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ABSTRACT

Meeting ambitious goals for carbon reduction and supporting an electric grid with high levels of renewable energy supply will require significant flexibility from the demand side. This paper outlines a system architecture and communication technology infrastructure to enable dynamic pricing to be used to finely tune coordination between the grid and its customers. Taking a cue from the success of Internet architecture, this system — Price-Based Grid Coordination — emphasizes simplicity and universality. It enables a wide variety of ways for prices and other signals to pass from the grid to individual flexible loads, including multiple possible locations for the intelligence that combines price signals with device functional needs. The paper includes a reference data model to describe how information from the utility level can be conveyed to customer devices, but independent of any particular protocol. The paper also summarizes technology standards development needs, and reviews research needs to address the full spectrum of coordination scenarios.

Introduction

Our evolving mechanisms for engaging load flexibility in buildings are a combination of organizations, technologies, and devices, which are shaped and guided by public policies. These are all organized by overall structures - system architectures - which can ensure that the result will not compromise building service needs, and significantly help to meet our economic and environmental goals.

Historically, revenue collection at the utility meter was solely to ensure adequate and fair collection of funds from customers to pay for the costs of building and operating the electricity supply infrastructure. However, with the advent of highly capable communication and computation technology, and the increasing need to shape demand to more closely match variable renewable supply (and address system capacity constraints), the price at the meter is increasingly a central *control signal* to influence the behavior of devices within buildings.

While many mechanisms for grid coordination have been implemented or proposed, one is poised to rise above the rest – dynamic pricing. While time-varying electricity prices have been used for decades, they have been deployed in ways with significant limitations, including:

- Only episodic price changes, as with Critical Peak and Variable Peak Pricing, that provides no value on most days.
- Fixed periods, as with Time Of Use pricing, that are incapable of addressing grid needs that are different every day.
- Prices with small differences between the high and low prices charged, which provide low reward to customers for shifting load.
- Lack of market scale, necessary to lead to automation of price distribution and wide availability of loads which are natively price responsive.

In response to this, three actions happened in parallel in California:

- The California Energy Commission (CEC) used its Load Management Standards process (CEC, 2021a) to outline policy needs for a leap forward in the use of pricing, and broad outlines for the technical distribution of dynamic prices.
- The California Public Utilities Commission (CPUC) has been exploring regulatory actions that could require large California utilities to offer compelling and effective dynamic tariffs (CPUC 2021a, 2021b)..
- Lawrence Berkeley National Laboratory (LBNL) developed a system architecture for implementing the distribution of such prices, to address many of the details needed to implement the policy visions from the CEC and CPUC. We call this Price-Based Grid Coordination (PBGC). This system is intimately tied to the communication technology needed to make it happen.

These three efforts are complementary, coming from policy, regulatory, and technology perspectives. The three organizations have collaborated on this topic area – formally and informally – particularly with the recent launch of the California Load Flexibility Research and Development Hub (CalFlexHub[1]), funded by the CEC, and led by LBNL.

This paper describes the basis and operation of PBGC, how it can be realized in current and future technologies, and research needs to create the full technology infrastructure to implement PBGC. Among the core purposes of CalFlexHub are to show PBGC working with real devices in real buildings and advance the research needed for the required technology infrastructure – particularly for flexible load technologies and communication standards.

While the focus of CalFlexHub is residential and commercial buildings, PBGC is intended for all customer types, including industry, agriculture, and EV charging stations. And while California is the venue for CalFlexHub work, it is intended that PBGC spread nationally and globally. The value of simple and universal technologies is one of the central lessons from the success of Internet technology and related IT technology (Carpenter, 1996).

PBGC addresses only the availability of energy. It does not cover power-related issues as are commonly implemented by inverters. It also does not address issues of electrical capacity constraints, though the application of digital technology to capacity is a promising topic area.

This paper is structured as follows: The following section presents the core of the system architecture proposed, Price-Based Grid Coordination (PBGC), covering the entities involved, the information communicated, and technologies that support it. The next section outlines the data model for dynamic pricing that will be used in CalFlexHub and is being merged into the key communication protocols. The next section reviews technology standards development and research needs, and how the project should prioritize and approach the numerous topics that merit attention. The last section offers some conclusions. Technology can evolve to better support price communication, but a necessary first step is to make appealing highly dynamic prices available to customers; only then will we see substantial introduction of products that can use these prices.

