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NIST Transactive Energy Market Federate

A TE Market for GridLAB-D Co-Simulations

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A TE Market for GridLAB-D Co-Simulations

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Abstract

The NIST Transactive Energy Market (TEM) federate was developed to simulate a local distribution electricity market. For a typical distribution grid customer's electricity tariff, utility power is offered at some price (whether a fixed or dynamic price) in unlimited quantities with the assumption that congestion is neglectable. However, in practice, there may be significant congestion, with overloading and voltage problems on a distribution circuit. Congestion could be tied to increasing electrification, including the addition of electric vehicle (EV) charging, while overvoltage may be tied to excess photovoltaic (PV) generation. It is possible that a local transformer serving four homes may be overloaded on a hot summer afternoon when each house has electric heat pumps, electric water heaters, and EV chargers consuming power. The aggregated load may also challenge the available capacity on the wider grid.

The TEM implements a market using the OASIS Common Transactive Services (CTS) standard framework with a TE Market Agent (TEMA) as the market operator and TE User Agents (TEUA) that buy and sell energy on behalf of loads, storage, and generation assets behind customer meters. The TEMA receives bids and offers, issues quotes and transactions and tracks the position of each market participant. The TEUA may represent a single distributed energy resource (DER; smart load, generator, or storage) or aggregate the load curves of multiple building systems. The TEUA may serve as an intelligent agent (e.g., estimating future load based on historical consumption and other data), and may additionally have access to house meter data and the ability to track position for different loads. The TEUA may buy and sell power in forward and real-time markets to optimize energy use. Behind the TEUA interface, controllers manage devices based on their understanding of device flexibility and owner priorities.

In initial simulation experiments, the NIST TEM implements a day-ahead hourly congestion-pricing-based quote-driven market. Market participants include all devices behind a specific service transformer. Initial prices of hourly power for the next day are set based on the bulk Day Ahead Market clearing price. Initial quotes are for a limited quantity of 75 % of the service transformer power flow rating. If the full amount of power available at this initial price is transacted (purchased by market participants) for some hour, then additional power (of a smaller quantity) is offered to the market for that hour at a higher price. Devices participating in the market may choose to pay the higher price for power in that hour, to move the load in time to a lower-price time interval, or to curtail. The market iterates until all devices have acquired power to meet their power needs according to their individual comfort and flexibility limits.

This paper introduces the NIST TEM design and implementation.

Keywords

co-simulation; Common Transactive Services; electricity markets; market agent; transactive energy; user agent.

Table of Contents

1. Introduction

1.1. What is TE and why does it matter?

Transactive Energy (TE) is a concept where markets are used as the mechanism for negotiating energy use and prices, recognizing that energy's value changes with time of day [1]. Existing wholesale energy markets provide a good example, and the goal is to bring energy markets to the distribution level, providing local optimization of distributed resources. Energy markets can provide an optimal solution to match supply and demand while providing good forward signals, e.g., price signals offering energy for sale for time intervals tomorrow. In the case of TE, offers to sell some quantity of energy for some price motivate investment in storage and provision of customer flexibility to meet grid reliability and capacity needs. A key concept in TE is the use of markets to expose the value of energy in time to incentivize provision of flexibility. Flexibility is the ability of a customer facility/device to shift, shed/add, or modulate energy use [2]. TE becomes the mechanism to incentivize, manage and pay for customer flexibility, including battery storage.

Another key TE concept is service orientation—allowing the customer to control his or her own devices and to provide grid services. In a market environment, the customer is presented with the economic value of energy now and in the near future to inform decisions about energy usage, or when to charge and discharge storage. The market allows the customer to optimize energy use to maximize personal or organizational benefit, minimizing energy cost while providing needed services in the building or home. That is, a homeowner needs to keep the house comfortable, provide hot water, charge the EV, etc., but one homeowner has a different idea of comfort and a different EV driving schedule compared to their neighbor. It is not ideal to have some external service provider control equipment in a house. An external actor would generally know less than the homeowner about planned schedules, comfort parameters and daily needs. External control may also present safety concerns, and additionally, a direct control connection is more difficult to maintain given a heterogenous ecosystem (APIs, network connections, security architectures, patches, etc.). For these reasons, it is better for the customer to maintain control and provide services to the grid based on perceived value.

TE provides a path for the local distribution utility to procure flexibility from the customer in a relatively simple way that does not require a variety of custom programs and specialized tariffs (e.g., different pricing for EV charging). A single TE local-market-based tariff may simultaneously address every smart device in the customer's home or facility. The retail market becomes the tool used to guide the battery when to charge and discharge, guide the EV to charge on low prices, and guide the heat pump to avoid running during peak prices, etc. Markets can also be used for frequency response services or voltage control. TE can replace specialized tariffs (e.g., for EV charging), support grid reliability and local resilience, improve voltage management, adapt to renewable energy use, and reduce infrastructure build-out by improving the capacity factor of the grid.

TE incentivizes the customer to invest in intelligent agents that can respond to prices to shift load and save money, while benefitting the grid. The price signals that incentivize local storage and load shifting expose the value to customers and promote a healthy balance between grid-scale and customer-owned storage and generation.

1.2. The TE Market (TEM) Simulation Federate and NIST TE Co-simulation

The NIST TEM is an implementation of a TE market that runs together with GridLAB-D (GLD) grid simulation and Flexible Resource Controller (FRC) [3] within the NIST TE Testbed, as seen in Fig. 1. The TEM takes baseline load and generation power profiles as input and uses the market and device energy cost algorithms to adjust the power profiles to minimize local congestion, save money for the device owner, and meet owner service requirements. For example, if an EV must charge overnight, the market will help the EV charger find the lowest-cost hours to charge while still getting the required charge quantity. The market enables neighbors to indirectly negotiate charging schedules such that one charges now and the other later; both neighbors and the grid benefit.

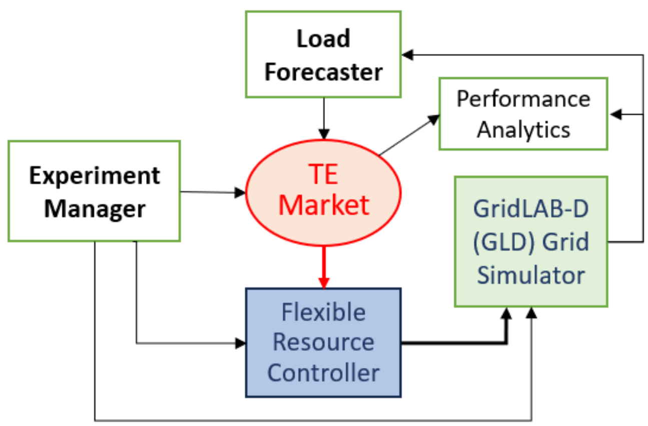


Fig. 1 High-level co-simulation federates and data flow directions.

The TEM outputs are updated power profiles to pass to the FRC. The FRC then passes power and temperature set points into the ongoing GLD simulation. GLD in turn outputs transformer power flow, metered energy at each house and voltages at each meter, and that data is used to evaluate performance of the TEM versus other pricing approaches, as well as for load forecasting and billing (settlement, comparing market transactions versus metered usage). More details on the data that is exchanged and subcomponents in the simulation are provided in the following sections.

The TE Testbed with the federates shown in Fig. 1 uses a middleware based on the High Level Architecture (HLA) standard described in [4] to communicate and coordinate between federates. For improved scalability to large distribution grids, there is a single aggregate FRC federate that controls all customer resources in GLD. Additional details on the implementation are provided in later sections.

The TEM operates as a day-ahead hourly congestion market. A market cycle begins when, at some time before 5:00 p.m. each day, the wholesale day-ahead market clearing prices (DAP) are distributed to all market participants as a quote for some initial quantity of energy tied to local service transformer capacity limits. A market agent operates the market, matching buy and sell tenders and creating transactions for power for each hour of the next day. As the transacted power flow through the transformer in some hour increases, the quoted price for that hour (for additional purchases) also increases. Customer device agents, the TE User Agents (TEUAs) in Fig. 2, use flexibility to select lower-priced time intervals and avoid congested hours if possible.

The TEM was designed to be a tool to schedule flexible loads to minimize cost to electricity customers while benefitting the grid and simultaneously meeting the service needs of the customers (comfort, scheduling, etc.).

