Smart Grids as Coupled Physical and Economic Systems

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NOTE. This presentation reviews key points from the following study:

Ref. [1] L. Tesfatsion (2025), "Design Strategies for Integrated Transmission and Distribution Systems: An Expanding Toolkit," Econ WP 25004, ISU Digital Repository, Iowa State University, Ames, IA 50011. https://www2.econ.iastate.edu/tesfatsi/DesignStrategiesForITDSystems.LTesfatsion.WPVersion.pdf

1. **Introduction: *I*ntegrated *T*ransmission and *D*istribution (*ITD*) Systems**
2. **ITD System Design: Nine Basic Goals**
3. **Operational Issues Facing Current U.S. ITD Systems**
4. **A Tiered Approach to *D*esign *R*eadiness *L*evel (*DRL*)**
5. **DRL Classifications for Recent ITD System Design Studies**
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1. Introduction: ITD Systems

- ***I***ntegrated ***T***ransmission and ***D***istribution (***ITD***) systems are complex systems encompassing strongly coupled physical and economic processes.

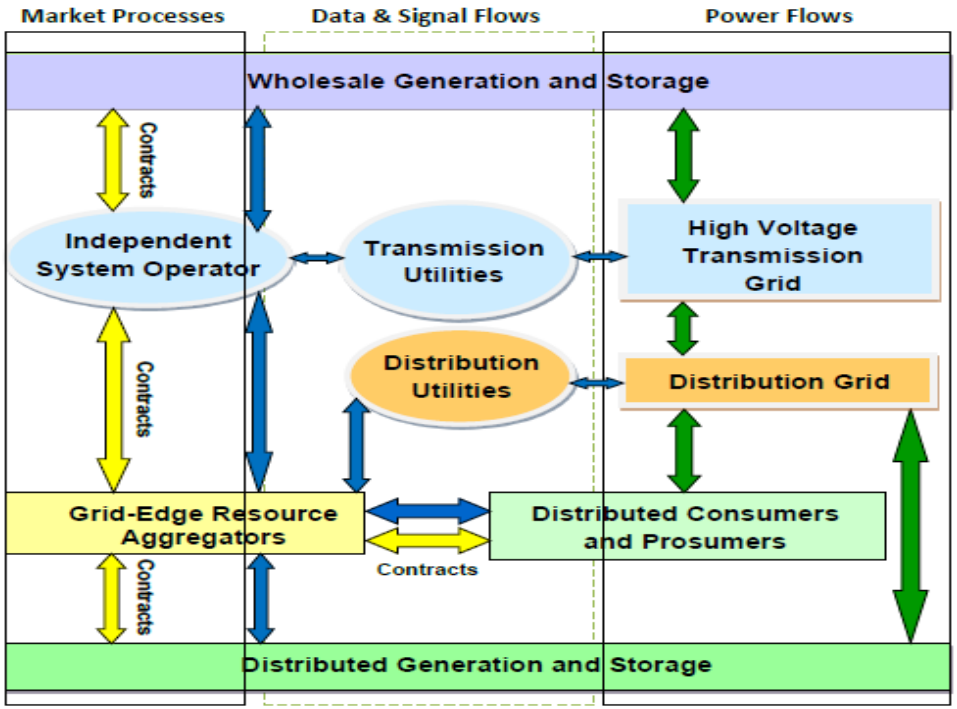


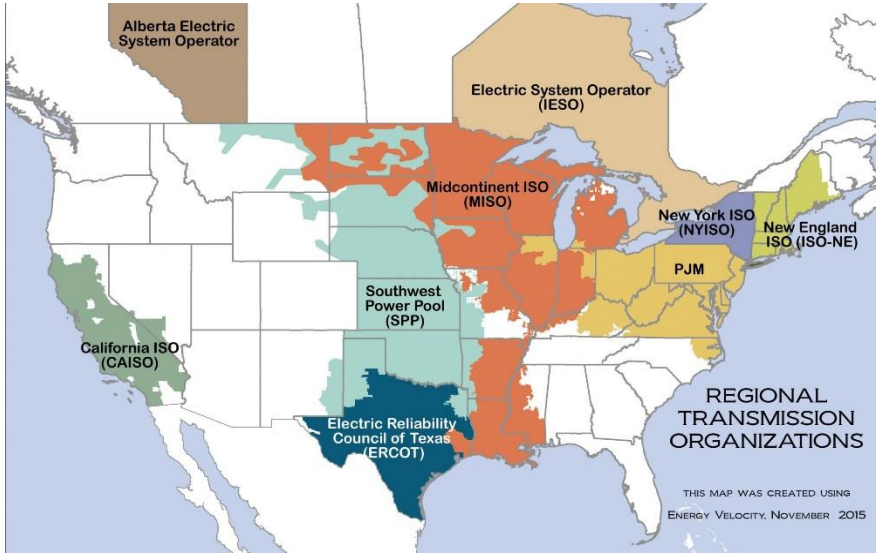
Fig. 1: *Schematic depiction of an ITD system consisting of linked transmission & distribution level operations*

- This presentation first summarizes nine basic goals for ITD system design.