Price-Based Grid Coordination

Context

The CEC has identified dynamic pricing as a core mechanism for coordinating customer electricity demand with the electricity grid, with the Load Management Standards (LMS) and Flexible Demand Appliance Standards (FDAS; CEC, 2020a) processes. The CPUC has various

[1] For more information see: http://calflexhub.org and a summer study paper on CalFlexHub (Piette et al., 2022).

activities which are moving in the same direction. Other mechanisms for grid coordination have been and continue to be used, and may co-exist with pricing, but should be designed to be implemented 'around' pricing - to fill in any gaps - and not displace or conflict with the central mechanism of pricing. As grid conditions on both the supply and demand side are different every day, to accomplish the flexibility California needs, the prices need to be[2]:

- Different every day
- Set on the day of operation or the day before
- Have time periodicity between hourly and five minutes

We call these "highly dynamic prices" (HDP[3]) to distinguish them from those that are less dynamic and less granular in time. The focus of this report is on communication needs for such prices. Obtaining the benefits of such prices requires three primary actions:

- **Creating** the retail prices
- **Transmitting** those prices from the retailer to flexible loads and other Distributed Energy Resources (DERs[4])
- **Using** those prices in modifying DER operation

This paper focuses only on the middle part — communication — but the communication infrastructure determines the range of coordination mechanisms supported.

Overall Architecture

A premise of PBGC is to isolate the complexity that exists within a building (or any customer site) from the complexity of the grid — and vice versa. The central information that passes between them, at the meter, is **price** and **quantity**. Figure 1 illustrates this concept. In the figure, the squares are entities (devices) that communicate, but there are only two entities at the interface[5], so the rest are hidden from the other side of the interface. Thus, the two domains can evolve separately without affecting the operation of the other, and the internal organization of the grid can vary by location. Changes at the interface can be limited to only one device in each domain.

The scope of PBGC is communication of prices[6] from a utility or other retailer to DER, or to other devices that make control decisions on behalf of the DER. It outlines but does not

[2] The first staff report for the CEC Load Management Standards process (CEC, 2020b) makes clear (page 2) that existing resources on the demand side are too expensive, too small, and too inflexible to meet the state's needs. It further states that prices need to change "at least hourly" and be locational, and be derived from wholesale market prices which are different every day. Wholesale prices include a five-minute granularity, and the report makes frequent reference to hourly, 15-minute, and 5-minute as likely time periodicities for rates. The CPUC in a staff proposal (CPUC, 2021a) noted that current approaches are scattered and inadequate ("complex, inefficient," and expensive) and that prices should be hourly or sub-hourly and be set day-ahead or hour-ahead.

[3] Tariffs identified as Real-Time Prices usually have these same characteristics. However, the term is commonly assumed to refer to a narrow calculation of a retail price from the spot wholesale price. While this is possible to do, there are many other ways to construct retail prices that are informed by wholesale conditions - and distribution system conditions and marginal greenhouse gas emissions. Thus, the HDP term is to refer to that much wider set of possible tariffs.

[4] Definitions of Distributed Energy Resources vary. In this paper, a DER is taken to be any device that can usefully change its operation in coordination with the utility grid.

[5] On the grid side it is the Price Server. On the building side it is a central gateway device that receives the price/GHG signal and redistributes it internally. Figure 2 shows communication to other devices; this is for convenience, but the grid does not in general know the identity of the devices receiving the signal as it is broadcasting the data. The grid only knows the identity and behavior of the customer as a whole.

[6] Also included is possible distribution of marginal greenhouse gas emissions, and a few non-price emergency messages such as impending power shutoff or a grid emergency.

cover any final communication of control signals to the DER. It does not cover how prices are created, functional control protocols, or algorithms that use the prices.

