Transactive Device Architecture and Opportunities

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Abstract

We describe an architecture for applying Transactive Energy [1] to a device or sets of devices at any type of facility (such as a residence, commercial building, industrial plant, electric vehicle, or generation plant). The devices may be of any type: appliances, building heating ventilating and air conditioning (HVAC) systems, refrigeration, pumps, water heating, lighting, computing, solar and wind generation, fossil-fueled generation, and storage[1].

We assume a transactive interface to the grid. One or more parties post forward tenders[2] (offers) to buy or sell energy delivered to or from the facility. The facility party (owner/operator) may accept all or part of these tenders at any time. The facility party may also post buy or sell tenders to other parties for energy delivered at the facility. Some of the parties may be under cost-of-service or other forms of utility regulation and ownership.

For each device we define a decentralized optimization problem to maximize the net benefits to the facility owner given the prices of forward tenders and other information.

And given the device optimal dispatches, we address the issue of accepting tenders to create transactions.

Finally, we outline some examples and opportunities for device manufacturers, regulators and grid participants.

1. TRANSACTIVE ENERGY

1.1. What is Transactive Energy?

Transactive Energy is based on buy and sell transactions of energy among parties that consume, produce, store, and transport electric energy. Parties can include end users owning energy consuming devices, storage and generation; central generation owners; and distribution and transmission grid operators. In this paper we use the term power when we quantify transactions of energy[3].

1.2. Forward Transactions

Transactive Energy transactions are for energy delivered over intervals of time such as a year, month, day, hour, 5-minutes or 4-seconds. The transactions may be executed years, months, days, hours, minutes, or seconds forward of delivery or at the time of delivery. Forward transactions among parties are necessary for four basic reasons:

1) Device, system, and grid operation generally must be planned and must reflect the physical limits of devices and systems to consume, produce or store energy, turn on or off, ramp up and down, and provide the services.
2) Devices, systems and grids must be manufactured, constructed, installed, and maintained and fuel must be purchased and scheduled for delivery ahead of actual operation.
3) Parties prefer stability in costs and revenues which can in part be accomplished with forward transactions for energy.
4) Forward transactions reduce the volume of spot market transactions and thereby reduce the leverage of large suppliers over spot market prices.

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[1] Transactive Energy can be applied to any energy commodity such as electricity, natural gas, oil and oil products. This paper focuses only on electricity.

[2] In ordinary conversation, the terms offer, bid, order, and tender are used interchangeably, sometimes with specific buy or sell implications. In formal descriptions of Transactive Energy we have settled on the term tender to either buy or sell a quantity of a product at a price.

[3] Power is the rate of flow of energy. For a given interval length the energy flow is the average power over the interval times the interval length. In ordinary conversation the terms power and energy are often used interchangeably without confusion.

1.3. **Real-Time Transactions**

In addition to forward transactions, transactions at the time of delivery (real-time transactions) are necessary to instantaneously balance energy production and usage and to assure that the grid operation is stable.

Contrary to often expressed misconceptions, Transactive Energy is not prices-to-devices broadcasting of price signals. Such price broadcasting has many problems including risks of grid instability, market abuse, volatile costs and revenues (see Section 2.6).

1.4. **Coordinated Decentralized Control**

Transactive Energy supports real-time coordinated decentralized control of electrical devices by the users and owners of these devices. Such coordination is accomplished using explicit priced tenders (offers) and transactions among parties to pay for electric energy consumed or produced by devices.

Coordinated decentralized control is an alternative to uncoordinated decentralized control or centralized control of devices. In electric grids with fixed prices for retail customers, for example, there is little coordination of device operation and grid conditions. Centralized control of retail devices conflicts with the desires of retail customers and is very complex and expensive because of the amount of information on device physics and customer preferences that needs to be collected. In fact, centralized control is generally not feasible, and coordinated decentralized control is the only practical option.

1.5. **Transactive Energy is a Business Process**

Transactive Energy also is a business process for energy transactions among parties. This business process uses the following definitions:

- An Energy Transaction is an exchange among parties of an Energy Commodity for a Payment.
- An Energy Commodity is a Quantity of Energy delivered at a location during an interval of time.
- A Payment is a transfer of currency from one Party to another.
- A Price is the Payment “per unit of the “Commodity”.

Transactive Energy transactions cover a wide range of complex contracts, algorithms and specific business processes including e-commerce for electricity [2]. To facilitate the e-commerce and its automation, standards for Transactive Energy, as described below are essential. The Organization for the Advancement of Structured Information Standards (OASIS) has developed such standards [3-5].

2. **TRANSACTIVE ENERGY MARKET INFORMATION EXCHANGE (TeMix)**

2.1. **What is TeMix?**

Transactive Energy Market Information Exchange (TeMix) is a profile (subset) of Transactive Energy standards as specified by OASIS. TeMix standards are focused on the simplification and automation of electric energy transactions.

TeMix has just two products; energy and energy transport, and call and put options on these.

Parties to transactions for these products and options on these products may be

1) Owners of end-use devices, generation, and storage with interval meters,
2) Financial parties providing risk management with no intention of delivery,
3) Suppliers and consumers of physical energy transport services, or
4) Suppliers and consumers of financial transport hedges.