- Next addressed is need for design modernization: Increasing climate-change & resource diversification pressures are hindering ability of current ITD systems to meet these goals.

- The remainder of the presentation discusses ongoing efforts to modernize ITD systems aided by new design tools, with a stress on AI-enhanced co-simulation platforms.

Empirical Focus: U.S. ITD systems



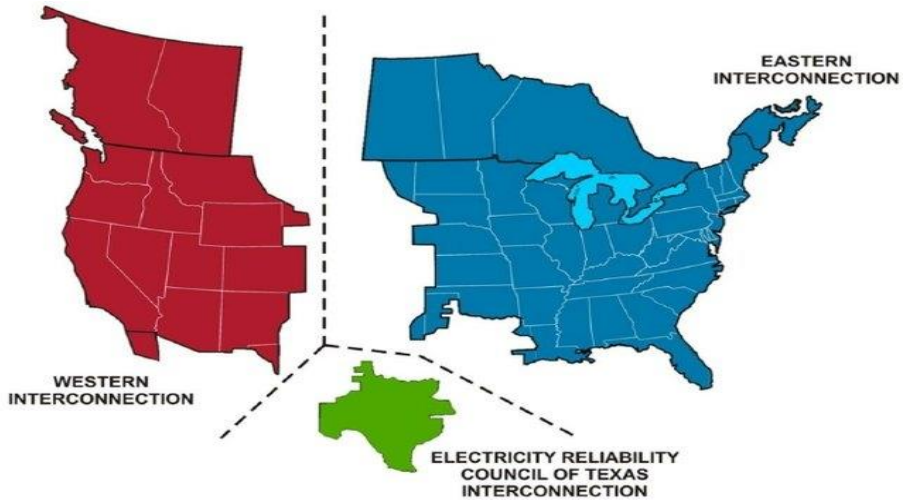


Fig. 2: *Seven U.S. ITD Systems (CAISO, ERCOT, ISO-NE, MISO, NYISO, PJM, SPP) operate over a high-voltage AC transmission grid consisting of three separately-synchronized parts.*

2. ITD System Design: Nine Basic Goals *Ref. [1, Sec. 2]*

Goal 1: Incentive Alignment *(system <—> private goals & constraints)*

Goal 2: Resource Adequacy *(protection against volumetric grid risk)*

Goal 3: Efficiency *(no wastage of resources)*

Goal 4: Reliability and Resiliency *(customer service retention/recovery)*

Goal 5: Fairness *(even playing field for all participants)*

Goal 6: Conceptual Coherency and Transparency

Goal 7: Minimum Administrative Intervention *(rule-based decision-making)*

Goal 8: Internalization of Externalities *(e.g., social costs of pollution)*

Goal 9: Minimal Transitional Disruption from Previous Design

3. Operational Issues Facing Current U.S. ITD Systems *Refs. [1, 2]*

Major Concern:

- Increasing reliance on intermittent power resources (e.g., wind & PV solar power facilities ***not fully firmed by storage***)
- Increasingly diverse loads (e.g., data centers, bitcoin companies, EVs, …)

⇒ **Increasing Volatility and Uncertainty of Real-Time Net Load**

[Net Load] := [Power Withdrawals + Power Losses − Non-Dispatched Power Injections]

⇒ **Increasing Volumetric Grid Risk** (*Grid power outflow* ≠ *Grid power inflow*)

➢ **System Operators** must act as ***"fiduciary conductors"*** tasked with orchestrating:

— *advance* availability and *just-in-time* dispatch of *increasingly diverse* power resources

— to service *just-in-time* power demands of *increasingly diverse* customers

— while meeting *just-in-time* power requirements for grid reliability.

➢ **Grids** must function as ***"flexibility-support mechanisms"***

3. Operational Issues Facing Current U.S. ITD Systems … Continued *Refs. [1, 2]*

Conceptually-problematic design features embedded in the legacy core design of U.S. ITD systems are hindering resolutions to these issues. These features include:

- **Market ↔ product misalignment:** Market designs are not well-aligned with the actual physical/econ attributes of transacted products: *e.g., distinct dynamic delivery attributes of grid-delivered energy (MWh) units; "joint product" cross-correlations, …*

- **Inappropriate primary emphasis on short-run markets** for grid-delivered energy (MWh), supplemented by ancillary service (MW) & capacity (MW) procurements. *The most critical system operator obligation is efficient assurance of "reserve adequacy"*, i.e., availability of diverse flexible power-production and power-absorption capabilities for possible dispatch during future operating periods to protect against volumetric grid risk (voltage instability, power imbalance, …)

- **Overly simplistic partitioning of supplier cost into "fixed" and "variable" components,** *thus ignoring dynamic "avoidability" considerations* critical for the conceptualization and assurance of supplier revenue sufficiency.