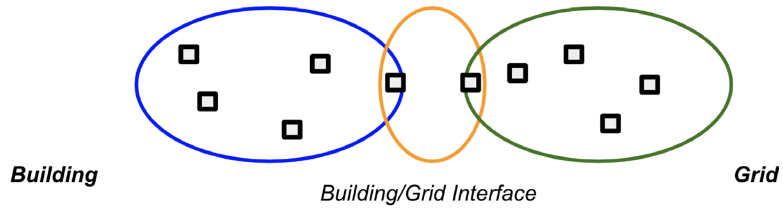

Figure 1. Isolating the complexity of buildings and the grid

Dynamic prices originate from the customer's electricity retailer. The retailer may have complex systems for creating the prices (and forecasts), but those complexities are all hidden from the customer, who only sees the result — the price. Similarly, the customer as a whole, and/or individual DER, may have sophisticated systems for using the price, but these are all hidden from the grid, which only sees the result in changes in power levels at the meter over time.

Figure 2 below shows (and Table 2 lists) a graphical illustration of PBGC, and Table 1 summarizes the key concepts shown. Note that Figure 2 shows all possible communication paths of information to a DER. Any individual DER will use only a single path from the price server to the DER[7]. The orange lines in the figure show functional control commands (see Table 1) sent after an entity other than the DER itself has combined the prices with functional operating considerations. Any of the four devices in the bottom half of the diagram can do the translation from price to functional control.

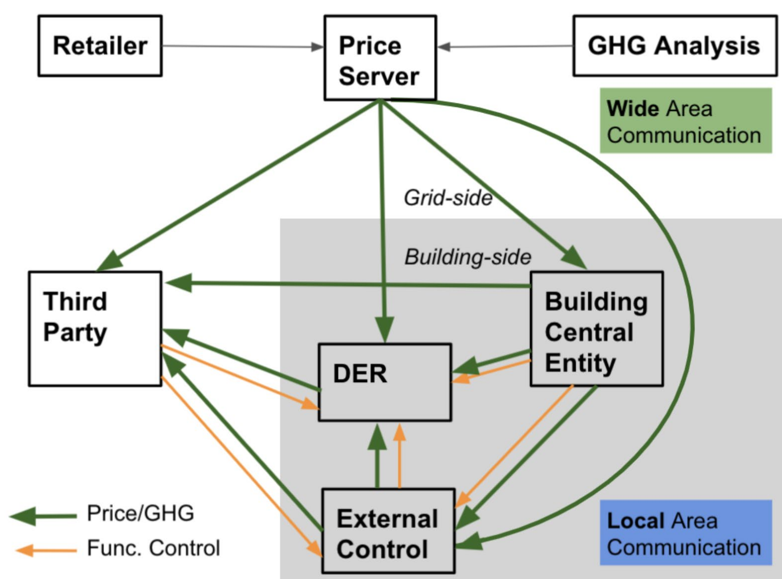

Figure 2. Price-Based Grid Coordination System Architecture

[7] The black lines carry prices and GHG (respectively).

Table 1. PBGC Key Concepts

Entity / Concept	Description
Retailer	Organization that the customer pays for electricity service
Price Server	Device that broadcasts prices over multiple communication paths
GHG Estimator	Organization that estimates marginal greenhouse gas emission rates
Third Party	Organization outside the customer site (cloud-based) that provides functional control commands to the DER, taking price into account
DER	Distributed energy resource within a customer site; flexible loads, thermal or electric storage, dispatchable generation, and EV charging
Building Central Entity (BCE)	Device that takes in price information and distributes prices and/or functional controls to multiple DER[8]
External Control	Hardware device serving and directly connected to a single DER
Price/GHG Signal	Current price and forecast of future prices, corresponding marginal GHG emission rates, and emergency signals
Functional Control Signal	Device operation commands such as for setpoints, on/off control, level control, etc.
Highly Dynamic Price (HDP)	Retail price that has periodicity between hourly and 5-minute, is set no longer than a day in advance, and is different every day.

Note that the diagram and text refer to the price information as being strictly one-way. The current protocols for communicating prices — OpenADR, IEEE 2030.5, CTA-2045, and the new MIDAS system (CEC, 2021b) from the CEC — are all bi-directional protocols, though for pricing, no substantive information needs to be passed in the reverse path, so thinking of the communication as one-way or a broadcast is appropriate.