A party may take the buy or sell side of a transaction. A consumer can sell by reducing his purchased position or by self-generating. A supplier can buy back from his sold position (see Figure [1] where the TeMix market process is highlighted).

With TeMix, where regulations permit, any party can transact with any other willing party, or with willing intermediaries. No information is required from a counterparty except for information discovered by issued tenders and responses to tenders. No control over another party is implied except as mutually agreed in an option transaction. Options may be transacted for risk management or reliability reasons.

TeMix characterizes the quantity of electricity delivered as the power (typically KW or MW) delivered over an interval. The energy delivered over the interval is the power times the length of the interval measured in hours with the resulting units of KWH or MWH. Reactive power and energy can also be transacted using TeMix but such transactions are beyond the scope of this paper.

2.2. **TeMix Market Processes**

To understand the role of transactive devices in TeMix it is important to understand how TeMix market processes work.

In fact, TeMix business processes employ the most basic concepts of ordinary business:

- You make an offer or tender of a product to me at a price, I choose to accept.
- You deliver the product, I deliver money.
- Each of us makes transactions we consider beneficial.
- And each is obligated to meet the needs of the other — reliably.

TeMix supports decentralized decisions and coordination using near-continuous, asynchronous communication[4] of TeMix tenders (offers) among parties. Many different market processes to reach agreements on transactions may use the TeMix model. Different parts of the energy market may employ different market processes.

The TeMix market process is illustrated in Figure 1

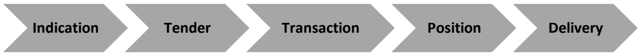

FIGURE 1: TEMIX MARKET PROCESS

- An Indication is non-binding and non-actionable. It is (1) a request for a Tender, (2) a forecast of usage or supply, or (3) a forecast of price.
- A Tender is a price and quantity for a Transaction with an expiration time.
- A Transaction is formed by accepting a Tender.
- A sequence of transactions leads to a Position.
- Delivery is the metered quantity delivered.
- Any difference between the Position at Delivery time and the metered quantity is used to create another Transaction with a party that provides balancing service Tenders.

This process is further illustrated in the next section.

2.3. TeMix Forward Transactions and Positions

TeMix forward transactions accumulate in forward physical and financial positions. Financial, hedge positions are cash-settled, perhaps based on a real-time price index. Forward physical positions are compared to metered delivery and any differences are settled by real-time transactions. Figure 2 illustrates such a sequence of forward transactions and positions. The figure shows KW transactions and positions for each night, day, and evening period. Initial year-ahead and then month-ahead transactions for each period combine to result in month-ahead positions for each period. These positions are then combined with day-ahead transactions to result in day-ahead positions. The day-ahead position is then compared to the metered quantity and the difference in each period is offset with real-time transactions.

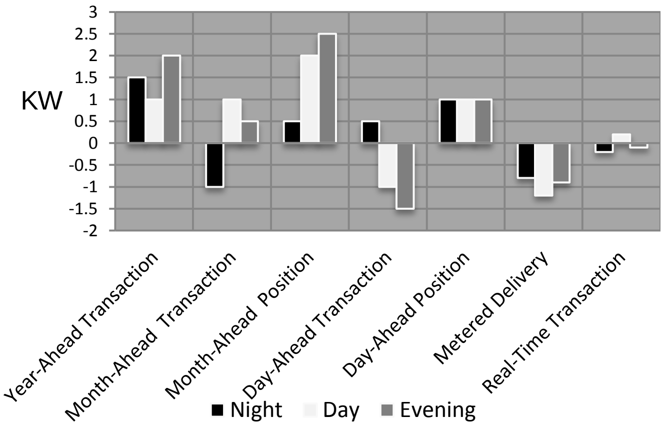

FIGURE 2: ILLUSTRATIVE TRANSACTIONS & POSITIONS SEQUENCE

In some markets, forward transactions by a party may be with several counterparties. The TeMix concepts are similar to concepts used in continuously traded bid/ask markets such as commodity and stock exchanges, and energy bilateral transactions.

2.4. Positions with Multiple Interval Durations

TeMix employs transactions defined on nested sets of interval durations. For example, a nested set of interval durations is a calendar year, calendar month, day, hour, 5-minutes and 4-seconds. Another nested set of interval durations is a calendar year, calendar month, day, hour, 15-minutes, 5-minutes and 6-seconds. Nested intervals must evenly fit within longer intervals without overlap. The shortest interval duration in a nested set is generally determined by the interval duration of the facility meter as set by the limits of the meter or local policy.

TeMix uses a convention that the power quantity for a transaction is at a constant level over an interval. This makes it easy to calculate the position for the shortest duration interval of a nested set of intervals. For example, using the first set described above, the position in any 4 second interval is the sum of the positions in all longer duration intervals in the set that contain this 4-second interval.

Standardizing the intervals makes it easier for parties to carry out transactions and the nested set of interval of various durations support positions that can match any desired or optimal consumption or production of energy by a facility and its devices.

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[4] Most commerce is a carried out in markets where transactions can be carried out at any time. This is in contrast to auctions wherein many tenders are cleared at prescribed times.