4. A Tiered Approach to Design Readiness Level (DRL)

Key Motivation: U.S. DOE's ***T***echnology ***R***eadiness ***L***evel (***TRL***) assessment scale in ***Ref. [3]***

- ITD systems are complex intertwined physical and economic processes.
- For complex real-world systems, traversing a complete design arc -- from initial concept to successful real-world deployment -- typically requires a series of modeling and testing efforts at different scales, and with different degrees of empirical fidelity.
- Moving too soon to real-world deployment entails a major risk of adverse unintended consequences.

Design Readiness Level (DRL) Considerations for ITD Systems:

Goal Support:

Facilitation of ITD system design goals **G-1** through **G-9**

Empirical Fidelity:

Alignment of design features with physical, economic, and legal realities

Development Level:

From **DRL-1** (Initial conceptualization) to **DRL-9** (real-world deployment)

Table 1: A nine-tiered approach to the determination of Design Readiness Level (DRL) Ref. [1, Sec. 4]

Design Readiness Level	DRL Tier	DRL Description
Conceptual idea	DRL-1	Conceptualization of a design with desired attributes
Explicit formulation	DRL-2	Initial modeling of design concept
Low-fidelity small-scale modeling & testing	DRL-3	Testing using a small-scale model with highly idealized real-world features
Medium-fidelity small-scale modeling & testing	DRL-4	Testing using a small-scale model with several salient real-world features
High-fidelity modeling & testing apart from scale	DRL-5	Testing using a small-scale model with many salient real-world features
Pilot study	DRL-6	Testing using a model reflecting expected deployment conditions apart from scale
Prototype study	DRL-7	Testing using a model reflecting expected deployment conditions at realistic scale
Field study	DRL-8	Use and evaluation in a real-world setting under real-world deployment conditions.
Real-world deployment	DRL-9	Real-world implementation for a full range of operating conditions

Table 2: *Classification of illustrative recent (post-2021 "Winter Storm Uri") ITD system design studies ranging from DRL-3 through DRL-8* ***Ref. [1, Sec. 5]***

Category	DRL Range	Illustrative ITD System Design Studies
Low-fidelity small-scale modeling & testing	DRL-3	Bilimoria et al. [14], Dimanchev et al. [15], Glachant et al. [16], Gu & Sioshansi [17], Joskow [18], Lo Prete et al. [19], Ma [20], Mays et al. [21], Palensky et al. [22], van der Veen et al. [23], Zhou et al. [24]
Medium-fidelity small-scale modeling & testing	DRL-4	Tesfatsion [3], Palensky et al. [22], Ballouz et al. [25], Battula & Tesfatsion [26], Chen et al. [27], Conejo & Wu [28], Hastings et al. [29], Li & Wang [30], Mishra et al. [31], Rehtanz et al. [32], Yao et al. [33]
High-fidelity modeling & testing apart from scale	DRL-5	Bichler & Knorr [7], Billimoria et al. [34], Doepfert et al. [35], Estanqueiro et al. [36], Ledesma et al. [37], Mengesha & Roy [38]
Pilot study	DRL-6	ADRA [39], Sun & Conejo [40]
Prototype and field studies	DRLs 7--8	Kirkham et al. [5], Rehtanz et al. [32], Yao et al. [33] , ADRA [39], Sun & Conejo [40], Hancher et al. [41], Ospina et al. [42]

Note: All reference numbers in Table 2 are from ***Ref. [1]***.

Nine Standardized *D*esign *R*eadiness *L*evels (*DRLs*)

DRL-1: Conceptual design idea

DRL-2: Explicit formulation

DRL-3: Low-fidelity small-scale modeling & testing

Basic design research at universities ...

DRL-4: Medium-fidelity small-scale modeling & testing

DRL-5: High-fidelity modeling & testing apart from scale

DRL-6: **Pilot study**: Testing using a model reflecting expected deployment conditions apart from scale

"Valley of Death"

DRL-7: **Prototype study**: Testing using a model reflecting expected deployment conditions at realistic scale

DRL-8: **Field study:** Use and evaluation in a real-world setting under real-world deployment conditions

DRL-9: **Real-world deployment**

Design research at government, business, and regulatory agencies …

"Valley of Death": Design Readiness Levels 4-6

- Relative infrequency of studies at **DRLs 4-6** hinders the development of designs across full design arcs:

Concept ⇨ *Implementation*

- **AI-Enhanced Co-Simulation Platforms**

— are well suited for bridging this "Valley of Death" ;

— support <u>continual cycling</u> through DRLs 1-9 by researchers & stakeholders in ***I***terative ***P***articipatory ***M***odeling *(**IPM**) processes.* ***Ref. [4]***

IPM Goal for ITM System Design: Successive design <u>improvements</u> for a continually evolving world rather than possibly quixotic searches for non-existent "optimal" designs.

Example: Agent-Based Co-Simulation Platforms *Ref. [5]*

Agent-Based **:=** The dynamics of a modeled system are driven by interactions among ***agents*** (*software entities*) with encapsulated ***states*** (*data, attributes, and/or methods*), starting from modeler-specified initial agent states.