Role of each Entity

The data being communicated are a current **price** and nonbinding[9] forecast of future prices, along with GHG signals (e.g., marginal emission rates for a grid region). The prices are continuously "streamed" each time a new future price is available or a price changes; eventually likely at five-minute intervals. This is analogous to how Netflix streams movies, sending data on a continuous basis. It is even more analogous to live streaming of real-time audio or video content over the Internet.

Retailers generally have restrictions on rates they can charge, but ideally have latitude to select prices that co-optimize for customer and grid benefit. The price that is broadcast should be the marginal impact on the bill of consuming more or fewer kilowatts at that time and not include bill elements such as fixed costs that are not affected by load shifting. That is, the

[8] Example BCEs could include a Building Automation System or even a simple Wi-Fi access point.
[9] The future prices could be guaranteed; this is an option for the retailer to choose. This need not change DER algorithms.

purpose of the price broadcast is DER coordination, not formal tariff publishing, penny-perfect bill calculation, or settlement.

The retailer communicates the price to a **price server** that may also serve other electricity retailers and/or regions; a retailer may operate its own price server. A service provider estimates the relevant marginal GHG emissions.[10] The price server makes no decisions. The price server may broadcast the data over multiple physical layer technologies such as broadband internet, cellular radio, FM radio, and satellite.

The price may be relayed directly to individual DER (**price-to-device**) or to a building central entity device[11] (**price-to-building**). For the latter, the price is then relayed to individual DER with an additional communication link. While such a **building "gateway" device** is not required, there are many advantages to having one (Nordman et al., 2022a). For a (potentially long) transition period, it will be easier for some DER to use price-to-device, including for buildings that lack a suitable central entity device. Also, for the transition, there will be many devices that cannot natively take in a price, so a control decision taking the price into account will need to be made by the building central entity, a third party (such as a vendor's cloud), or an **external control** device such as a CTA-2045 module.

Third parties can assist in control decisions. This is commonly a device manufacturer but does not have to be. Such third parties may get the price from the price server just as any customer does, or from a device in the building. Traditional demand response "aggregators" are a subset of third parties; aggregators have a financial relationship with the grid, but other third parties usually do not.

Prices can be locational, to vary by region, as grid conditions indicate. What size of regions might be used in the future is unclear and it could range from a large section of a major utility down to an individual feeder off of a distribution substation. Note that as used here and often elsewhere, "locational" refers to a portion of the grid. This contrasts with the term "local" which refers to the inside of a single customer site; this usage is derived from IT systems that have a local area network that is generally coincident with the customer site. "Local prices" are an important feature of this architecture. A local price is one that is specific to a single customer site, or a portion of a customer. Local prices recognize that for a variety of reasons, the availability of electricity within a customer site can diverge from what it is at the meter[12]. Only the meter price is used for cash exchange, but the local price can be used in DER decision-making to best reflect the customer's interests.

Possible Communications Paths

Table 2 shows most of the paths that information might take as it travels from the price server to a DER. Most DERs will only use one path when installed at a customer site, but there is no barrier except for configuration complexity to allow for switching between multiple paths. Entities in the Price Communication Pathway are responsible for transmitting the price signal; the intelligence is located in the entities that decide how to control the DER based on the price

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[10] GHG signals for CalFlexHub are provided by WattTime (http://watttime.org), for multiple geographies, at 5-minute intervals.

[11] It is labeled here as a "building central entity" as the functionality involved can be hosted by a variety of different devices, and should be a function of an existing device rather than installing a new one only for this purpose. This could be a building or energy management system for a large building, or for a small one even a network device like a Wi-Fi router.

[12] This can occur with differential buy/sell prices at the meter, capacity constraints, microgrid operation, inclusion of GHG emissions in the price, and DC power domains within the building.

signal; and the Functional Control Communication path is required to transmit the functional control command from the intelligence to the DER.