A significant benefit of this approach is that any transaction for an interval modifies a contracted baseline that is defined by the positions for the interval. There is always a contracted baseline. Hence there is no need to estimate what a party might have consumed as is necessary with most forms of demand response.

2.5. **TeMix Protocol**

The TeMix protocol for web services communication of messages to create tenders and transactions is described in [1]. The protocol supports manual and automated creation of tenders and transactions among many Parties and their software systems and devices at high volumes and high speed as may be necessary.

2.6. **Market Stability**

Stability of any electricity market requires rules, regulatory oversight and careful implementation especially as electricity service is so critical to society.

The concept of broadcasting prices-to-devices is based on the idea that wholesale spot prices can be broadcast with retail adders to retail devices that can respond [6]. There are several problems with this approach that TeMix is designed to overcome:

- If the retail tariff price differs from the broadcast price then customers may not respond or respond in the wrong direction. For example, if the retail customer pays a flat, fixed price, price signals may only result in unknown voluntary responses.
- If the response to a broadcast price is large, the actual real-time price may be very different from the broadcast price. For example, a forecast grid shortage that results in a high broadcast price could result in a large load reduction and an actual real-time price that is very low.
- If the response to the broadcast price is delayed then the response may be counterproductive and unstable.
- If a large portion of customer load is responsive to a broadcast spot price then customers may be more exposed to price manipulation by large suppliers.

The TeMix design addresses these problems by associating a quantity and an actionable price with every tender; using frequent small tenders and transaction; and using sequences of forward transactions to build positions in each interval. Forward contracted positions among parties can be an effective way to limit the exercise of supplier market power.

TeMix supports a device and facility management architecture that responds to sequences of tenders with forward and real-time transactions and not just responses to price signals where the relationship of the signal to actual costs of energy and actual transactions is unclear. The design is intended to significantly improve market stability and efficiency. The design, however, does not replace the need for market oversight and rules.

3. FACILITY INTERFACE

A Facility is defined here as a building, factory, home, generation or storage facility, an electric vehicle, or a centrally managed campus.

An Energy Service Interface (ESI) is a bi-directional, logical, abstract interface that supports the secure communication of information between internal devices (i.e., electrical loads, storage and generation) of a facility and external parties [7]. It comprises applications and systems that provide secure interfaces between parties for the purpose of facilitating machine-to-machine communications. A single ESI may use one or several wireless and wired communications technologies.

3.1. **TeMix Service Interface**

The TeMix Service Interface (TSI) is a particular implementation of an ESI for a single facility with one or more devices. We assume a single TSI for a facility. However, TSIs may be nested such as a set of facility TSIs within a campus TSI.

Devices and the TeMix Service Interface for a facility are illustrated in Figure 3.

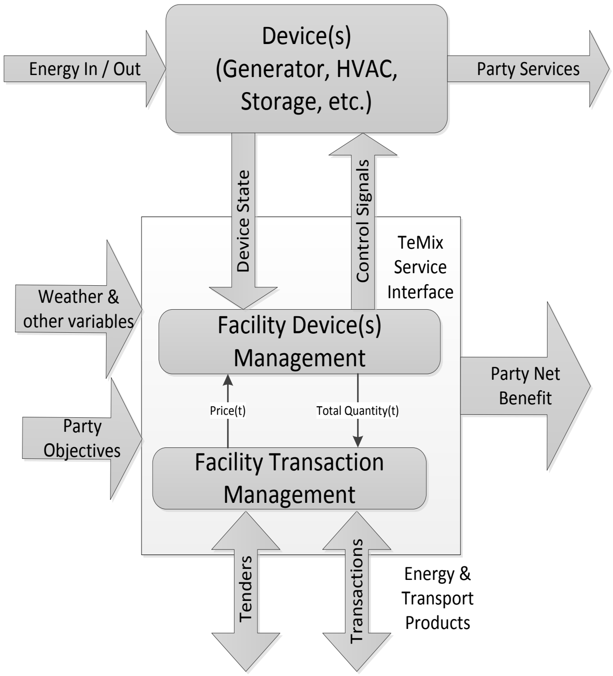

FIGURE 3: DEVICES AND TEMIX SERVICE INTERFACE

A settlement meter is required for each facility. The meter may use the TSI communications or different communications with external parties. Individual devices may also have meters, but settlement for a facility is based on the overall facility deliveries (either usage or supply).

As illustrated: at the bottom of Figure 3, the TSI does all or some of the following:

1) Receive tenders from other parties,
2) Create transactions by accepting all or part of tenders it receives,
3) Create tenders to other parties, and
4) Receive transactions from other parties based on tenders created in 3).

The TSI at a facility location may also employ transport products to transact at other grid locations and pay for and schedule delivery of the energy to or from the other location and the facility location.

Importantly, there is no communication of device state or characteristics to the outside and no control signals from outside of the TSI to devices. This means that only tenders and transactions are used among parties connected on the grid to coordinate operation of devices within grid constraints. This simplification of the interfaces and communication supports privacy, scalability and self-management of devices. It also enables innovation and specialization within the Interface to get better results for customers without having to change the service interface.

A TSI to one or more end devices may reside at the device, at the facility, or outside the facility in a network or cloud application. When the TSI is located outside the facility only then are control signals and device state communicated outside of the facility. This may look like direct load control, but it is control by the facility's own management system and not another party.