Agent-based co-simulation platforms permit:

- Reduced computational complexity
- Flexible tailoring of model simplifications to purposes at hand
- Matching of modeled agents to empirical referents
- Careful modeling and testing of multidisciplinary aspects

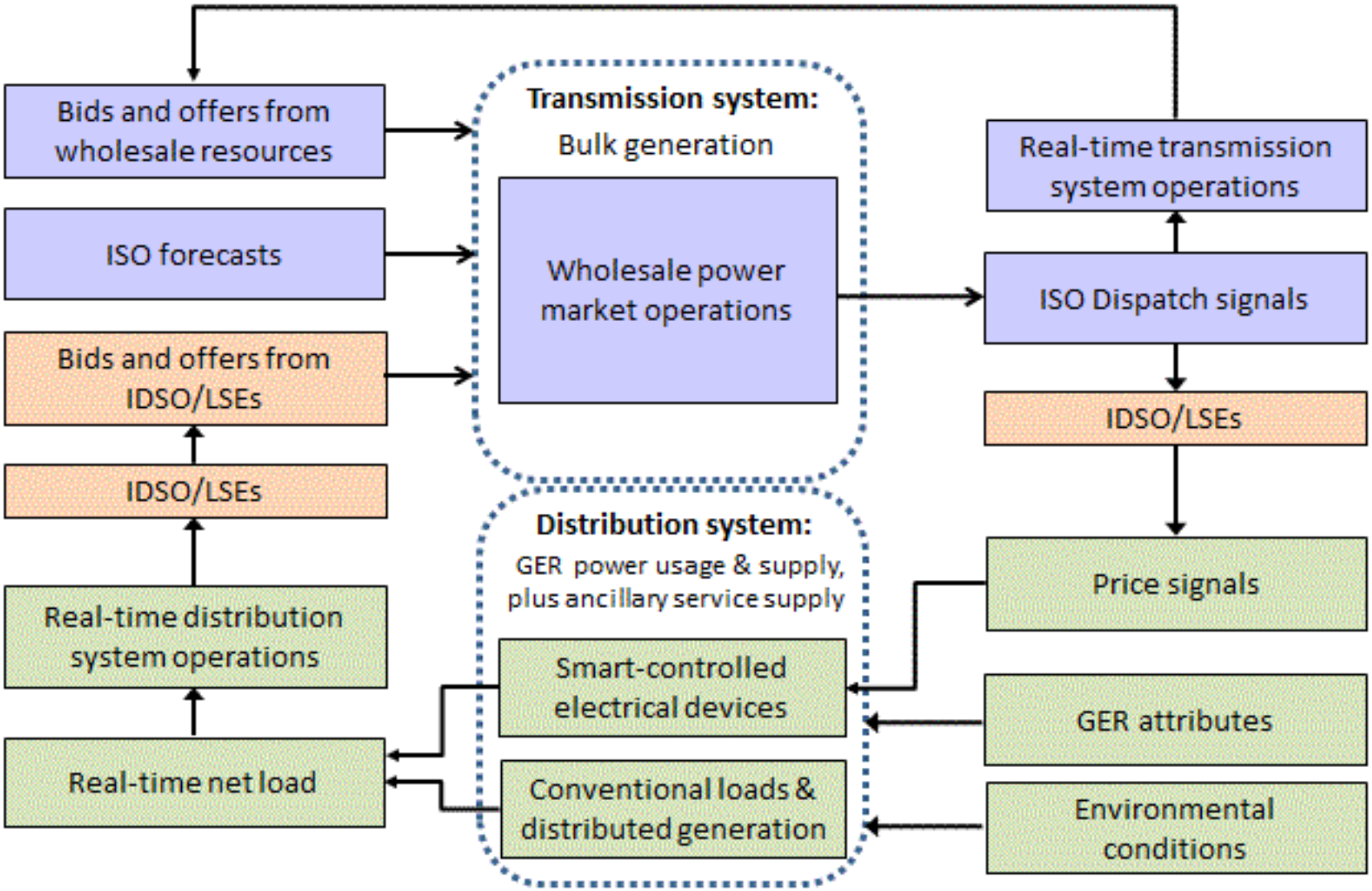
  (e.g., coupled physical and economic processes)

Illustration: An ITD system design study supported by an agent-based co-sim platform