1.3. Common Transactive Services

This document uses the semantics and data model of the Common Transactive Services (CTS) standard [5] that enables energy consumers and producers to interact through energy markets using its rich TE data model. CTS elements cover these message sets: market tenders and transactions, market position, trade negotiation, market discovery and market trading data (tickers for, e.g., standing bids and offers), as well as delivery (meter data). CTS does not specify communication technology or any network layer details.

CTS uses the market architecture presented in Fig. 2.

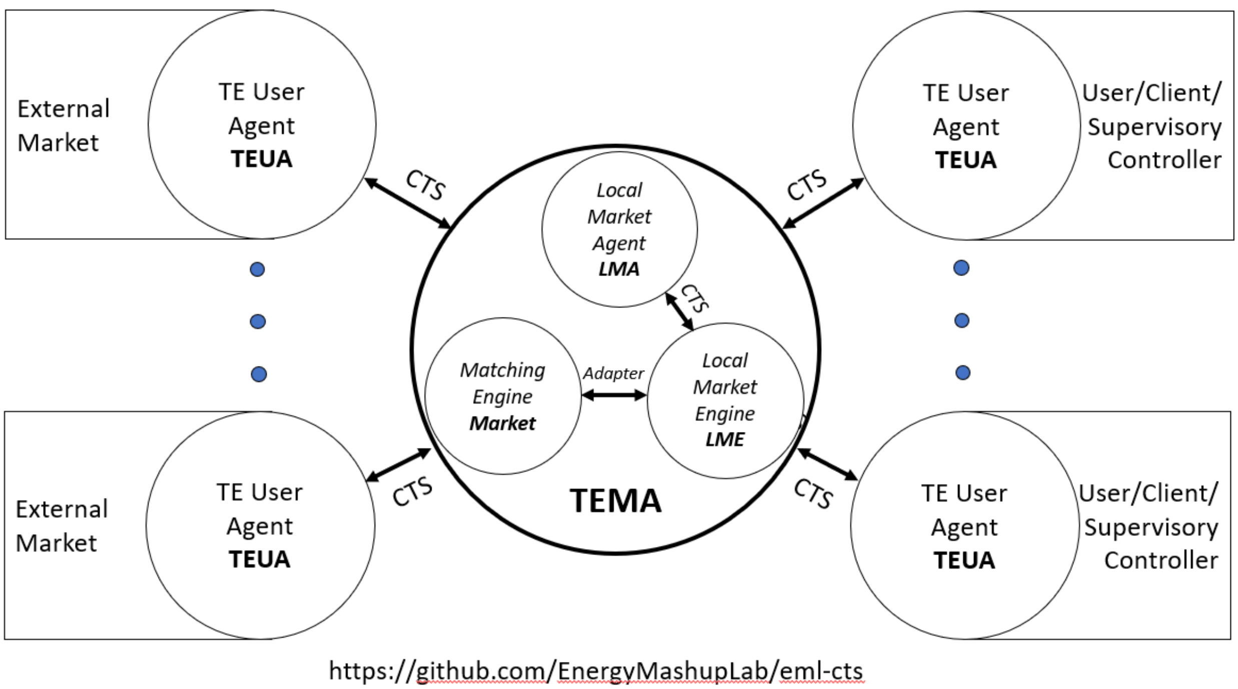


Fig. 1 CTS logical market architecture showing TE User Agents interacting with local TE Market Agent.

CTS serves the communications between user agents (TEUAs) and the local market agent (TEMA). The TEMA internally operates some market engine (e.g., order book market, auction). The TEUA represents one or more customer device controllers; it may also represent an external market such as the wholesale market or a sister market (e.g., a microgrid sharing resources with this market). The external market is effectively an aggregation of resources participating in the market.

Market pricing in forward and real-time markets presents the opportunity for intelligent agents (TEUA) to schedule storage and load use so as to benefit the owner based on price variation across the day, while also providing capacity, congestion management and regulation to the grid. The intelligent agent adjusts market power purchases based on its knowledge of the state of the DER and ability to shift or store energy. The 24/7 market signals provide a mechanism for optimal DER interaction to support the grid.

The current version of the CTS standard is available at the OASIS Energy Interoperation Technical Committee website [6]. CTS also has a reference implementation available for use [7]. An introduction to the functionality and use cases for CTS can be found in [8].

2. Experimental Design

2.1. TEM Implementation Overview

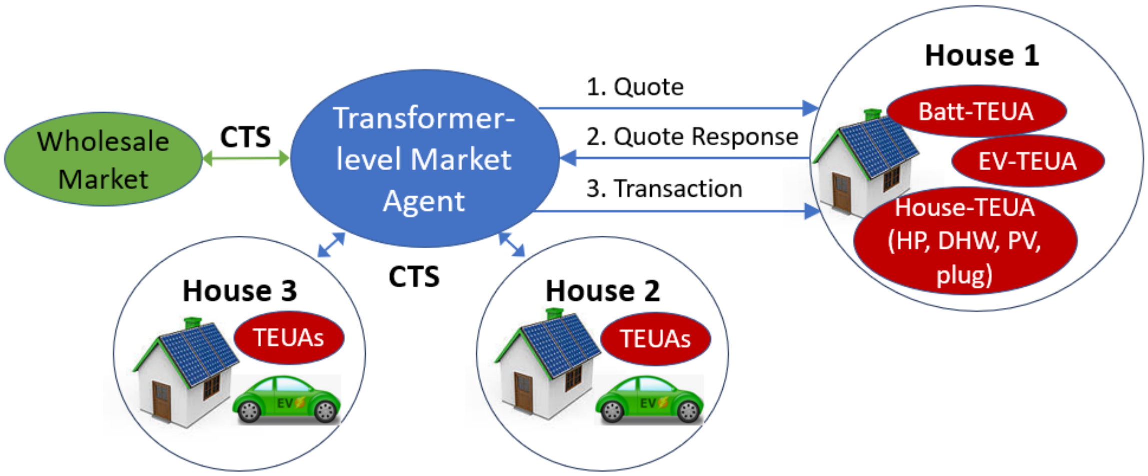


Fig. 2 TEM implementation schematic showing three market phase communications.

Figure 3 shows a TEM schematic where the TEM includes both the Market Agent operating the market (managing utility quotes and transacting power) and the TEUA representing different loads and DER within each house. Note that in initial simulation experiments each house, as shown in the "House 1" circle, has three separate TEUAs representing the devices as indicated. The "House-TEUA" aggregates heat pump (HP), domestic hot water (DHW) and plug load consumption together with photovoltaic (PV) generation.

Fig. 2 shows the key CTS messages (Quote, Quote Response, Transaction) that serve the three Steps of each round of the market. The market completes one cycle each day and each cycle has multiple rounds.[1] The cycle begins after the TEMA receives the wholesale market hourly DAP (CAISO Day Ahead Market prices for July, 2017 [4]) and then generates a limited quantity tender (distributed in Step 1 as a Quote) with prices to sell and to buy for each time interval of the next 24 hours. In Step 2, TEUAs respond with a Quote Response to buy (or sell) some amount of power for each time interval. In Step 3, the TEMA responds with a Transaction that confirms the quantity of power transacted, which could be less than the original quote response. More details on the market operation are shared below.

The TEM, as implemented, represents a CTS "quote-driven" market [5]. For this market type, there is one dominant power supplier who sets the price. That participant's prices are distributed to all market participants, and any buy or sell tenders will be at the same price. This is the logical result, since no one will pay more for power if they can get it from the utility, nor will a neighbor (generally) sell for less since they are only competing with the utility price.

[1] CTS, and markets in general, do not include this concept of a "round". It is not needed from the market participant perspective. However, for simulation purposes, in order to have better accounting and user visibility of the market operation (i.e., when reviewing logs), it is helpful to include market rounds.