TeMix option tenders and transactions are also available at the TSI. These options can support frequency regulation services (for example on 4-second intervals) and contingency reserves sold to a grid operator, for example.

As illustrated at the bottom of Figure 3, the TSI has two functions:

1) **Facility Device(s) Management** to determine the optimal current and forward operating levels for each device and the total quantity of energy used or produced by all devices for each interval.
2) **Facility Transaction Management** to accept tenders and execute transactions to buy or sell quantities of energy to support the total quantity of energy for all facility devices. Also to issue forward tenders that may be accepted by other Parties and result in transactions. Facility Transaction Management addresses both long-term forward transactions and short-term spot transactions.

3.2. Devices

A device, in this context, produces or consumes energy and may store energy. Large generators, distributed generators, variable wind and solar renewables, and battery storage are devices. Residential, commercial and industrial customer air conditioning, heating, pumps, lighting, and electronic equipment are also devices.

Devices may be passive or active (with on / off, or variable control). Some devices respond to control nearly instantly while others require notification lead and ramp time. Some devices may be integral to a building or process.

As illustrated in Figure 3, device energy input and output and device services are determined by control signals and the physics of each device. A generator outputs energy. A consuming device inputs energy and produces services to the party such as heating and cooling. Storage both inputs and outputs energy. Except for co-generators, generators and storage typically do not provide services to the party other than the net value of electrical energy output or input.

Typically each device also has local control loops tightly integrated within the devices for safety, device sequencing and protection. The control signals described here are higher level control signals such as thermostat temperature set point or generator set points.

4. FACILITY DEVICE MANAGEMENT

Facility Device Management methods at a TeMix Service Interface can be as simple as turning a device on when the price tendered is lower than a threshold price and turning it off when the price is higher than a threshold price. Or management of a device may be based on optimal control, forward tenders, and automated forecasting and learning. We will describe the optimal control approach because it is more robust and new technology can enable optimal device control at low cost. Other rule-based or algorithmic control methods may be satisfactory, but the optimal control approach is an ideal against which other control methods can be measured.

In this section we will first consider optimal device management for a single device at a facility and then consider optimal management for multiple devices at a facility.

We employ a standard optimization technique which we will now describe.

4.1. **Model Predicative Control**

Model Predictive Control (MPC), also known as Receding Horizon Control (RHC), is a general purpose control scheme that involves repeatedly solving a constrained optimization problem, using predictions of future costs, disturbances, and constraints over a moving time horizon to choose the optimal control action. [8].

In general, An MPC problem is characterized by the following four ideas [9]:

1) Explicit use of a model to predict the output of a system being controlled along a sequence of time steps up to a future time horizon.
2) Calculation of a control sequence to optimize a performance index; typically net costs or net benefits.
3) A receding horizon strategy, so that at each time step, the horizon is moved towards the future, which involves the application of the first control signal of the sequence calculated at each time step as in 2 above[5].
4) Repeat steps 2 and 3.

In recent years, principles of MPC have been used for managing energy use in buildings based on forward information such as weather forecasts, electricity prices, building occupancy etc[10]. Applications of MPC to device and building management often are justified by operational savings based on more static electricity prices. Where MPC is already has value, the additional cost of implementing TeMix dynamic tenders and transactions can result in additional savings at negligible cost.

One can intuitively see that determination of optimal device control signals indicated in Figure 3 can be formulated as a receding horizon MPC problem. In this case, the objective function or performance index (step 2 above) for the MPC problem is to maximize Net Benefits based on party objectives, current state and characteristics of the devices, and external variables such as weather and fuel prices. Net Benefits are the total net benefits over the moving time horizon.

4.2. **Device Optimization Problem**

The device optimization problem is to maximize Net Benefits of device operation given a number of inputs including the prices of buy and sell tenders.

Net Benefits are benefits less costs. For a generator, the benefits equal the net revenues from energy payments and the costs equal the costs of fuel and other operating costs. For an end use device, the benefit is the value of the device's services to the party and the cost is the net payment for buy and sell transactions.

For an end use device the optimization problem is written as follows:

$$\text{Net Benefit}(\tau) = \max_{z} \sum_{t=\tau}^{H(\tau)} f[z_t, t] - p(t) * x[z_t, t]$$

- τ is the current time interval,
- $H(\tau)$ is the current horizon.
- t is the index to the time intervals in the moving time horizon,
- $z(t)$ is the control level for the device in each interval of the moving time horizon,
- z_t is the vector of control levels $z(t)$ for the current and prior intervals t,
- The function $f[z_t, t]$ encodes the device operational benefits and device physics and constraints given current and previous control levels,
- The function $x[z_t, t]$ gives the power quantity used in interval t as a function of the control levels z_t in current and prior intervals of the moving time horizon. Power production is a negative quantity for x,
- $p[t]$ is the forward energy price in each forward interval. $p(t)$ depends on forward tender prices as described in Section 5.1., and
- $x^*(t)$ is the current optimal power quantity in each forward interval.

The MPC formulation can include the presence of energy storage devices taking into account the unique physics and economics of each device in balancing energy usage and supply within grid constraints.