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

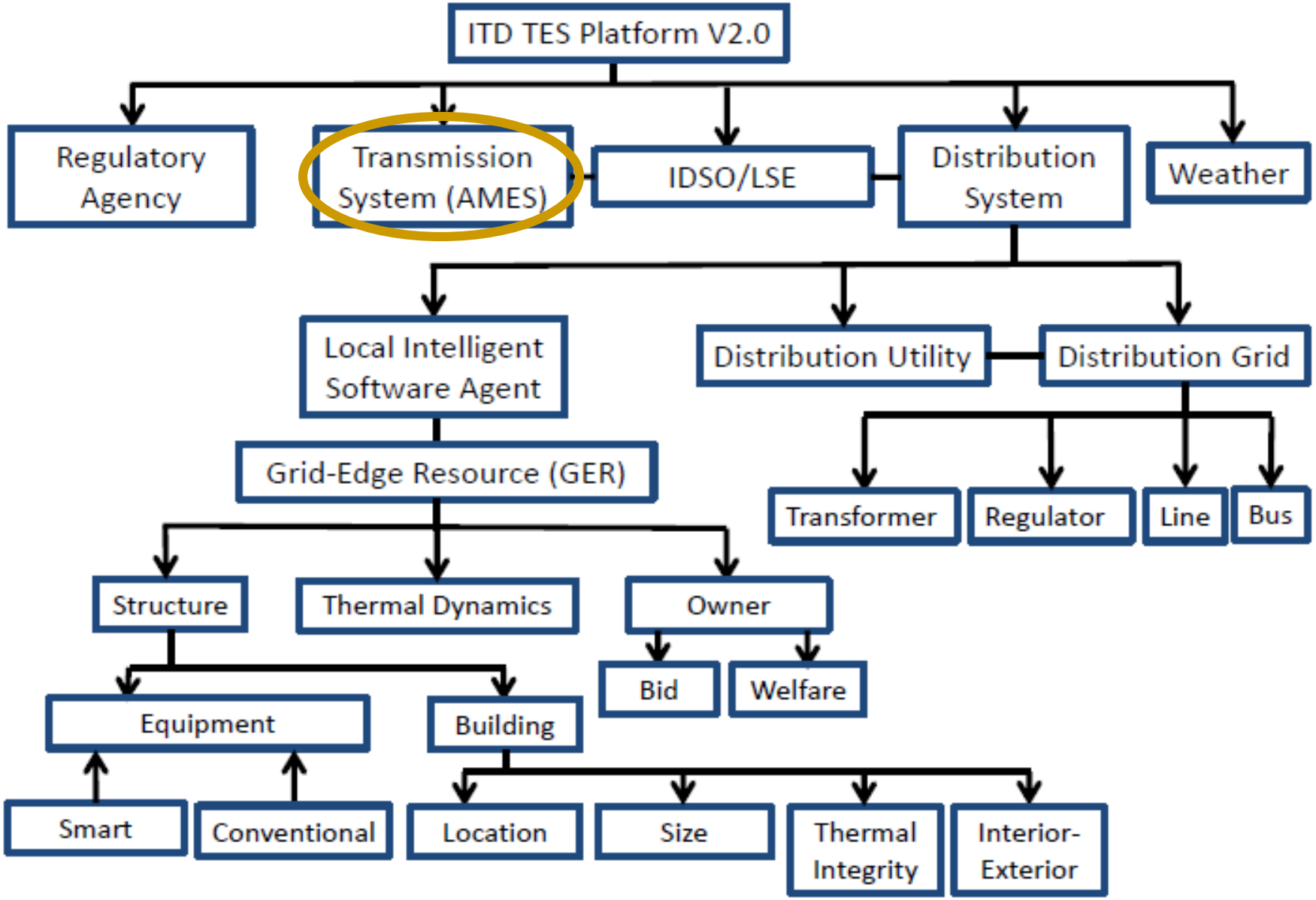
Ref. [7] S. Battula & L. Tesfatsion (2021), **ITD TES Platform V2**, Open-Source Co-Simulation Platform (Java/Python/C++/C), *GitHub Code/Data Repository*

Schematic Depiction of ITD System Operations Co-Simulated by the ITD TES Platform V2 *Ref. [7]*