Table 2. Possible Paths from the Price Server to DER

Price Communication Pathway	**Location of Intelligence**	**Functional Control Communication**
Price Server >	DER	
Price Server > BCE >	DER	
Price Server >	BCE	=> DER
Price Server >	BCE	=> External Control => DER
Price Server > BCE > External Control >	DER	
Price Server > BCE >	External Control	=> DER
Price Server > BCE > External Control >	Third Party	=> External Control => DER
Price Server > BCE >	Third Party	=> DER
Price Server > External Control >	DER	
Price Server >	External Control	=> DER
Price Server > External Control >	Third Party	=> DER
Price Server >	Third Party	=> DER
Price Server > External Control >	Third Party	=> DER

Note: ">" designates a Price/GHG signal; "=>" designates a Functional Control command

The core of price-based coordination is that the basic signal is one-way, sending prices from the grid to customers. There are return paths to the utility in the form of individual meter readings to compute the financial impacts of customer actions, and for grid management purposes, metering of feeders and substations. By only requiring the broadcasting of information, the overall system can be relatively simple (compared to alternative methods[13]). The price signal is a current price and a series of future prices for roughly one day into the future[14], along with the estimated relevant GHG emission factors.

The communication in the system is to be standard across all implementations, but the architecture does not specify or limit how prices are determined and how DERs use them, so these can be areas of innovation for utilities, product manufacturers, and others. The presence of the price forecast enables the algorithms to understand the benefits of any load shift or shed that the DER can accomplish. Examples of functional controls are turning a device (or component of a device) on or off, or to change a setpoint or operational level. A common translation of prices to functional control will be to change the device operation to shift some energy from high-price

[13] Examples include Two-way Transactive Energy, with complex communications and customer forecasting needed (e.g. Widergren et al., 2022) and event-based demand response with normal day counterfactual calculations.

[14] A few applications require 2, 3, or more days of future forecast. Examples include agricultural pumping, any long-term storage (including chilled/heated water), and even some water heating. These should be facilitated as feasible, but it may not be necessary to send (much) more than 24 hours of price to most customers and devices.

(and/or high-GHG emission) times to times with lower prices (and/or GHG levels). Functional control commands are sent today with a variety of communication protocols. PBGC does not change this.

As an example, consider a day when there is a large surge in wind power starting at 2am, and excess solar production mid-day. Since load would otherwise not rise during these times to match demand, the grid would have lower prices in the middle of the night and the middle of the day; there would be higher price times during morning and evening peaks in demand. A customer's water heater would do extra heating during the low-price times, and postpone some heating otherwise called for during the high-price times. An air conditioner could pre-cool mid-day and mostly coast through the late afternoon and evening. An EV charger could wait until the 2am price drop before initiating charging. Controls could be direct, such as turning a compressor on or off, or indirect, as with changing a setpoint.

Figure 3 annotates Figure 2 with common examples of the entities shown.