2.2. Market Operation in Co-simulation

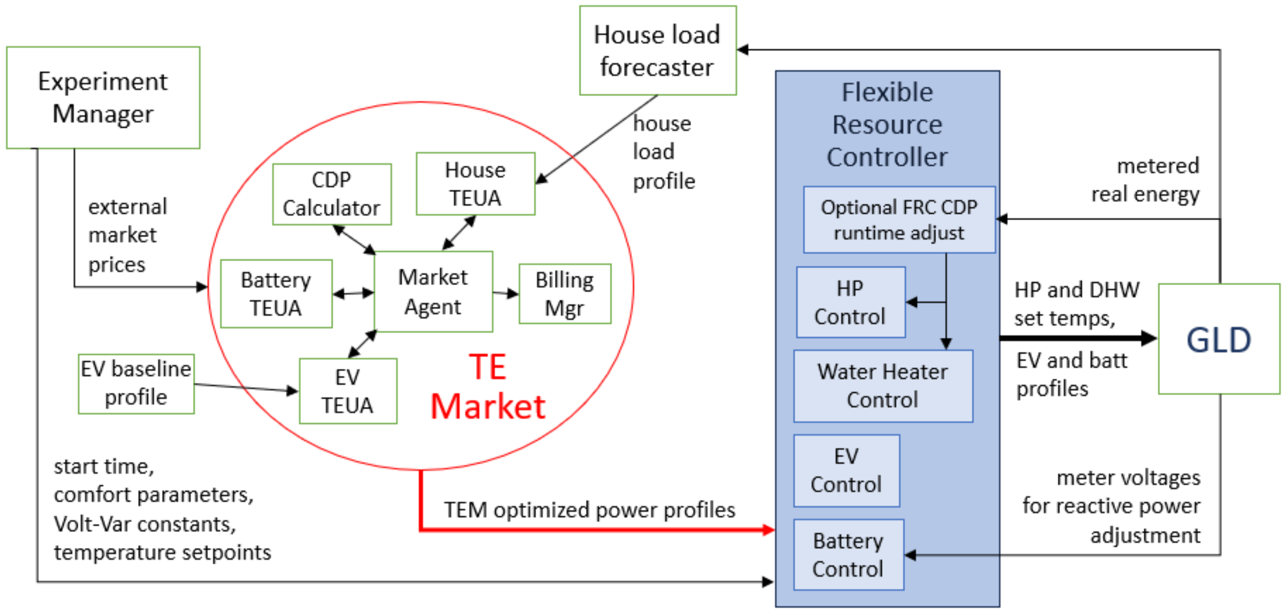


Fig. 3 TEM and FRC internal components and data values communicated among federates. GLD is the GridLAB-D grid simulator. CDP is the Congestion Dynamic Price.

The market is shown in the red circle of Fig. 3 with TEMA Market Agent, TEUAs, plus some helper components, and connections are shown to other simulation federates. An experiment is directed by the Experiment Manager, which provides time signals, model parameters, and external market price signals (DAP) for the other federates. The market operates at regular intervals coordinated with the grid simulator.

In its initial implementation, the TEM runs daily to optimize planned next-day load profiles in each house. The market takes external market prices as input, along with the daily EV baseline charging profiles ("EV profile init", Fig. 3) [3] for each car and forecast house load profiles. The market operates in rounds to iterate toward optimized profiles; TEUAs use their available flexibility to shift load to lower price intervals. Optimized profiles are passed to the Flexible Resource Controller (FRC), which then passes power (for EV and Battery) and temperature set points for Heat Pump (HP) and Domestic Hot Water (DHW) to GridLAB-D (GLD). Fig. 3 also shows a Billing Manager that tracks the transactions of each TEUA and the cumulative transacted power and cost for each house.[2] The aggregated sum of all market-transacted power flows equals the transformer flow.

The FRC passes those values into GLD on 5-min intervals as the experiment proceeds. The details of the FRC and interactions with GLD are documented in [3]. Output from GLD is used for evaluation of TEM performance compared to other price response approaches. The FRC provides optional HP and DHW set point adjustments based on GLD-measured transformer power flows, shown as a "FRC CDP runtime adjust" function in Fig. 4. This may be used

[2] TEM version 1 tracks transactions in a log file. The Billing Manager is not implemented in code.

independently of the TEM adjustment of EV and Battery power profiles. Finally, GLD metered energy is used in house load forecasting that is fed back to the TEM.

Other TEM market approaches might be used; for example, a real-time market (e.g., every 5 min) that optimizes TEUA energy use based on some localized real-time market price. The pattern for interaction with the FRC and GLD remains the same.

For the initial NIST TEM implementation, the TEM participants include all the device TEUAs behind a specific service transformer, as shown in Fig. 2. There may be one or more houses behind the transformer. Each house has an EV, Battery, PV, HP and DHW. The HP, DHW and PV are combined into the House TEUA, which also includes the non-controlled plug loads. The EV-TEUA and Batt-TEUA (Fig. 3) are independent agents that understand their own schedules (flexibility for charge and discharge given occupant needs) and manage power purchases in the market.

Each TEUA acts independently, negotiating and adjusting its power profile to get the needed power at the lowest cost, given occupant power flexibility. At the end of the market rounds, all devices have purchased their next-day hourly power profile and final market prices are set.

Although the TEUAs in a given house act independently, they all reside under the same house meter. When paying the bill for power used (settlement), the aggregated transactions of EV, Battery and House TEUAs for each hour interval are compared against the metered energy used in that interval.

In a typical energy market, such as the existing wholesale markets, a participant may adjust position in a later round by selling back power. For example, a TEUA may acquire power in Round 1 for a given time interval, but then the price (in a later round) rises significantly due to congestion. The TEUA could sell back some of the power in favor of moving the load to a cheaper interval (if flexibility allows) and pocket the difference as profit. However, while the TEM allows for this, none of the TEUAs (in the initial implementation) have been configured to exercise this function.

2.3. Market Rounds and Flexibility Class

The TEM, as implemented, operates in a series of “rounds” that serve to iterate on market positions until equilibrium is reached. Each round has 3 steps as shown in Table 1.

Table 1 Steps of each market round.

Step 1: Quote	Step 2: Quote Response	Step 3: Transaction
TEMA distributes a quote to all participants providing utility buy and sell prices and quantities for each interval. Prices are based on DAP with congestion multiplier.	TEUA market participants return quote responses (requested quantity for each interval at the given price) according to their expected power needs or power generation, with flexibility used as available to adjust load profiles in order to reduce participant costs.	TEMA looks at total requested power in each interval vs. available (per quote) quantity, reducing quantity to each party if needed, then issues transactions to TEUAs stating the amount of energy transacted in each time interval.

At the end of the market round, the transformer loading is recalculated based on power transacted with the utility that will determine the quoted buy and sell prices in the next round, and rounds continue until all behind-the-transformer quote responses are satisfied. At that point, the market cycle is completed.

Each TEUA receives a flexibility class designation. Flexibility Class 1 (FC1) devices are less flexible and are eligible to buy energy in Round 1. Flexibility Class 2 (FC2) devices are more flexible and are only eligible to sell in Round 1 and must wait until Round 2 to buy. The House TEUAs (containing PV and load) are classified as FC1 because the PV and plug loads are inflexible. The HP and DHW (included in House TEUA), along with plug loads, are given first round access to available power because they are less flexible relative to EV and battery. The EV TEUAs are classified FC2, while batteries are classified FC3. EVs likely have a more constrained charge window and requirement to charge compared to batteries. Flexibility class ordering allows the less flexible devices to get access to power first at the lowest prices (assuming some congestion will happen in later rounds), while the higher-level flexibility class devices can then respond better to any adjusted prices. This is in the best interest of the customer to save money. The batteries only enter the market after FC1 and FC2 loads are finished buying power, and only enter if it is still economical at that point. If the use case is to buy low and sell high, then the battery TEUA needs to evaluate whether it can get power at an acceptable price differential, allowing for losses, battery degradation, ROI, etc.

The FC3 battery determines when to enter the market based on observing price changes across the bid stream from one round to the next, but will not enter before Round 3. That is, FC1 devices likely can buy needed power in all time intervals without congestion at the service transformer. The prices will then remain the same at the start of Round 2. In Round 2, it is possible that EVs may have small charge amounts and that there will still be no congestion and no price changes going into Round 3. That is, the EVs could get all the power they need in Round 2 with no congestion. Whether there are price changes going into Round 2 or 3, or not, the market TEMA must continue to Round 3. At this point (and at every following round), the FC3 batteries are looking for price changes compared to the last round. If there are no price changes, then this shows that all tenders from the previous round were filled with no congestion leading to price changes. The batteries then evaluate whether it is economical to buy power, and, if so, to submit buy and sell tenders into the market. However, it is technically possible that price could change even with no subsequent tenders in the present round. For this reason, the market must not close on the first round with no received tenders but must wait an additional round. This will ensure that FC3 batteries can enter the market. Additionally, batteries must check for economical conditions on each new round before submitting additional tenders.