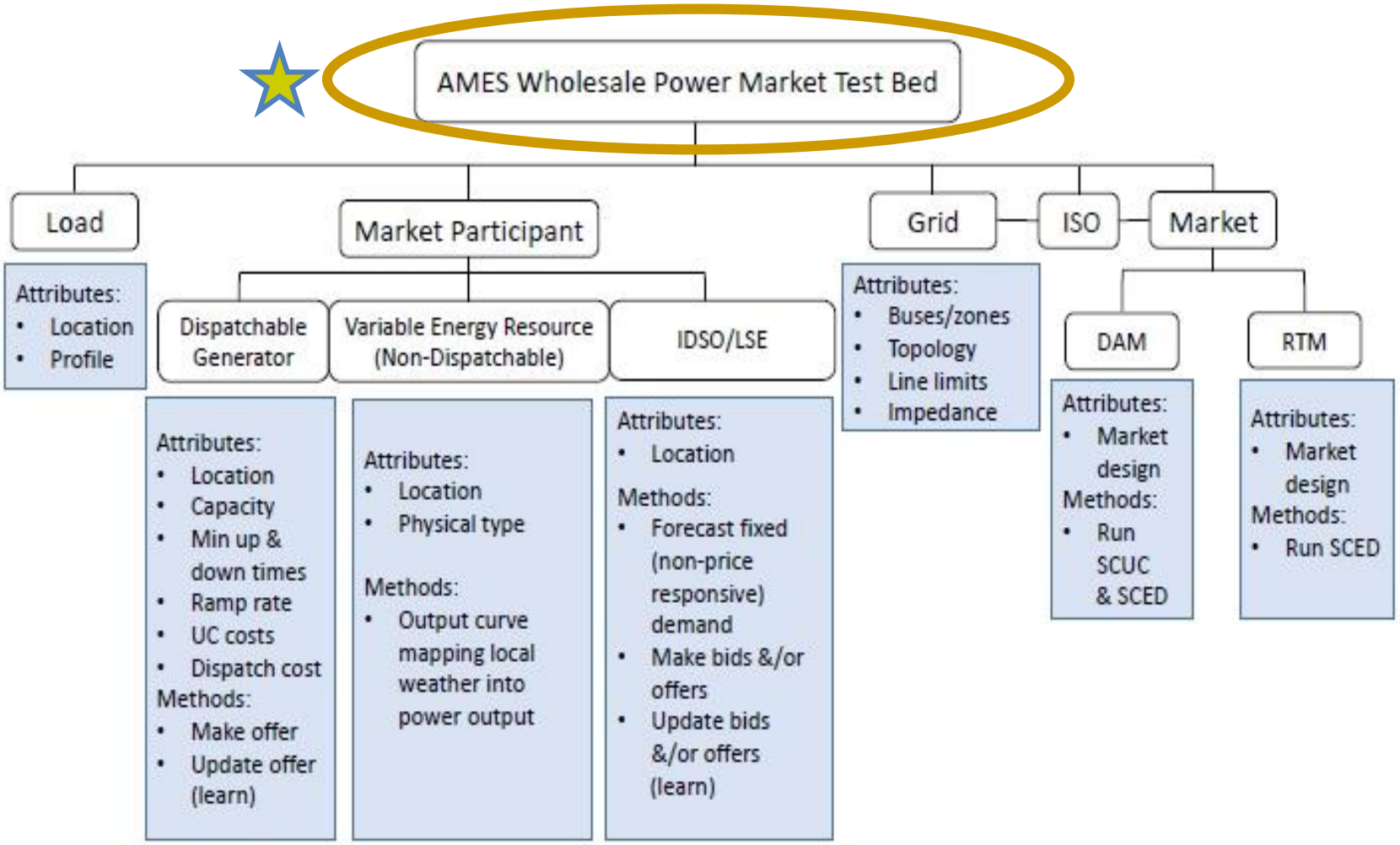


General Agent Hierarchy for the ITD TES Platform V2 *Ref. [7]*

Down Arrows ⇩ Denote "Has A" Relations; Up Arrows ⇧ Denote "Is A" Relations

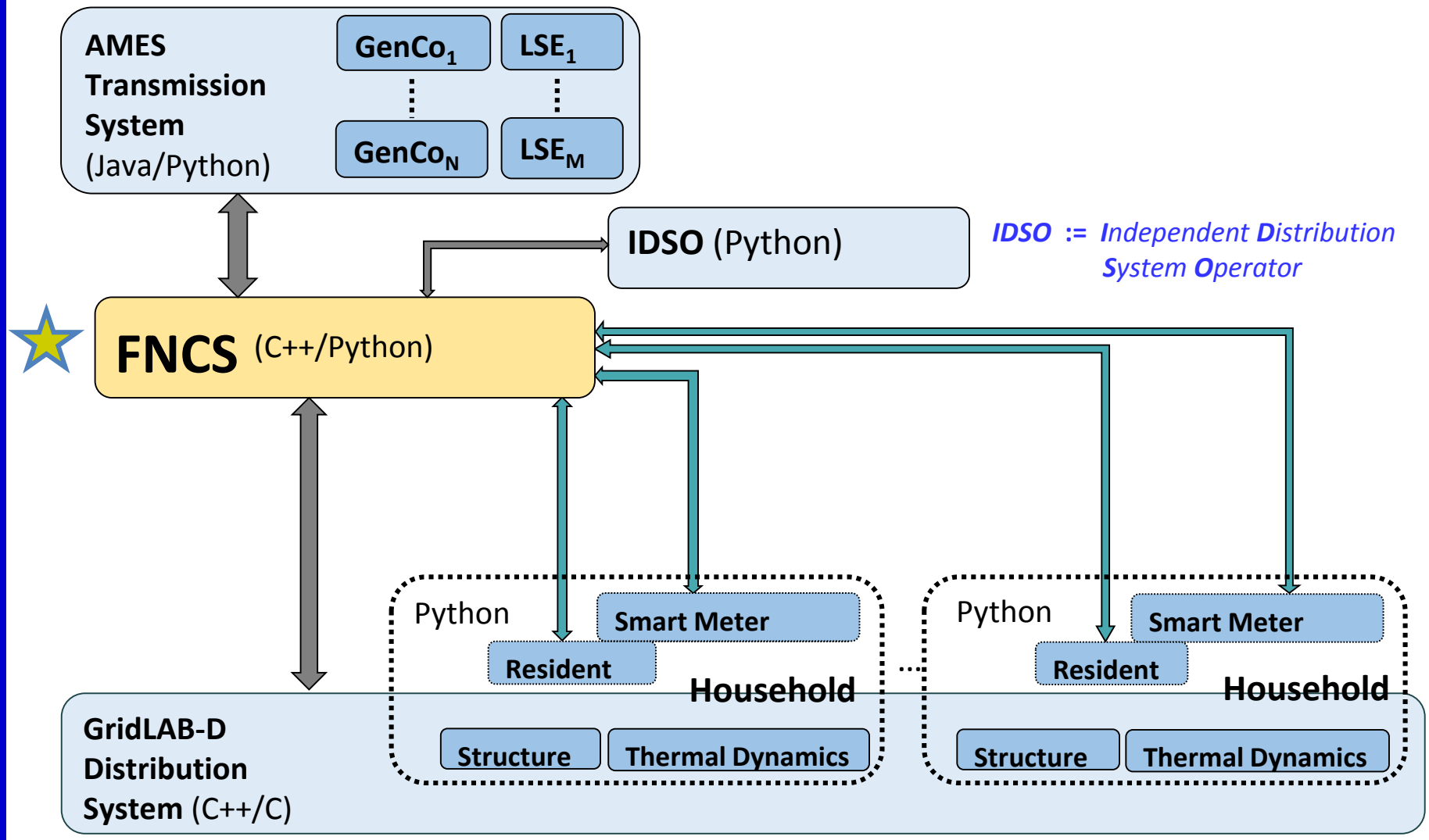


Agent Hierarchy for the AMES (V5.0) Transmission-System Component for the ITD TES Platform V2