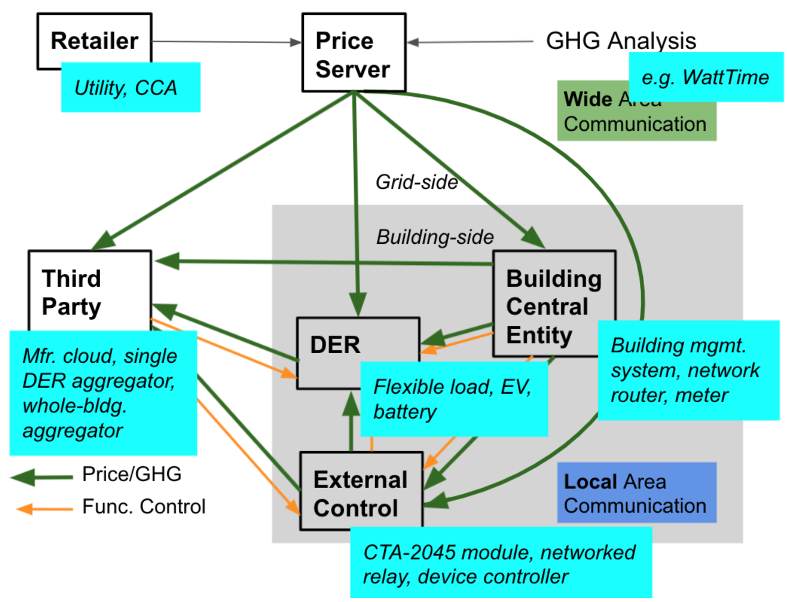

Figure 3. Price-Based Grid Coordination System Architecture *(annotated)*

PBGC is broadly consistent with the visions and details outlined in the CEC and CPUC processes. The terminology used is sometimes different. PBGC delves into much further technical detail. The CEC has established the Market Informed Demand Automation Server (MIDAS) as a price server for California time-varying electricity prices. MIDAS is currently used by cloud-based services for managing customer DER on Time Of Use tariffs. MIDAS uses a CEC-specific REST API format for distributing prices and GHG signals.

Price Streaming Data Model

In the summer of 2020, Berkeley Lab created the data model below to describe the information needed to transmit time-varying prices on an ongoing basis — to "stream" the prices. Static data fields change infrequently or never. Dynamic data are updated on an ongoing basis, ideally on a five-minute cadence, but also likely hourly, initially. We expect the data model to evolve modestly through the course of the CalFlexHub project, including adding an explicit way to represent location (currently it is to be part of the rate name).

Static Data

RetailerLong - text string of retailer full name, e.g., "Pacific Gas and Electric."

RetailerShort - text string of retailer's abbreviation, e.g., "PGE".

RateNameLong - text string of rate name, e.g., "Residential Time of Use-A." This is unique to each retailer.

RateNameShort - text string of rate name, e.g., "TOUA." This is unique to each retailer.

Country - Alpha-2 code per ISO 3166-1.

State - Coding per ISO 3166-2.

Currency - per ISO 4217.[15]

DateAnnounced - ISO 8601 extended format,[16] "YYYY-MM-DD," e.g., "2020-05-26." This "publishing date" is particularly helpful if there is an update to the rate after the initial announcement. This is only a date, no time.

DateEffective - ISO 8601 extended format, as date/time.[17] This is the first date that the rate is planned to be available. No end date is specified.

URL – a web page with a description of the tariff in both machine- and human-readable forms. It should contain the current/correct tariff if there are multiple versions.

BindingPrices - True/false. True if prices are fixed once transmitted.

LocalPrice - True/false. True if the price has been adapted from a grid price by a building entity, or created entirely locally (within the building). If left out, the default is false.

Dynamic Data

CurrentTime - ISO 8601 extended format, "hh" or "hh:mm" or "hh:mm:ss." Standard Time (not daylight saving time), including the time zone of the area covered by the rate.

OffsetToFirstPrice - ISO 8601 extended format, "hh" or "hh:mm" or "hh:mm:ss." Duration of time between CurrentTime and the first price in the sequence.

IntervalCount – number of intervals in the forecast, including the first price.

For Each Interval

TimeStamp - ISO 8601 extended format, "hh" or "hh:mm" or "hh:mm:ss,". This is relative time from the FirstPrice time, not the time of day. Allowed to go over 24 (but not over 99) to extend to more than 24 hours (note that this is likely not consistent with ISO 8601). Each timestamp must be greater than the preceding timestamp.

Price - numeric value of currency in text with appropriate number of digits. Price for purchasing electricity.

ExportPrice - numeric value of currency in text with appropriate number of digits. Price is for customers exporting electricity back to the grid. May be the same as Price, and assumed to be if "ExportPrice" is not present.

An example set of data following this data model is shown in Figure 4 in JSON encoding.

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[15] https://www.currency-iso.org/en/home/tables/table-a1.html.

[16] https://en.wikipedia.org/wiki/ISO_8601#Calendar_dates.

[17] https://en.wikipedia.org/wiki/ISO_8601#Calendar_dates.

The data streams are to generally include GHG data. These are well suited to price model since the easiest way to use GHG data (in kg/kWh) are to multiply them by a burden factor (in $/kg) and optimize to a new (local) price stream. Even emergency signals (not yet described in the model) can be mapped onto prices for device control.