Note that if there are multiple quote responses requesting (in total) more power than is available in the sell quote for any of the steps above, then the available power will be divided among the requestors in proportion to their percentage of the total requested. The result will be that each buy tender is only partially filled, and the TEMA moves to the next step.[3] Whatever part of the quote response requested quantity remains unfilled is cancelled, and the TEUA must reconsider power needs with new prices in the next round.

As implemented, market rounds follow a strict schedule. The quote stream is released and then the TEMA waits for all TEUA quote responses to be received back before proceeding. Note that each TEUA responds with requested quantities for all time intervals (even if zero), and then transactions are processed and communicated. Using this approach simplifies simulation communications, reduces the computational burden on the TEUA (since all new prices are received together and evaluated once per round), and also avoids one TEUA always getting first dibs on power (getting the lowest price because it is the first to respond with a tender). This last condition would be possible in real life—the neighbor with the smarter controller and/or the fastest computer/network might always get the cheapest power.

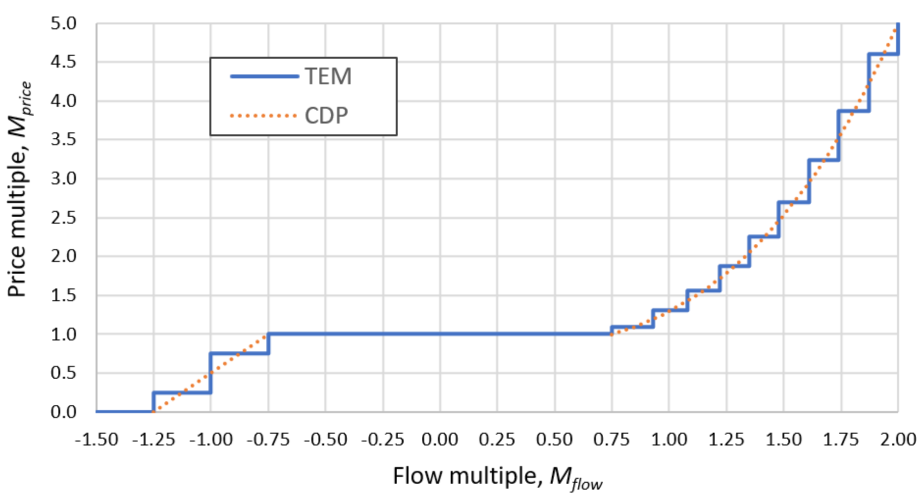
2.4. Congestion Price Calculation

TEUAs buy power in the market for each hour of the next day as needed according to their own internal algorithms. The price paid depends on the power flow through the local service transformer. As power flow increases and the transformer becomes congested (meaning the power flow is near or above capacity rating), the price will rise.

Price increases as a function of transformer loading according to the step function shown in Fig. 5, using normalized price as a function of normalized transformer flow.

$$M_{flow} = (transformer\ power\ flow)/(transformer\ capacity\ rating), \quad (1)$$

$$M_{price} = (congestion\ price)/DAP, \quad (2)$$



M_{flow} Steps	M_{price}
M_{flow} ≤ -1.25	0.000
(-1.25, -1.0]	0.250
(-1.0, -0.75]	0.750
(-0.75, 0.75]	1.000
(0.75, 0.93]	1.090
(0.93, 1.08]	1.304
(1.08, 1.22]	1.565
(1.22, 1.35]	1.877
(1.35, 1.48]	2.250
(1.48, 1.61]	2.701
(1.61, 1.74]	3.239
(1.74, 1.87]	3.870
(1.87, 2.00]	4.602
M_{flow} > 2.00	5.000

[3] The authors understand that this is not a reasonable approach in a real-life market implementation. A typical load needs certainty that it will get a certain amount of power to complete some process (e.g., make toast, or run the dishwasher cycle) at some price. The approach implemented here ensures that power is fairly distributed in the simulation (not one house always first to market) and this approach works well for batteries.

Fig. 4 Transformer congestion pricing curve. The stepped curve serves the TEM, modeled after the congestion dynamic price (CDP) used for real-time transformer-based price formation [3].

This exponentially increasing function is not necessarily what some public utility commission would select[4], but that is only a peripheral issue to the TEM simulations. There are many factors that may be used to adjust a local price, and this pricing curve only uses transformer loading as an indication of a broader measure of congestion. In the final analysis, local market agents (TEMA) and user agents (TEUA) don't need to know the factors that lead to the price but rather need to know the resulting prices and be able to adjust bidding and control based on the prices.

The price multiplier (relative to DAP) increases as congestion levels rise above 75 % capacity, Fig. 5. Price increases with flow into the building and decreases below DAP for strong negative flows out to the grid. The underlying congestion dynamic price (CDP) function [3] used for real-time congestion price calculation in the FRC is also shown. The steps are used to define the quantities to sell in each round, as discussed below.

In a forward market, there is no real-time measurement of the power flow through the transformer. Instead, the Flow Multiple for each time interval *i* is calculated as:

$$M_{flow,i} = (\sum buy\ transactions_i - \sum sell\ transactions_i)/Capacity_{trans}, \qquad (3)$$

aggregating all the buy and sell transactions across all rounds up to the present and summed across all the TEUAs behind the transformer to find the committed power flow through the transformer for each given hourly interval. M_{price} for the next round for this interval is then found from the table in Fig. 4 using the updated M_{flow}. In the case where M_{flow} is at the vertical step, the different prices on either side become the prices for next round buy and sell quotes.

2.5. Determining Buy and Sell Quotes

At the start of each market round, the TEMA calculates the local energy market prices using Equation 3 and M_{price} from Fig. 5. The TEMA then issues two quotes to market participants, one a sell quote (price TEUA will pay for power) and the other a buy quote (what will be paid for power sold by a TEUA). For a given M_{flow}, the sell quote will be for the price and quantity of the step (or part of a step) in the direction to the right in Fig. 4 and the buy quote for the price and quantity of the step (or part of a step) to the left in Fig. 4.

[4] A similar approach was adopted for a TE pilot in California [9]. Another analysis examines this to consider a wider set of inputs for prices [10].

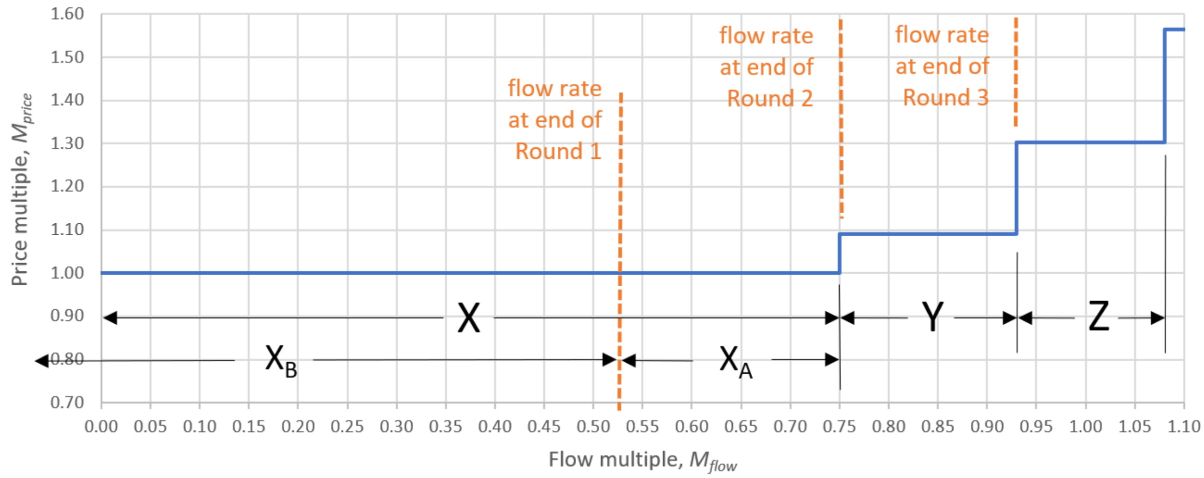


Fig. 5 Close up view of Fig. 5 steps providing example quote quantities and prices.