AMES (***A***gent-based ***M***odeling of ***E***lectricity ***S***ystems) Package, OSS (Java/Python) ***Ref. [8]***

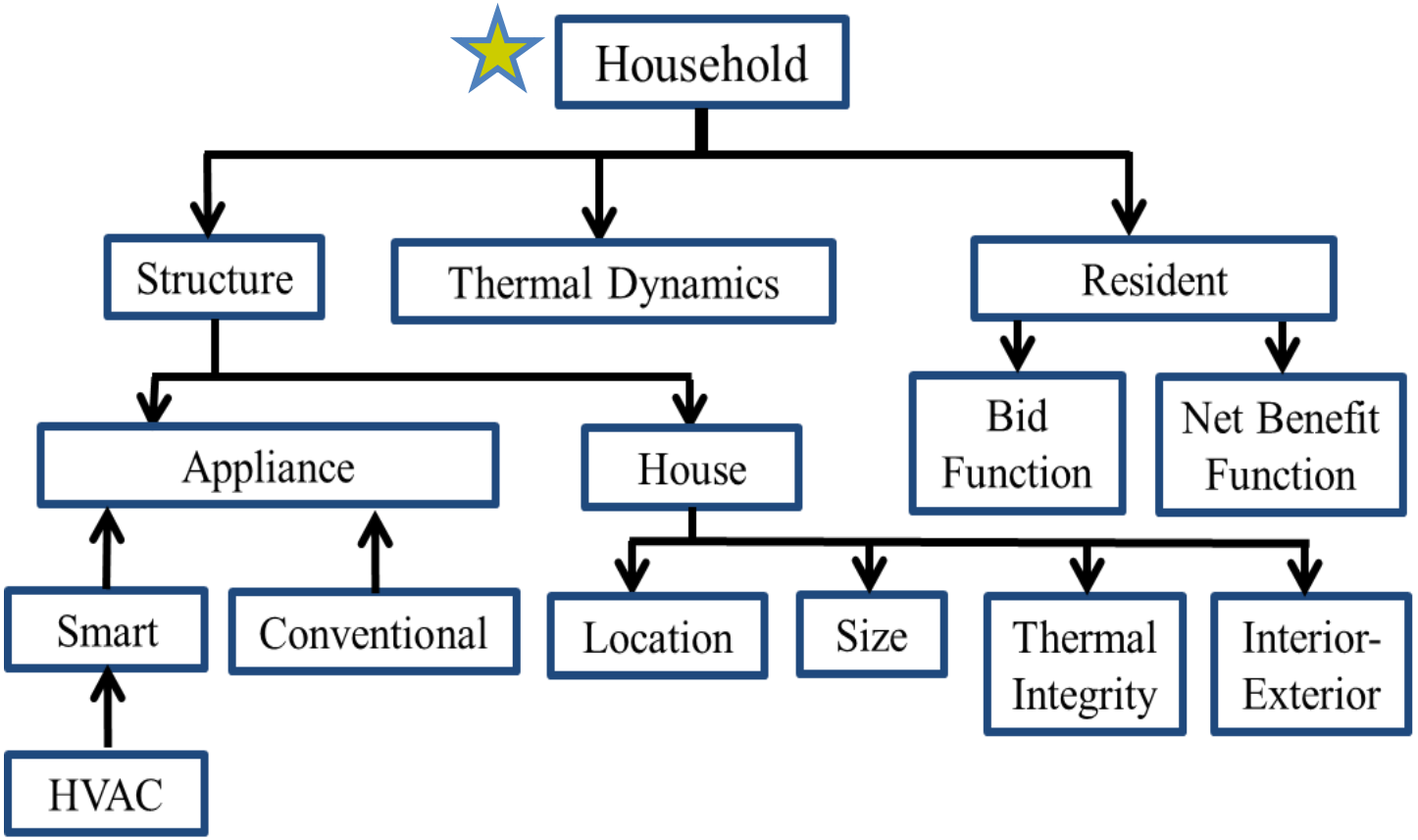
Depiction of the specific ITD TES Platform V2 components (Java/Python/C++/C) co-simulated for the illustrative ITD system design study [6]