The specific encoding of the series of timestamps can be done in multiple ways and translated unambiguously. The method shown here was created to allow the receiving device's internal sense of time to differ from that of the sending device. Also, prices, will often be retransmitted; with this method, on retransmission the offset can be changed without changing each interval. The LocalPrice is not needed for wide area communication, and likely won't change DER operation, but is included for transparency, and for cases when a device receives prices from multiple sources.


```
{
  "Static Data": {
    "RetailerLong": "Pacific Gas and Electric",
    "RetailerShort": "PGE",
    "RateNameLong": "Residential Time of Use-A",
    "RateNameShort": "TOUA",
    "Country": "US",
    "State": "CA",
    "Currency": "USD",
    "DateAnnounced": "2020-01-03",
    "DateEffective": "2020-07-16",
    "URL": "http://pge.com/tariffs/current/TOUA/html",
    "BindingPrices": false,
    "LocalPrice": false
  },
  "Dynamic Data": {
     "CurrentTime": "2021-05-06-T09:55:30",
    "OffsetToFirstPrice": "0:04:30",
    "IntervalCount": 4,
    "IntervalData" [
      {
        "TimeStamp": "0:00",
        "Price": 0.15
      }, {
        "TimeStamp": "0:00",
        "Price": 0.15
      }, {
        "TimeStamp": "0:00",
        "Price": 0.15
      }, {
        "TimeStamp": "0:00",
        "Price": 0.15
      }
    ]
  }
}
```


Figure 4. JSON Encoding of Example Data in the Price Streaming Data Model
(Note: These prices were fabricated; they are not derived from a real rate.)

Standards Development and Research needs

The purpose of this data model is to facilitate full capability in, and interoperability among, communication protocols. The data model above was added to CTA-2045 in 2020 (CTA, 2021), in the 2045B revision. As of June 2022, it is in the process of being added to IEEE 2030.5. And for OpenADR, a consistent way of using the standard to encode this data has been proposed, and discussions are underway to consider adding it to the standard itself.

The following is an annotated list of topics related to dynamic price distribution that deserve inquiry. Many of these topics overlap. While we expect to explore many through CalFlexHub, there is much more that should be done than we will be able to address, and we expect to identify additional areas in the course of our research. More detail on these can be found in (Nordman, 2022b). Price communication will no doubt make its way into additional technology standards (it is already in Ethernet) for both wide area, and particularly local area communication, and these should be harmonized with this data model as feasible.

Data Model — The data model above 3 has received scrutiny by many reviewers, but is likely to evolve over time. It would be advantageous to deposit the content with a standards development organization to provide formal processes for distribution and revision.

Local vs WAN Communication — Transmitting price data from its source to customers over wide-area networks is essential to all grid coordination. However, as shown in Figure 2, there will also be important communication of prices within buildings, and the needs from protocols are somewhat different between the two contexts. Such differences might suggest adaptations of technology standards, or conventions in how they are used.

Emergency Signals — The routine information to be sent to customers is dynamic prices, plus a parallel stream of GHG emission estimates. However, there are occasional anomalous conditions that should or may be of interest to customers and to their DER, for grid emergencies or health or safety alerts. These should be standardized and included in communication standards.

Retailer and Tariff Discovery — Building owners will periodically need to have a short code for their electricity retailer and the particular tariff that they are on. These might be discoverable through manual or automatic means; technology and standards could facilitate both.

Price Server Discovery — An individual DER (or external control or building central entity device) needs to have methods to determine what device on the Internet can provide streaming prices. Such capabilities (‘service discovery’ or ‘device discovery’) are common in IT technology. LBNL has developed a proposal for standard naming of URLs for leading to the URL where the customer’s prices can be found.

Cybersecurity and Privacy — These two topics can manifest themselves in many different ways and can have severe consequences when they lead to problems. They also are often intertwined. While the use of one-way pricing greatly reduces the concerns for both compared to alternative grid coordination mechanisms, they are still present.

Physical and Network Layer Considerations — Most research areas are independent of the physical layer technologies used to move the price/GHG signals. However, questions exist about how particular technologies could be made more efficient, convenient, capable, and cost-effective.

Signal Reliability — Reliability of different communication mechanisms needs to be better understood. This includes how often each signal is likely to be interrupted, and for how long. It also includes coverage assessment of each signal across regions.