Consider this example for how rounds progress and power allotments proceed, Fig. 6. Round 1 will always begin with a quote (representing the utility) to sell power from 0 up to 75 % of transformer capacity (M_{flow} = 0.75) at the DAP price (M_{price} = 1.0). Simultaneously, the TEMA issues a quote to buy power from 0 to 75 % of transformer capacity in the backflow direction at DAP. The sell quote will be for the quantity of power indicated by the "X" in Fig. 6. In Round 1 (considering a single interval for a single house as an example), suppose that the PV generation is small and that the House TEUAs buy power to satisfy house loads, and the result of Round 1 for that interval is that only part of the 0.75 M_{flow} quantity is sold to the House TEUA, as shown by the left-most dashed vertical line in Fig. 6.

In Round 2, a new sell quote is released for the quantity of power indicated as "X_A" in Fig. 6 for the remaining power up to M_{flow} = 0.75 at the same M_{price} = 1.0. The buy tender is for the quantity of power shown as "X_B", extending from the dashed line all the way down to M_{flow} = -0.75. Now suppose for Round 2 that the EVs (FC2) together purchase the remaining flow quantity up to M_{flow} = 0.75. That would be all the power ("X_A") that is available to buy in that time interval in Round 2 and the round ends with M_{flow} = 0.75.

For Round 3, the TEMA issues a new sell quote for the quantity of power indicated as "Y" in Fig. 6 at M_{price} = 1.09. The buy quote would then be for the step to the left, that is, for -0.75 < M_{flow} < 0.75 and still at M_{price} = 1.0. And let us suppose that the owners of the house want to charge their EV fast, so they purchase all of "Y", that is, the flow rate from M_{flow} = 0.75 up to M_{flow} = 0.93. For a transformer rated at 25 kW capacity, this translates to a quantity of power equal to (0.93 - 0.75) * 25, or 4.5 kW, times one hour interval, which is then 4.5 kWh of energy. And that energy is sold at a price of 1.09*DAP (from table in Fig. 5). Since the EV consumed all of "Y" (and ignoring other TEUA purchases or sales), Round 3 ends with M_{flow} = 0.93. Note as an aside that the EV owner may have wanted to purchase more power in this interval, but that additional power was not available in Round 3 and the additional amount would have to wait for Round 4.

At the start of Round 4, the TEMA offers to sell the quantity of power represented by "Z" at M_{price} = 1.30 for the quantity of M_{flow} = 0.93 up to M_{flow} = 1.08. Simultaneously, the TEMA issues a quote to buy power represented by “Y” at the price of M_{price} = 1.09. The owners can buy more for the EV, or perhaps may decide to sell back the power they just bought because they decide they don’t really need to charge the EV, or because they are leaving soon and can shut off the heat pump, etc.

This example shows that the buy and sell prices and quantities from the utility will track along the congestion curve and next round buy and sell prices will be different if a quoted quantity is sold out and a step change in price is reached. However, if only part of a quoted quantity is sold (e.g., only part of “X”), then in the next round the quotes for buy and sell are the quantities of “X” above and below the current flow rate, with both quotes at the same price. Also, if multiple TEUAs all request power and the total is more than the quoted sell tender quantity, then the power is split among them proportionally.

2.6. Settlement

For settlement, the recorded flow through an individual house meter (output from grid simulator, totaled across each hour) is compared to the sum of TEM transactions (for each hour) for the TEUAs behind that meter. Settlement is handled outside of the TEM, but the TEM logs transactions for each TEUA and meter as required for settlement.

The TEUA position for settlement for a given time interval is the sum of all transactions in that time interval for a given TEUA at market close. This is the amount of power that a TEUA has transacted in each hour of the next day, which could be a negative quantity for some intervals (e.g., at noon when the sun is shining and PV generation exceeds loads). The market transaction log contains an array of tuples: quantity of energy and average cost for each of the 24 hourly intervals for each TEUA. The TEM-based house meter position will be the sum of all house TEUA positions. Settlement requires an actor that has access to both the meter data and market transaction data. This settlement actor (Billing Manager) compares the GLD meter-measured power flow in each hour to the TEM-transacted position for each meter. Any difference between the two in any time interval must be settled at some agreed on ex-post transaction price. That price could be the market closing price (buy or sell, as appropriate) for each time interval.

However, there is potential for gaming. Some TEUA might under-purchase power to avoid M_{price} rising with congestion, but then in real-time actually use much more power with the intent to pay for that power at a lower market closing price for that time interval, despite M_{flow} being much higher than would be indicated for that price from Fig. 5. One solution for this could be to use the higher Fig. 5 price associated with the final M_{flow} to settle this large deviation, which would likely cost the TEUA more than if it had more accurately purchased the same power ahead of time, thus reducing the incentive for gaming. This has not been implemented in the TEM as of publication and is not needed with honest TEUA algorithms.

3. TEUA Response Strategies

Each house is represented by three TEUAs: House, EV, Battery. This section looks at the market power purchasing strategy for each of these.

3.1. House TEUA

The House TEUA aggregates HP, DHW, plugs and PV. In real life, PV output must be forecast based on weather and season. Plug loads are estimated based on typical load patterns and day of the week. In our simulations, the plug loads do not change day to day and are known from previous simulation experiments. The PV output is also known because we are using historical data. The HP and DHW have some limited flexibility. The HP and DHW controllers adjust their energy profiles by raising house temperatures (HP precooling) or lowering temperatures (DHW) during the peak DAP hours [3]. However, it is not simple to further shift HP and DHW loads in response to congestion, since the connection between temperature adjustments and power is not simple. Rather, the initial approach used in the TEM is for the House TEUA to purchase energy according to the forecast profiles (which include some time-shifting to reduce cost). That is, even with congestion price increases, the House TEUA will continue to buy needed power without any additional shifting in time.

The HP power estimates are based on previous GridLAB-D runs with DAP response. For the DAP response approach, heat pumps shift load off-peak by precooling and then allow house set points to rise during the high price period, resulting in lower consumption when prices are high. The resulting power curve is given to the house TEUA to aggregate with needed DHW and plug loads while subtracting PV generation. This becomes the first-round buy tender (which may include a negative value in an hour where PV generation is greater than the load).

Note that the House TEUA is unlikely to encounter congestion-based market price increases since it has first access to power (FC1 device) and the transformer should be able to provide power uncongested when EV and Battery are not yet seeking to purchase power. Note also that if for some reason load is very high such that there is congestion and a rising price, the battery could choose to sell power into that interval and effectively reduce the price.

The water heater follows the DAP response strategy presented in [3], reducing the set point temperature in the afternoon in order to reduce heating of water during the higher-priced hours.

The DHW and HP could make simulation runtime adjustments to house and water heater set points in response to high CDP, with set point adjustment following the CDP Adjust functionality presented in [3]. CDP is calculated during GLD run-time based on the actual measured transformer power flow. However, it is expected that this CDP will never reach a value high enough to trigger additional adjustments, considering the TEM design to shift load and avoid high prices. Note also that the use of this function would only make sense if the TE tariff also rewarded response to this 5-min congestion price signal.

3.2. EV TEUA

The EV looks to buy within the designated charge window (either day or night). The approach to determining EV charge windows and charge amounts is presented in [3]. The max charge rate for the EV is 7.2 kW. The EV can purchase energy starting in the second round (FC2 device). The EV TEUA looks to buy power during the lowest-price intervals within the charging window (day or night). Compared to the baseline or DAP EV charge profiles [3] with ramps, the final charge profile from the TEM will be more granular hourly amounts with no ramps.

The EV purchase strategy is as follows:

1. Examine TEMA quote and find low-priced intervals in the charging window.
2. Request the full amount of power needed up to the quoted available quantity in the lowest-priced interval. Any remaining needed power is requested from the next-lowest-priced interval, etc., staying within the charging window.
3. When the transaction is returned, possibly only allotting a portion of the requested power, recalculate the amount of charge still needed and repeat from step 1 until all needed energy is purchased.

3.3. Battery TEUA

The Battery develops its power profile by seeking to sell power in the highest-priced hourly intervals and buy in the following lowest-priced intervals. However, the battery does not begin to buy and sell power until after the EVs are done charging, and only if price differentials indicate that it is economical to buy low and sell high (which assumes the use case is arbitrage).

