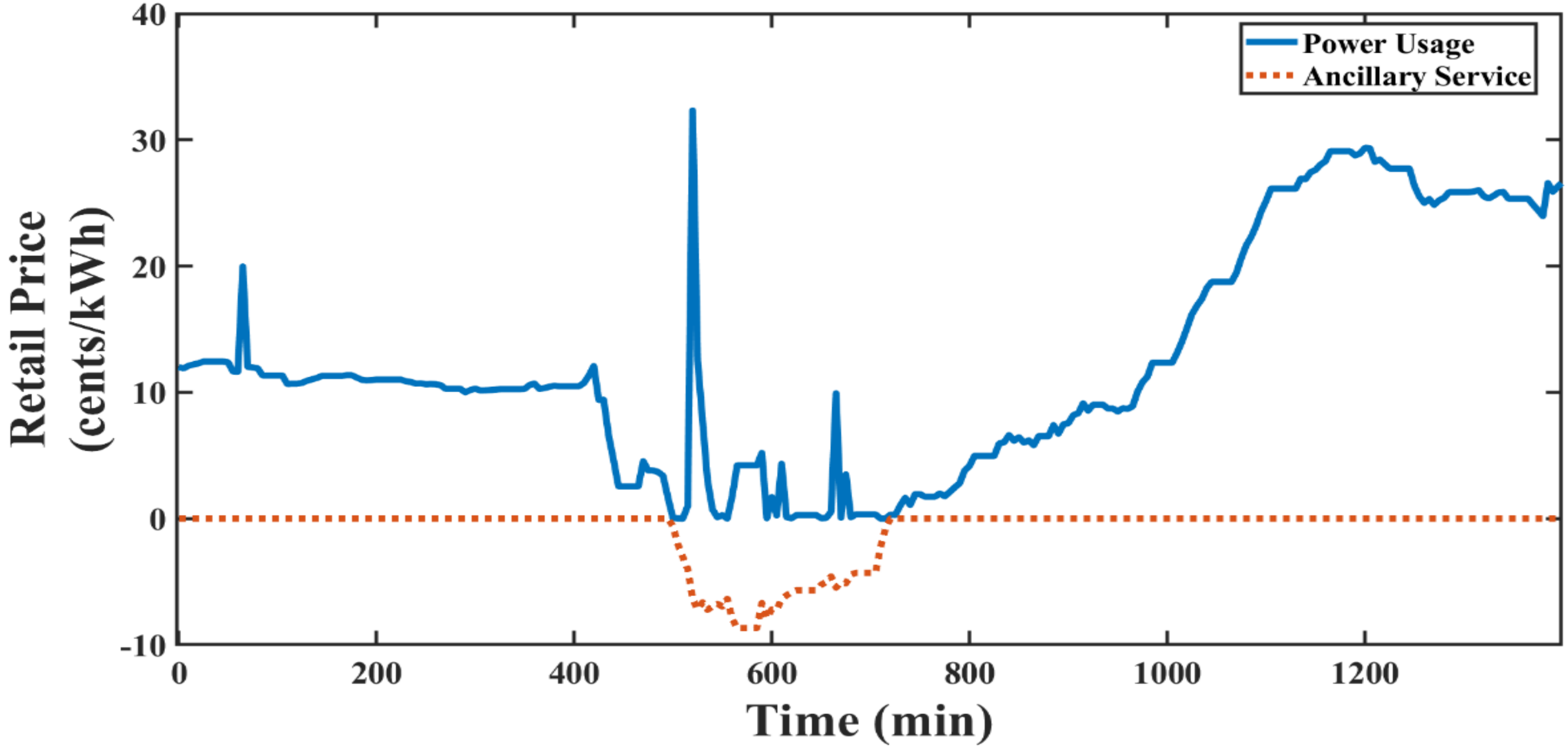


Fig. 24: The positive and negative retail price signals communicated by the IDSO to households on day D+1 to match total household load to the target load profile depicted in Fig. 23. The IDSO must now resort to the use of ancillary services in order to achieve its load-matching goal.

Conclusion

- The objective of our DOE project has been to investigate the ability of IDSOs, functioning as linkage agents for ITD systems, to facilitate the flexible availability and use of reserve in support of ITD system operations.

- The primary contribution of our DOE project research is that we have formulated an innovative energy management approach that provides promising support for our project objective.

- Specifically, we have developed a new type of IDSO-managed TES design for distribution system operations, as well as new types of contracts permitting IDSOs to participate in transmission system operations as providers of reserve harnessed from GERs in return for appropriate compensation.

Conclusion … Continued

- The efficacy of our approach has been demonstrated by means of detailed conceptual analyses as well as test-case simulations conducted with our newly developed ITD TES Platform V2.0.

- Two-year support for the continuation of the research undertaken in our DOE project has been received from the *Power Systems Energy Research Center (PSERC)*.

- This funding will permit us to explore more fully the ITD Household Test Cases outlined in Table 1 (slide 28) as well as the more extensive lists of test cases outlined in Table 1 in the written version of our Q15 DOE project report.