Error Conditions — In theory, most error conditions should never occur, but some attention is needed to understand how devices should best respond when they do.

Operation during Connectivity Loss — As with the electricity grid, any form of communication is to some degree unreliable. Mechanisms that adapt to such conditions as they occur will benefit the user and grid.

Customer Repowering — When a customer loses connection to the grid, either because of widespread grid failure, or just a feeder or transformer failure, it may be advantageous to have many DERs wait for a time before entering full operation, with or without any communication from the grid. This can allow power levels to rise slowly rather than suddenly rise to high levels.

Standard URL Content — The PBGC data model includes a URL for a web page with additional information about the tariff. However, there is no document that clarifies what information should be there, and in what format. The information should be in a human readable format, understandable by an ordinary but interested person, as well as a standard machine-readable format.

Differential Buy/Sell Prices — The PBGC data model includes the possibility of prices for the grid buying electricity from retail customers that are different from those for selling electricity to them. When this is used, a building central entity can create a 'local price' that selects the appropriate level depending on the direction of flow of power at the meter.

GHG Integration — For customers who choose to use the GHG emission values in optimizing DER behavior, the question arises as to how to do this. One option is to choose a \$/kg CO_2 value, multiply it by the emissions value, and then add this to the retail price (or possibly a constant fraction of the retail price).

GHG Signal Details — There are different metrics of GHG emissions that are calculated today, and different potential ways to calculate each metric. Both of these need attention, to understand which metrics / signals are most appropriate for customer devices to use in their decision making, and in determining the best ways to calculate that metric.

Locationality — For tariffs that vary by location, key questions include the optimal size of such regions, what mechanisms could be established for customers to determine their location within the grid, how should the location be encoded, and if it should it be a separate data element in the data model.

Daylight Saving Time — The transitions to and from Daylight Saving Time can introduce complexities and potential errors, particularly if the dates when the transitions are scheduled to occur change. Such dates vary across countries. PGBC attempts to mitigate this by only sending out price times in standard time.

International Considerations — The PBGC data model - and the core relevant communication protocols - all include Currency to allow other countries to readily use it. There may be other international considerations that suggest changes in technology standards.

Dynamic Capacity Management — Dynamic Capacity Management enables the grid to have knowledge of maximum capacity of consumption (or export) of customers to maximize utilization of infrastructure without exceeding capacity limits of devices or wires. It is not directly about price-based load flexibility, but it necessarily affects the behavior of DER in buildings.

Adequately addressing the list above will require many years and individuals, but should cover most of what is needed for the technology foundation for success of Price-Based Grid Coordination. Also needed of course is good prices being charged by retailers (and algorithms for creating those prices), and effective technology for flexible loads and other DER to integrate price response with device operational needs. And, we will need a sound transition plan to move customers with devices that are not price-responsive to owning ones that are, through retrofit, replacement, and use of controls as shown in Figure 1.

Conclusions and Next Steps

Digital communication of prices is not itself new, though it is not widely used, as most customers have rates that vary not at all, or only occasionally, and/or in a highly predictable manner (e.g., TOU rates). PBGC has several new features:

- A clear articulation of the types or relevant devices involved, including where there can be a translation from a grid signal (price and GHG) to device functional control
- Clear identification of what occurs entirely within a customer site, to understand the implications when grid power, internet communications, or both are temporarily lost
- The concept of a "local price" of electricity,[18] which is useful for a variety of reasons

This paper presented Price-Based Grid Coordination, particularly the communication technology needs to support it. PBGC is intended to be the simplest system that can well meet needs for load flexibility to most cost-effectively help meet energy and carbon goals. The paper also articulates a data model for communicating dynamic prices, and reviews research needs.

The PBGC model is highly aligned with the goals of California public policies, most notably the CEC's LMS and FDAS, and MIDAS price distribution system. Deployment of these policies and technologies should enable significantly greater integration of renewable energy sources and electricity storage into the grid. It should also do so at lower cost and other burdens than other proposed mechanisms for building to grid integration.

[18] *Local* in this case is strictly inside of a single customer site.

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