A significant advantage of modern optimization methods is that complex device optimization can be solved in seconds and sub seconds even with very detailed models of the device or building physics and the party's preferences[6] [11].

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[5] In the application of MPC to forward transactions as described in Section 5.3, several forward control signals and not just the first may be used.

[6] This optimization problem may be convex or non-convex. However modern optimization methods can generally solve both convex and non-convex problems at least approximately.

Or optimization methods can be embedded in the device. This means new generations of products that can greatly improve energy efficiency while providing flexibility in energy use so that energy use can better respond to grid supply.

4.3. Multiple Devices at a Facility

A set of devices at a facility can be managed as a single optimization problem. However, often the functioning of a device is independent of others. For example, a pool pump will generally operate without any interactions with an air conditioner in the home.

For multiple devices at a facility where each device is indexed by *i*, the optimization problem can be written as

$$\text{Net Benefit}(\tau) = \max_{\mathrm{z}} \sum_{t=\tau}^{H(\tau)} \sum_{i} \mathrm{f}[i, \mathrm{z}_t(i), t] - \mathrm{p}(t) \ * \ \mathrm{x}[i, \mathrm{z}_t(i), \mathrm{i}, t]$$

When f[i,z] and x[i,z] are both separable across the devices then the optimization problem can be solved independently for each device *i*.

$$\text{Net Benefit}(\tau) = \sum_{i} \max_{\mathrm{z}} \sum_{t=\tau}^{\mathrm{H}(\tau)} \mathrm{f}_i[\mathrm{z}_t(i), t] - \mathrm{p}(t) \ * \ \mathrm{x}_i[\mathrm{z}_t(i), t]$$

The optimal total power quantity is the sum of the energy quantity for each device, as follows:

$$X^*(t) = \sum_{i} \mathrm{x}_i^*[t]$$

When the benefit functions f_i[] and the cost functions x_i[] for each device *i* are separable, then given p(t) each such device at a facility can be operated independently of the other devices. This provides a significant simplification over joint optimization of several devices' operations.

5. FACILITY TRANSACTION MANAGEMENT

The optimization problem described in Section 3.1 (or any other device operation rules or forecasts) results in a forward plan or profile of energy use and production $x^*(t)$ beginning with the next time interval τ.

Forward time interval durations will depend on the market, the party, and the device. Time interval durations may be as long as year, month, day, or hour or as short as 15-minutes, 5- minutes, 1-minutes or 4-seconds.

5.1. Using Forward Tender Prices

In a competitive retail market with several counter parties making tenders, or a regulated retail market with tenders from a single party, the forward prices p(t) to be used for device optimization will depend on the best forward tenders in each interval. For now, we assume that a sequence of buy and sell tenders is available for the current moving time horizon to determine the prices p(t) used for device optimization.

There may be multiple buy or sell tenders at different prices from the same party or several parties (in competitive markets). The best (lowest price) buy tender will typically have a slightly higher price than the best (highest price) sell tender in each forward interval. One approach is to set p(t) to the price that is midway between the best buy and best sell price in each interval.

In other cases the party may need to develop or use independent price forecasts as well as tender prices. For example, the party may have tenders for some of the forward intervals. Or some tenders may have expired or been accepted but may still be useful for forecasting. In other cases, indicative forward prices may be available which cannot be used to create transactions, but may otherwise be useful for forecasting.

5.2. Requirements for Transactions

Any differences between the current optimal profile and the prior transactions for the current time horizon, τ to $\mathrm{H}(\tau)$, indicates a need to accept either buy or sell tenders in each of the forward intervals.

We will designate the net forward power position of the facility arising from previous forward transactions for interval t as $Y(t)$. We designate the net power from each previous forward transaction for interval t by $y(t, j)$ where the index j is an index over all previous transactions for the device in interval t. The value of y is either the transaction buy quantity or the negative of the transaction sell quantities.

Thus the net position in interval t is given by

$$Y(t) = \sum_{j} y(t, j)$$

The incremental quantity we need to purchase (sell, if negative) is the difference (gap) between the current total optimal quantity $X^*(t)$ and the current net position $Y(t)$.

The gap quantity to buy (sell if negative) is

$$\mathrm{w}(t) = X^*(t) - Y(t)$$

The next issue is how much of each tender to accept to fill the gap.

5.3. Accepting Forward Tenders to Create Forward Transactions

At a given time τ the forward planned power $X^*(t)$ typically depends on forecasts of several variables that are uncertain.

Such variables may include weather, fuel prices, device performance, and building occupancy.

The forward prices p(t) will typically be different each time the optimization is run at time interval τ as a result of uncertainty underlying the overall market and local conditions.