Whereas the DAP response pattern (as presented in [3]) has a predetermined smooth ramp-up and ramp-down pattern for battery charge and discharge, the TEM pattern will vary depending on House TEUA and EV charge patterns. However, each house has the same battery and controller, such that every Battery TEUA will bid for the same power in the same intervals. Note that the battery can never charge above 100 % or below 0 %, so the TEM Battery TEUA tracks State of Charge (SoC) along with market position during the progressive market iterations.

The implemented TEM battery strategy is described below and operates on the assumption that the market starts at 5 p.m., thus the battery starts full and must discharge (on evening price peak) before charging (generally overnight during low price period, depending on congestion).

For each round, the battery must balance the power discharged with the power charged, accounting for round trip losses.[5] On its first trading round, the battery will look for the highest-priced interval to sell and lowest-priced interval to buy. After confirming an acceptable price differential, the TEUA will submit quote responses asking to sell and buy energy in these intervals with the goal of discharging and then fully recharging the battery. At the end of the round, it is possible that the resulting transactions will not provide the battery with all of the requested discharge or charge amounts of power for some intervals. At this point, the simplistic

[5] Current round-trip efficiency taken as 86 % based on battery in use in the GLD model.

TEM implementation will proceed to the next round, and potentially additional rounds, with a goal of balancing out the current imbalance of sold power vs. bought power.

When the battery transactions are balanced, meaning that the transacted quantity bought balances the total transacted quantity sold (including losses), then the battery TEUA will again look at the highest and lowest priced time intervals and repeat the process described above until it can no longer formulate a quote response. This happens when either the battery has been fully discharged, or it fails to find two intervals with an acceptable price differential[6].

The bid to buy and sell in these intervals is calculated as the minimum value of

(1) the remaining charge flexibility (max rate of 5 kW)[7] for both intervals,

(2) the total quantity of energy tendered to buy in the battery sell interval or

(3) the total quantity of energy tendered to sell in the battery buy interval, and

(4) the minimum estimated SOC for all intervals between the two intervals (inclusive)[8].

For the case where the round ends with the total transacted buy quantity *less than* the amount needed to compensate for transacted sell quantities, the battery needs to find additional low-price buy intervals to fully charge the battery. In this case, the battery agent uses the following market round(s) to find additional low-priced intervals for charging before attempting to discharge the battery further. The buy quantity for these rounds is the total quantity required to balance the transaction, although this will be limited by the available amount in the quote and cannot exceed the max charge rate of 5 kW (that is, requested quantity cannot exceed 5 kWh). Note that the battery agent may be unable to find another buy interval with an acceptable price differential, and in this case will not fully recharge the battery.

For the case where the round ends with the transacted buy quantity *greater than* the total transacted quantity in the sell intervals (again, accounting for losses), the battery needs to find alternative high-priced sell intervals to discharge to prevent it from exceeding its maximum capacity. In this case, the highest-priced time interval preceding earlier buy intervals in previous round(s) is selected. The sell quantity for this interval is determined as the minimum value of (1) the charge flexibility (max rate of 5 kW) for the sell interval, (2) the available quantity of energy tendered to buy by the market for that interval, and (3) the minimum estimated SOC for all intervals between the selected highest-price interval and the buy interval from the previous round(s).

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[6] Price differential was initially set to \$0.01.

[7] The battery used initially has a max charge and discharge rate of 5 kW.

[8] Battery SOC must remain between 0 and 100 in all intervals.

4. TEM Implementation in code

The federates that were implemented to represent the market, including the messages they exchange, are shown in Fig. 7. The Market Agent federate runs multiple simultaneous and independent market instances, one for each transformer of interest in the GridLAB-D simulation. The User Agent federate likewise runs a set of independent agents that represent the different resources for each house (FC1 devices, the electric vehicle, and the battery). The houses were aggregated into a single federate to reduce the total number of processes and thus improve the scalability of the simulation.

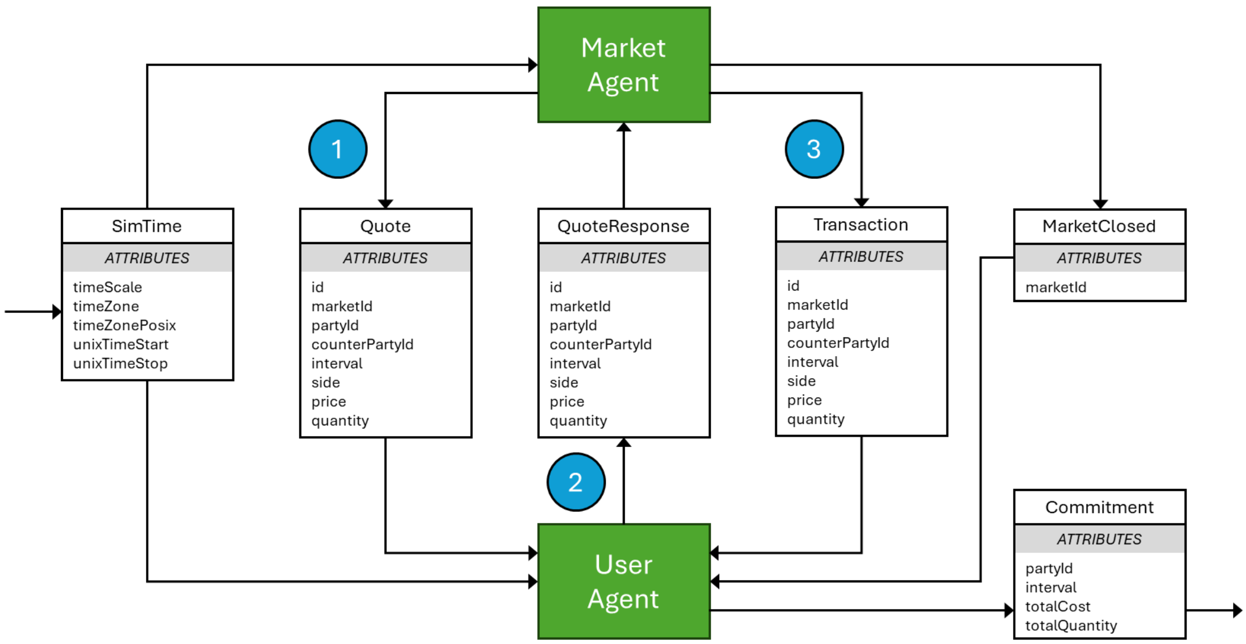

Figure 6 Market Federates and their Messages

4.1. Market Agent Overview

During its initialization, the Market Agent (Fig. 7) receives information on the simulated scenario time from the message SimTime sent by a time management federate not shown in the figure. When the scenario time becomes 17:00, the Market Agent starts a new set of markets for each transformer. It also starts these markets when the simulation begins, in case the simulation starts at a time other than 17:00, to ensure there is always a valid market result during execution.

The progression of scenario time is paused[9] when the market is running and will not resume until all the transformer markets have closed. This means that, in the simulation, all market actions (quotes, quote responses, and transactions) occur at the same time of 17:00. This is a simulation artifact due to how the market was implemented to simplify data management by

[9] This is necessary to prevent the GridLAB-D simulation from running until the market resolves.

ensuring that there is only ever one relevant market result to process (that is valid from 17:00 to 16:59 of the following day). In an actual implementation, the market would run before 17:00.

A market closes when it completes two consecutive rounds without any transactions. When it closes, the Market Agent sends the MarketClosed message to the User Agent. When all of the markets have closed, the Market Agent unpauses the progression of scenario time.

4.2. User Agent Overview

The User Agent (Fig. 7) is entirely reactive to the messages received from the market. It recognizes that a new market instance has started when it receives a quote from the Market Agent that contains an unknown marketId. It knows the market instance has ended when it receives a MarketClosed message from the Market Agent that contains a matching marketId.

For each active market, the User Agent tracks the current position of each individual resource in that market based on transactions received. If the active markets contain 4 total houses, then the User Agent tracks the positions of 12 resources (a battery, an electric vehicle, and the FC1 devices for each house). The current implementation has one of each resource per house. The User Agent determines which houses participate in the active markets based on their transformer, as each market represents a single transformer on the distribution grid.