FNCS := Framework for Network Co-Simulation, developed by researchers at the Pacific Northwest National Laboratory (PNNL) during 2011-2016

Agent hierarchy for a "Household" component implemented by the ITD TES Platform V2 [7] for the illustrative ITD system design study [6]

Down Arrows ⇩ Denote "Has A" Relations; Up Arrows ⇧ Denote "Is A" Relations



Ref. [9] S. Battula and L. Tesfatsion (2021), *Household Component: ITD TES Platform V2* (Open Source, Python) GitHub Code/Data Repository

Conclusion: Key Points *Refs. [1,2]*

- U.S. ITD systems are currently attempting to decarbonize their grid operations and to diversify their participants.

- Conceptually-problematic aspects of the legacy core designs of these ITD systems are hindering these modernization efforts:
  - Market ↔ product misalignment issues;
  - Benefit/cost formulation and measurement issues;
  - Revenue insufficiency and supply-offer formulation issues;
  - Settlement timing issues; . . .

- ***Ptolemaic Epicycle Design Conundrum:***

  Conceptually-problematic core rules of operation result in operational difficulties. Attempts to resolve these operational difficulties by augmentation of the core rules with a new rule layer results in further operational difficulties. Rule layer accretion then continues to occur because correction of fundamental inconsistencies in the core rules is persistently deemed to be too costly to correct.

- ***Needed:*** A fundamental modernization of legacy core ITD system designs.

- ***Proposed Way Forward:***

  Systematic efforts to traverse complete design arcs from DRL-1 (conceptual idea) to DRL-9 (real-world deployment) -- *supported by an expanded multidisciplinary perspective and an expanded AI-enhanced set of tools (e.g., agent-based co-simulation platforms)* -- could help stakeholders and researchers achieve this needed modernization.

References (with Links)

Ref. [1] L. Tesfatsion (2025), "Design Strategies for Integrated Transmission and Distribution Systems: An Expanding Toolkit," Econ WP 25004, ISU Digital Repository, Iowa State University, Ames, IA 50011 https://www2.econ.iastate.edu/tesfatsi/DesignStrategiesForITDSystems.LTesfatsion.WPVersion.pdf

Ref. [2] L. Tesfatsion (2024), *Economics of Grid-Supported Electric Power Markets: A Fundamental Reconsideration* (Preprint,pdf), Foundations and Trends in Electric Energy Systems, Vol. 8, No. 1, NOW Publishers, Delft, The Netherlands, 123pp.

Ref. [3] DOE (2015), *Technology Readiness Level Assessment Guide,* Office of Management, Department of Energy, DOE G 413.3-4A

Ref. [4] L. Tesfatsion (2025), *Empirical Validation and Verification of Agent-Based Models*, Resource Site https://www2.econ.iastate.edu/tesfatsi/empvalid.htm

Ref. [5] L. Tesfatsion (2018), Electric Power Markets in Transition: Agent-Based Modeling Tools for Transactive Energy Support. Chapter 13 (pp. 715-766) in C. Hommes and B. Le Baron (Eds.), *Handbook of Computational Economics 4: Heterogeneous Agent Models*, Amsterdam, The Netherlands: North Holland (Elsevier) https://www2.econ.iastate.edu/tesfatsi/TESHandbookChapter.LTesfatsion.pdf

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

References (with Links) … Continued

Ref. [7] S. Battula & L. Tesfatsion (2021), *The ITD TES Platform V2* (Open Source, Java/Python/C++/C) GitHub Code/Data Repository .

Note: The ITD TES Platform V2 is an agent-based co-simulation platform permitting the development and performance testing of *Transactive Energy System (TES)* designs for *Integrated Transmission and Distribution (ITD)* systems.

Ref. [8] L. Tesfatsion (2025), *AMES Market Package: Homepage* (Open Source, Java/Python) https://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

Note: *AMES* (*A*gent-based *M*odeling of *E*lectricity *S*ystems) is an agent-based computational platform whose default settings permit the dynamic study of U.S. RTO/ISO-managed day-ahead and real-time wholesale power markets operating in tandem over a high-voltage transmission grid during successive days, with grid congestion handled by *L*ocational *M*arginal *P*ricing (*LMP*). AMES V5.0 provides the default transmission system component for the ITD TES Platform V2.

Ref. [9] S. Battula and L. Tesfatsion (2021), *Household Component: ITD TES Platform V2* (Open Source, Python) GitHub Code/Data Repository

Note: This household component for the ITD TES Platform V2 consists of Python code/data for a household electrically connected to a distribution grid within an ITD system. The default settings for this component enable the household to participate in a bid-based TES design implemented for the ITD system.