Detailed modeling of these uncertainties is unlikely to be worth the effort except in special cases. A reasonable tender acceptance policy is where the fraction of the target quantity to be accepted is given by the function shown in Figure 4 which is expressed as:

$$W(t) = w(t)\, e^{-\alpha(t-\tau)}$$

Where

- W(t) is the quantity of the best buy tender to be accepted if W(t) > 0
- -W(t) is the quantity of the best sell tender to be accepted if W(t) < 0
- quantity accepted must be less than the quantity of the best buy or sell tender

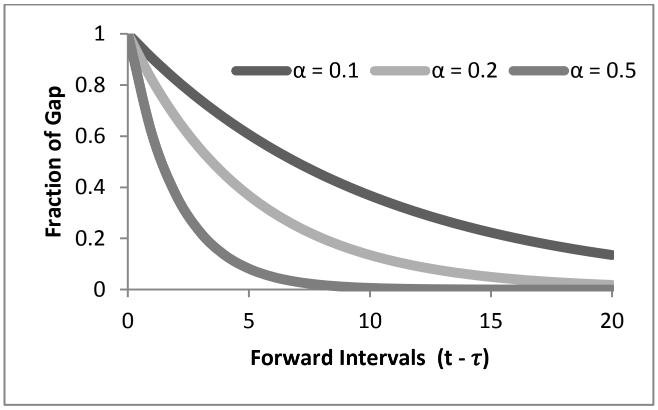

FIGURE 4: FORWARD GAP TRANSACTION FUNCTION

This policy allows the gap, w(t), to be closed at t = τ. For subsequent intervals a decreasing fraction of the gap is closed. The parameter α can be set based on customer risk preferences, uncertainty levels and experience and should be less than 1. A larger α will result in more forward transactions and also more transactions closer to the current interval to modify positions as uncertainty is resolved. A smaller α will rely on smaller longer-term forward positions.

As uncertainty in forward uncertain variables including power prices is resolved, the position in a given interval t may increase or decrease. Each transaction is settled at the price associated with the tender underlying each transaction. This provides forward hedging and risk management. It also provides forward information on the likely energy usage or production which is necessary in order to commit and ramp generation and usage devices.

5.4. Creating Tenders

A party also can create tenders that may be accepted by other parties. For example, a buy tender can be created at a lower price than the best buy tender, or a sell tender can be created at a higher price than the best sell tender. The MPC optimization will produce shadow prices that are the energy opportunity costs in each interval. This shadow price is the minimum sell price and the maximum buy price for any new tenders.

5.5. Integrated Optimization and Transaction Management

While it is useful to explain the optimization of device operation, tender acceptance, and tender creation as separate steps, the optimization can be formulated as a single optimization problem. And the optimization can incorporate learning algorithms on device performance and forecasts of external variables. As this is a paper with an emphasis on architecture, further specification of the integrated optimization is beyond the scope of this paper.

6. DEVICE MANAGEMENT EXAMPLES

We summarize two applications of TeMix and Model Predicative Control to (MPC) commercial refrigeration, residential air conditioning and building heating ventilating and air conditioning (HVAC). Each of the applications is designed to use forward forecasts of real-time prices for energy as well as many other variables. The examples illustrate the sophisticated response that can be expected from a combination of MPC and TeMix.

Each of these applications using MPC can use forward tender prices, accept tenders and create forward and real-time transactions as described in Section 5 of this paper and as further illustrated in Section 7.

6.1. Commercial Refrigeration

This example implements management and control of a commercial multi-zone refrigeration system, consisting of several cooling units that share a common compressor, and is used to cool multiple areas or rooms. In each time interval we choose cooling capacity to each unit and a common evaporation temperature. The goal is to minimize the total energy cost, using forward electricity prices p(t) while satisfying minimum and maximum temperature constraints in each of the zones.

The formulation and demonstration of this commercial refrigeration optimization problem is published in [12].

The solutions are fast enough to be carried out in real-time and the savings are on the order of 30% compared to a standard thermostat system.

The method exhibits sophisticated response to real-time variations in electricity prices. The method can easily be adapted to accept tenders and create forward and real-time transactions as described in this paper.

6.2. Residential Air Conditioning

This example describes optimal management of a residential air conditioning system for cooling a residence using the device management problem formulation of this paper.

The example shares many aspects of the first example of commercial refrigeration management. The control variable is the temperature set point in each time interval. The goal is to maximize net benefit to the occupants of the residence which is modeled as a comfort measure less the costs of electricity used by the air conditioner.

6.2.1. Residential Air Conditioning Optimization Problem

Returning to the RHC problem formulation, the residential air conditioning optimization problem is written as

$$\text{Net Benefit}(\tau) = \max_{z} \sum_{t=\tau}^{H(\tau)} f[z_t, t] - p(t) * x[z_t, t]$$

- $z(t)$ is the temperature set point in each interval, and
- z_t is the vector of temperature set points $z(t)$ for the current and prior intervals.

The function $x[z_t, t]$ models the power quantity (energy flow rate) in each interval as a function of the current and previous temperature set points z(t). This quantity will depend on interior and exterior temperature, solar radiation, the physics of the residence including thermal inertia, the capacity and efficiency of the air conditioner, and many other parameters for current and previous intervals.

Previous, current and forward values for the weather related parameters may depend on sensors at the residence and weather forecasts. Learning algorithms can infer the physics of the residence and air conditioner by observing and inferring the response of the air conditioner power usage to all of the parameters including the set point z(t).

6.2.2. Residential Air Conditioning Benefit Function

The benefit function $f[z_t, t]$ models the *comfort* of the occupants of the residence as a function of the current and previous temperature set point $z(t)$.

This benefit function can be decomposed into two functions:

1) $T[z_t, t]$ the actual interior temperature given the air conditioner temperature set point, and
2) $comfort[T, t]$ the comfort of the occupants given the actual interior temperature.