The position is tracked as a pair of 24-element arrays, with one array to track the price paid per market interval (hour) and another to track the quantity transacted per interval. When the User Agent receives a MarketClosed message, it generates Commitment messages [3] for that market based on the tracked position. A total of 24 Commitment messages are generated for each resource, with the partyId set to the resource identifier, the interval set to the market hour, and the total cost and total quantity set to the position for that interval. These Commitment messages are sent to a controller, such as the Flexible Resource Controller, to guide control decisions for the next day based on market results.

4.3. Market Rounds

The active markets proceed in rounds, with the steps of a single round indicated by the numeric labels in Fig. 7. At the start of each round, the Market Agent sends two quotes for each hour of the day based on the congestion pricing curve explained in prior sections to indicate the current price and quantity of power that the market is buying and selling. The values used to populate this Quote message are listed in Table 2.

Table 2 Attributes of the Market Messages

	Quote	QuoteResponse	Transaction
id	an integer to indicate the current market round	the quote **id**	the quote response **id**
marketId	the market transformer ID	the market transformer ID	the market transformer ID
partyId	the string “utility”	a unique resource identifier[10]	the string “utility”

[10] The name of the resource in the GridLAB-D simulation is currently used for the unique resource identifier.

counterPartyId	the market transformer ID	the string "utility"	the quote response **partyId**
interval[11]	an integer between [0, 23] that represents which hour the quote is relevant to	the quote **interval**	the quote response **interval**
side	a character in {'b', 's'} to indicate buy or sell quote	the quote **side**	the quote response **side**
price	a string value for the current congestion price for the interval with 4 decimals	the quote **price**	the quote response **price**
quantity	a string value for the current available quantity for the interval with 4 decimals	quantity calculated based on the forecasted needs	quantity calculated based on the aggregate value of the quote responses

When the User Agent receives a quote, it responds with a Quote Response for every resource involved in the market, even if that Quote Response lists a desired quantity of 0. The Market Agent does not progress to the next round until it receives a Quote Response from every resource, which is why even resources not participating in the current round must respond with a 0-quantity quote response. This is a requirement because the Market Agent cannot compute the transactions without the complete set of quote responses, as the transaction quantities depend on the total quantity of power requested by the resources. The values used to populate the Quote Response message are also listed in Table 2.

When the Market Agent receives all the quote responses, it discards the 0-quantity responses and compares the total quantity requested in each interval to the available quantity. From this comparison, it computes the proportional quantity each resource will receive and responds with a Transaction. The values used to populate this Transaction message are also listed in Table 2.

From the Transactions, the User Agent updates the internal state of each resource, including its current market position. For the batteries, the User Agent determines whether there is a mismatch of power between the buy and sell transactions that would result in the battery being over- or undercharged. These updates determine whether and how the resource participates in future market rounds.

4.4. Market Configuration

The User Agent contains three different resource agents (FC1 devices, electric vehicle, and battery) that can be configured using a combination of JSON and CSV files. For the FC1 devices, the forecasted load for each house for each hour of simulation is configured with a CSV file. The forecasted load is defined as the combination of plug loads, the water heater, the heat pump, and any solar generation presented as a single aggregate value where negative values indicate excess generation from the house to the grid. For the electric vehicle, the coefficients used for the distribution of charge amounts are configured with a JSON file. For the battery, the

[11] Because the market begins at 17:00, the value 17 is the first interval (hour) of the market and the values [0, 16] represent intervals from the following morning/afternoon.

maximum charge rate, the total capacity, and the price differential that is considered economically acceptable are configured with a JSON file.

The Market Agent requires three configuration files. The first file specifies the transformers from the GridLAB-D simulation that should run a market instance and their capacities to compute congestion-based pricing. The second file lists the names of all the user agents (the individual resources for each house) that will participate in the market. These names are used to determine when all of the quote responses have been received. The third file provides the day-ahead price information for each hour of the simulation for use in selecting the initial quote prices. Some of this information (the day-ahead prices, the user agent names) could be obtained during the simulation through use of additional messages, which could be the subject of future work.

5. Conclusion

The NIST TEM federate has been designed to enable quote-driven market operation at the level of the service transformer with multiple TE user agents participating in the market. The TEM market runs once per day to negotiate power usage for the following day, which allows for optimal use of customer device flexibility and the lowest energy prices for customers while still meeting customer comfort and scheduling needs. The TEM operates in co-simulation together with the NIST Flexible Resource Controller and GridLAB-D. Although the TEM operates a specific market design attached to a specific grid model, the TEM market design and grid configuration can be modified to study other market designs and other grids.

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Appendix A. Data semantics tied to CTS standard

The data attributes of Table 2 above are derived from the CTS data model. This appendix shows the derivation and gives a rationale for reducing the full CTS data model for quotes and transactions to the Table 2 attributes used in the initial simulation implementation.

A.1. Step 1 Quote

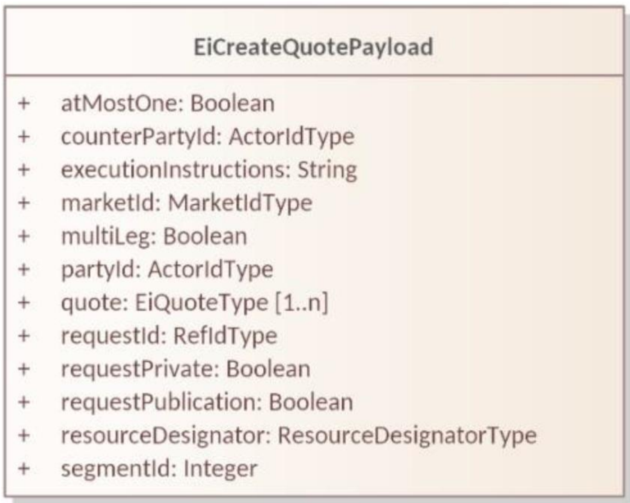

Fig. A-1 EiCreateQuotePayload attributes taken from CTS v1.0, 9.6.2 Quote Messages, Fig 9-9 Negotiation Facet Quote Payloads.

Discussion of Fig. A-1 attributes and rationale for inclusion in simulation:

- atMostOne: use of atMostOne applies to when there are multiple quotes for the same interval and only one can be lifted. The simulation case has only one quote per time interval. Therefore, this is not used in simulation.
- counterPartyID is the marketID. The utility sends quotes to the market and then the market passes them to individual TEUAs.
- executionInstructions are not needed for the simulation case.
- marketID is tied to the transformer. Market participants are all TEUAs below the transformer.
- multiLeg: each of the enclosed quotes must be accepted or none. This is not needed for the simulation.
- partyID is for the utility—the party that originates the quote.
    - In the quote response, PartyID flips to the TEUA, e.g., “122-1 ev”
- segmentID is tied to the market type. Currently, there is only a DA market, “DAM”. Not used in the simulation.
- Quote Details—the CTS Quote data model is shown in Fig. A-2 and attributes of that are discussed below the figure.

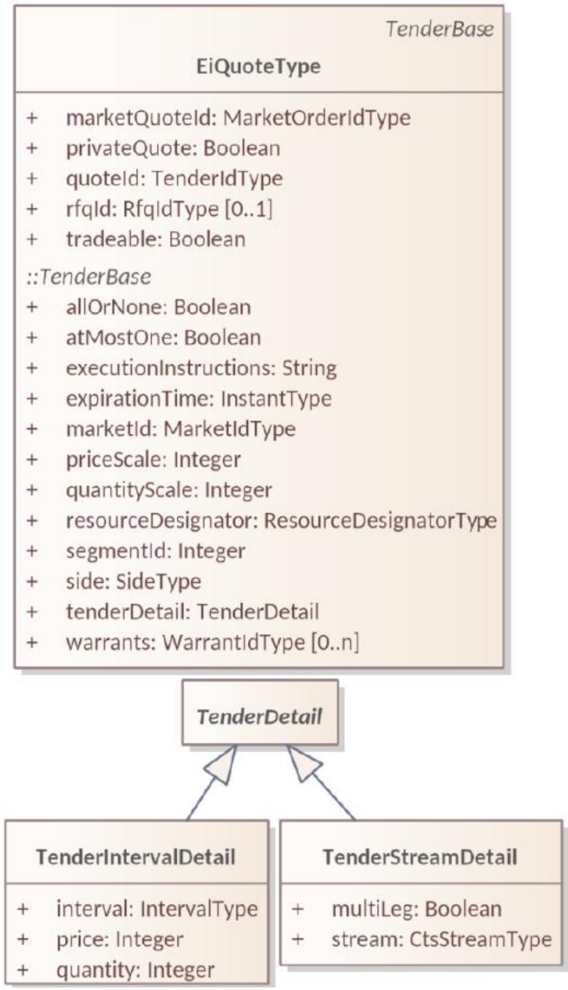

Fig. A-2 EiQuoteType attributes taken from CTS v1.0 9.5.3 Quote Messages, Fig 9-7 UML Class Diagram of EiQuoteType showing inherited attributes.