We can then write

$$f[z_t, t] = comfort[\, T[z(t), t], t \,].$$

The $T[z_t, t]$ function will use much of the same information used in the power usage function $x[z_t, t]$.

The comfort function $comfort[T, t]$ expresses the tradeoff preference of the residential party between comfort and cost. One way to express the tradeoff is using the function

$$comfort[T, t] = -\,abs[\, a * (T - T')^{\,b} \,]$$

Where

- T' is the desired temperature,
- T is the current temperature,
- a is the benefit sensitivity,
- b is the benefit sensitivity shape.

The comfort at the desired temperature T' is arbitrarily set to 0.0 without impact on results. The curve shows the reduction in comfort measured in $/hour as the temperature deviates above or below the desired temperature.

This function is plotted in Figure 5 with T' = 72 °F for three values of b and with a = 0.01.

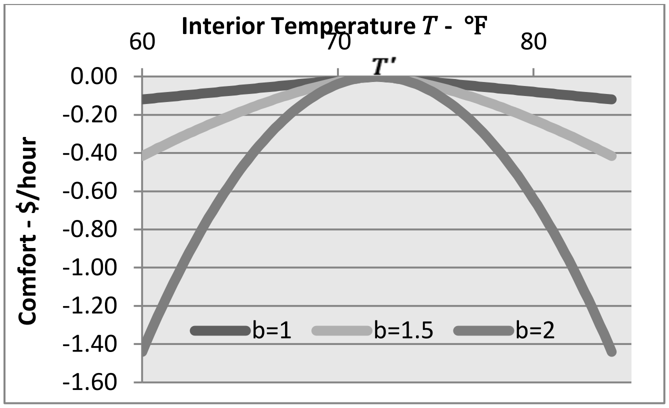

FIGURE 5: COMFORT BENEFIT FUNCTION

A benefit function is necessary, because with time varying prices, limited cooling capacity, varying exterior temperatures, and thermal inertia; the optimization produces variable interior temperatures T. Typical operation will pre cool to T lower than T' when prices are low and expected to rise. And typical operation will allow T to rise above T' when prices are high and expected to decline, or exterior temperatures are predicted to drop and natural cooling may occur, or occupancy is predicted to drop.

In use, the benefit function parameters may change depending on occupancy, time of day, etc. The desired temperature T' is set by the user and perhaps set by a learned pattern.

To set the benefit sensitivity a and the sensitivity shape b, the customer can be provided with historical information on his monthly bill and the variation in interior temperature that would result for different choices of the parameters T', a, and b. In general, higher values of a and b will result in higher monthly power bills and less temperature variability or more comfort. Larger values of T' will result in lower monthly air conditioning power bills and presumably less comfort when T' is above some threshold. Typically, the customer will presented with a simple, intuitive user interface with a slider that adjusts a with a fixed, default value for b.

7. FACILITY TRANSACTION MANAGEMENT EXAMPLE

The examples of Facility Device Management in Section 6 apply to retail parties. In this section we illustrate how a retail energy provider may post both forward and spot tenders for power. And, we illustrate Facility Transaction Management for the retail facility party.

7.1. Retail Energy Provider Forward Tenders

A Retail Energy Provider (REP) is an independent entity that sells (and buys) power to (from) retail facilities. A REP may be a regulated cost-of-service entity or a competitive entity. Details of how the REP determines tender quantities and prices are beyond the scope of this paper.

We assume that the REP provides forward tenders for power under its tariff. For example, the REP may provide several types of price buy and sell tenders at a KW rate as follows[7]:

1) each of next 10 calendar years
2) each of next 24 calendar days
3) each day of the next calendar month
4) each hour of the next 24 hours
5) each 5-minutes of the next 12 5-minute intervals
6) after each 5-minute interval, the balance between the facility net forward position and the metered quantity

Each the above tenders will typically expire within a reasonable time after creation; when new tenders may be created (possibly at different prices and quantities to reflect supply and demand and other changing factors.) For example, as wind and solar ramp, the prices of hourly and 5-minute tenders may change significantly.

This process can be simplified to work only with a subset of the tenders as suggested above list of buy and sell tenders. For example, just #6 in the above list (5-minute ex-post tenders) or, #6 plus forward tenders only for the monthly blocks (#2 in the above list) could be used.

This process can be extended in several ways to meet REP, customer and regulatory needs. For example,

- The REP may tender other types of blocks (such as peak- and off-peak blocks) at any time
- The retail facility party may create its own tenders.
- Tenders may be limited in size, but created frequently to support market and grid stability.
- A retail customer may receive and act on tenders from more than one REP where policy allows.
- Subsidized, low-cost tenders for longer-term blocks of power may be tendered to eligible customers while spot tenders are the same for all customers without destroying the benefits of TeMix.
- Energy commodity tenders and network tenders for transport (T&D) may be unbundled and separate tenders for each provided. The commodity tenders would be from REPs and the network tenders would be from T&D operators.

7.2. Retail Facility Transaction Management

The objective of Retail Transaction Management is to maintain an “optimal” portfolio of forward transactions to

1) To maximize the net benefits forward and real-time transactions and the operation of all facility devices.
2) To maximize the profits from sale of any self-generation and storage.
3) To manage the risks of the portfolio of forward and real-time transactions.
4) To respond to volatile spot prices for example by shifting activities and using storage and thermal inertia.

In section 5, we described the formulation of the Facility Transaction Management problem as a Model Predictive Control (MPC) optimization problem.

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[7] The REP’s buy and sell prices may be the same for each block, or more typically there will be a buy/ sell price spread with the sell price slightly higher than the buy price.

The MPC model will include forecasting of long-term needs, prices, and other inputs as well as the short-term operation. Simple formulation of the long-term model may work very well and there is opportunity for innovation by vendors and facility owners.

One simple approach for residential customers is to present the customer with an automatically transacted forward portfolio where the forward year- and month-ahead hourly positions track historical consumption hourly patterns. If the customer agrees, then after each hour, the actual usage would be compared to the forward position and the metered delivery, and an additional hourly transaction for the balance would be made automatically. The customer would have a strong incentive to reduce usage when hourly tendered prices are high and use more when hourly prices are low. The forward portfolio would assure a relatively stable bill.

8. OPPORTUNITIES

Interval metering of retail loads has a very significant penetration in US markets [13]. Most wholesale and large commercial customers, and about 50% of residential customers have interval meters as of 2012, and installations continue at a high rate. Broadband communication networks to facilities are increasingly the norm. Adoption of smart building and device control systems are rising, and finally, there is significant economic and political pressure to reform electricity rates tariffs to facilitate greater penetration of variable renewables at reduced investment.

This means great opportunities for smart device and controls vendors, but only if rates and tariffs are based on the standard concepts of Transactive Energy. And these devices and systems will have a market wherever Transactive Energy standards are implemented even though the local market conditions may be very different.

The opportunities that exist for smart device and controls vendors can be further realized by adopting optimization for device and facility management, and forward buy and sell transactions. The use of optimization automates the tailoring of devices to specific customer and grid needs. The benefits to customers can be significant and in an ideal world, customers would purchase these devices and controls simply because under transactive energy rates and tariffs, they save money while at the same time, satisfying the needs of the grid, and facilitate the integration of renewables and distributed generation.

Utilities, independent retailor and suppliers may also wish to align with software and smart device vendors to educate customers, regulators, and legislators on this approach to facility energy management and grid modernization.

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Biographies

Edward G. Cazalet

Dr. Cazalet is a leader in the design and implementation of markets for electricity, the development of smart grid standards, and the analysis of transmission, generation, storage and demand management investments. Dr. Cazalet has decades of electric power and related experience as an executive, board member, consultant, and entrepreneur.

He is a former Governor of the California Independent System Operator (http://www.caiso.com) and founder of TeMix Inc. (http://www.temix.com/), MegaWatt Storage Farms Inc. (http://www.megawattsf.com), The Cazalet Group (http://www.cazalet.com), Automated Power Exchange, Inc. (APX) (http://www.apx.com), and Decision Focus, Inc.

Dr. Cazalet has successfully promoted storage legislation and policy both in California and at the Federal level. He has advocated new electricity market designs to promote the integration of renewables and the use of price responsive demand as well as storage to support high penetration of variable renewables and efficient grid operation and investment by the grid participants including customers.

Dr. Cazalet is co-chair of the OASIS Energy Market Information Exchange (EMIX) Technical Committee and a member of the OASIS Technical Committees on Energy Interoperation and Scheduling.

Dr. Cazalet holds a PhD from Stanford University in economics, decision analysis and power system planning and engineering degrees from the University of Washington.

Chellury Ram Sastry

Dr. Chellury Ram Sastry is currently a Senior Manager at Samsung Telecommunications America LLC, focusing on various advanced R&D thrust areas including machine to machine communication, smart/connected home, and smart energy technologies including interoperability and standards.

Prior to joining Samsung, Ram was a Smart Grid Program Director with the Energy, Environment, and Material Sciences division at Battelle Memorial Institute, Columbus, OH. He was also with the Electricity Infrastructure Group in the Energy and Environment Directorate at Pacific Northwest National Laboratory (PNNL), Richland, WA managed and operated by Battelle. He was responsible for providing R&D, business development, and technical marketing leadership in various thrust areas including advanced smart grid enabled demand management to provide value-add services to residential and small commercial building customers, transmission/distribution modeling & simulation, and smart grid data analytics.

Prior to joining Battelle/PNNL, Ram was a Project Manager and Senior Research Scientist with Siemens Corporate Research (SCR), Princeton, NJ. One of the highlights of his tenure at SCR was an R&D program he was responsible for to enhance the product portfolio of various Siemens businesses (smart homes, remote health care, industrial automation etc.) based on radio frequency identification (RFID), wireless sensor networks, and embedded machine-to-machine technologies.

He has published several papers in refereed journal and conference proceedings, and has been a plenary speaker at well-known conferences including Connectivity Week, Grid-Interop etc. He also has several patents against his name, and a number of provisional patent and patent applications under consideration.

Ram has a B.S. degree in electrical engineering from Indian Institute of Technology, Chennai, India M.S. /Ph.D. degrees in electrical engineering and an M.A. degree in Mathematics from University of Pittsburgh.