Discussion of attributes and rationale for inclusion in simulation

- marketQuoteID is an ID for the quote assigned by the market. It is a reference in a lookup table used to match a quote response to the quote. For simulation purposes, these fields are used:
  - id: integer to indicate the current market round
  - side: either "s" for sell or "b" for buy
- privateQuote – simulation quote is not private. Not used in the simulation.
- quoteID only applies to off-market. Not used in the simulation.
- allOrNone should be false, which is the default. Not used in the simulation.
- ExecutionsInstructions. Not used in the simulation.
- expirationTime. Not used in the simulation.
- marketID, same as above. Not used in the simulation.
- priceScale, dollars are used for prices with no scaling. Not used in the simulation.
- quantityScale, kW is used for the units. Not used in the simulation.

- resourceDesignator is “energy”. Not used in the simulation.
- side: buy or sell. “buy” is the price the utility is paying to buy from the customer TEUA, “sell” is the utility selling price for the customer to buy from the utility.
- tenderDetail should include:
    - interval: in simulation, the interval, prices ($) and quantities (kWh) are passed for the 24 hourly intervals.

The utility sends quotes (two new quotes for each round for each market, price and quantity for buy and sell for each interval of tomorrow) and the market distributes to TEUAs.

A.2. Step 2 Quote Response

The TEUAs respond with buy and sell quotes back to the market for what they want for each interval (also streams). Here is the AcceptQuote message payload.

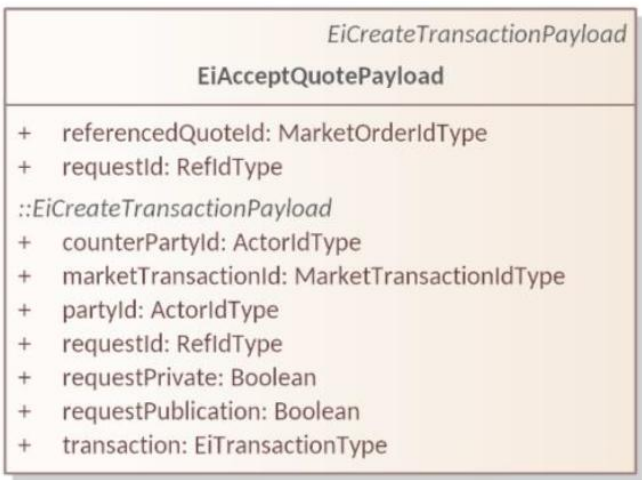

Fig. A-3 EiAcceptQuotePayload attributes taken from CTS v1.0 9.6.2 Quote Messages, Fig 9-9 Negotiation Facet Quote Payloads.

Discussion of Fig. A-3 attributes and rationale for inclusion in simulation:

- referenceQuoteID references the marketQuoteID from the Quote message (id).
- requestID is used as a reference for the step 3 AcceptedQuote transaction message. In simulation, this is equivalent to partyID, e.g., “122-ev”. The simulation uses partyID.
- partyID is the TEUA.
- counterPartyID, which party the quote response is being sent to (“utility”).
- transaction:EiTransactionType has the quote with quantity for each interval. For this, reference CTS 6.3 Fig 6-2 EiTransactionType and contained TenderIntervalDetail (see Step 3 below).
- In simulation, other elements are not required.

A.3. Step 3 Transaction

The transaction data attributes are taken from the EiAcceptedQuotePayload, Fig. A-4.

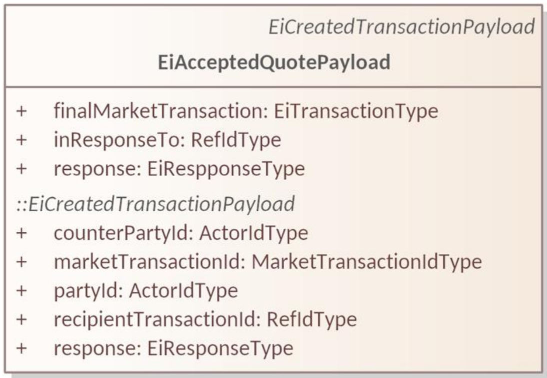

Fig. A-4 EiAcceptedQuotePayload attributes taken from CTS v1.0 9.6.2 Quote Messages, Fig 9-9 Negotiation Facet Quote Payloads.

The final transaction details are included from the transactionType in Fig. A-5.

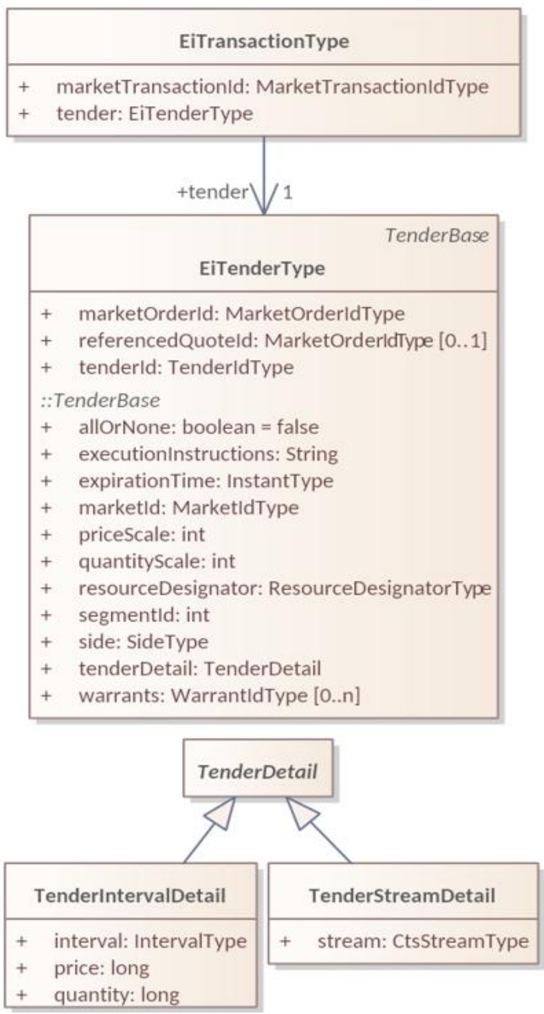

Fig. A-5 EiTransactionType, EiTenderType and TenderDetail attributes taken from CTS v1.0, 6.3 Information Model for the Transaction Facet, Fig 6-2 UML Class Diagram of EiTransactionType.

For simulation purposes, only these elements are required:

- original quoteID as reference (id),
- partyID (TEMA is the one sending the transaction to both util and TEUA),
- counterPartyID (TEUA), plus the
- final transacted prices and quantities.
- There is no need for a unique marketTransactionID since it's just a handle for the details of the transaction.

A.4. Final Exchanged Attributes

Initial Step 1 Quote from util to market, each round, follows this format:

- marketID: "xfmr_122".
- partyID: "utility".
- counterPartyID: "xfmr_122" (util sends quote to market, market then broadcasts to all parties via ticker).
- marketQuoteID (id): indicates market round.
- side: "b" for buy, "s" for sell.
- tenderDetail stream:
    - interval: an integer indicating hour of the day from 0 to 23.
    - price: string value for current interval price.
    - quantity: string value for current interval quantity.

The Step 2 Quote Response from TEUA to util, each round, follows this format:

- marketID: "xfmr_122".
- partyID: "122-1 ev".
- counterPartyID: "utility".
- id: round "7".
- side: "s" (note: EVs buy power, util sells power, and this is a market sell quote response).
- tenderDetail stream:
    - interval: an integer indicating hour of the day from 0 to 23.
    - price: string value for current interval price.
    - quantity: string value for current interval quantity.

And the final Step 3 Transaction for each TEUA for each round for each day market for either buy or sell quote will repeat the same data fields from Step 2, except:

- CounterPartyID: "122-1 ev".
- tenderDetail stream details give final transacted quantities (potentially less than request).