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Modeling Value Flows in Utility Rate Structures

December 2022

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Abstract

As the increased adoption of distributed energy resources continues to challenge flat utility rate structures, time-varying rates and more dynamic mechanisms like transactive energy systems can better coordinate and compensate customer-sited distributed energy resources to provide grid services. However, adopting new utility policies can be a timely process and requires a high level of transparency into the energy system. A wide range of stakeholders must understand who may be affected by policy changes and how. This work employs the valuation methodology developed under Pacific Northwest National Laboratory's Transactive Systems Program to outline the functional differences in value flow under a series of conventional rate structures and a transactive energy system. The resulting value model illustrates the nuances that arise and highlights future avenues of work that will become necessary as utilities across the country continue to develop new rate structures and market mechanisms.

Acknowledgments

This work was supported by the U.S. Department of Energy, Office of Electricity, Advanced Grid Research and Development Program.

Acronyms and Abbreviations

CPP	Critical peak pricing
DER	Distributed energy resource
ISO	Independent System Operator
kWh	kilowatt-hour
RTP	Real time pricing
RTO	Regional Transmission Operator
TE	Transactive energy
TOU	Time-of-use

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1.0 Introduction

Distributed energy resources (DERs), like solar photovoltaics (PV) and smart thermostats, are being adopted at an increased pace across the United States and are poised to continue to do so in the future (Wood Mackenzie 2020). DERs offer a range of services to the electric grid from generation to efficiency and flexibility, but they also challenge many existing utility policies and rate structures that are disconnected from time-dependent grid needs.

Although flat rates that charge customers a single price per kilowatt-hour (kWh) for the electricity they consume continue to dominate the utility policy landscape in the United States, an increasing number of utilities are turning to more dynamic, time-varying rates to better account for grid needs and incentivize complementary end-use behaviors (Preziuso and Odonkor 2022; Faruqui et al. 2019). For example, investor-owned utilities in California have placed their residential customers, by default, on time-of-use (TOU) rates that charge different prices based on time of day, and other utilities across the country continue to deploy similar rates and pilot comparable programs as well (American Public Power Association, ComEd). Beyond these more conventional utility rates, transactive energy (TE) systems that rely on economic and control mechanisms to dynamically balance supply and demand across the system at-large, provide yet a more interactive market mechanism to capitalize on the potential benefits that DERs can provide to the electric grid (GridWise Architecture Council 2015). Dynamic TE rates arise out of the market embedded within the TE system and have many similarities with dynamic real-time rates. However, TE rates can include additional price contributions to address distribution system constraints (e.g., congestion constraints).

This transition to more dynamic rates is largely rooted in efforts to deploy rates that reflect cost causation and motivate end-use behaviors that better contribute to an evolving electric grid. In the absence of rate structures that are linked to time-dependent grid needs, customers who consume electricity during peak periods are likely underpaying for the costs that their demand creates during those times and those who consume during off-peak periods are overpaying; in essence, this can create a subsidy effect. As such, categorically understanding cost structure is important in developing and deploying new utility rates.

Rate design principles have historically guided such innovation in rate design. Bonbright (1961) and Garfield and Lovejoy (1964) developed principles that largely focus on “stability, simplicity, and consistency while limiting opportunity for cross subsidization” (Boff, Ganguli, and Somani 2022). These traditional principles supported the widespread adoption of the flat rates we see today, best suited for an energy system dominated by vertically integrated utilities. Such rate design principles have since evolved as renewable energy technologies have been adopted at greater scale and the capabilities of end users on the demand side have advanced. Newer rate design principles that support dynamic rates focus on capturing cost causation, fairly valuing grid services, supporting desired system outcomes such as improved grid resilience and flexibility, and embedding gradualism to prevent abrupt changes in customer bills (Sherwood et al. 2016). Additional principles specific to TE rates that stem from the presence of a retail market mechanism have also been explored in modeling environments. These principles indicate that TE rates should (on average) benefit customers; preserve interests of fairness, simplicity, and transparency; not produce greater aggregate costs for those who migrate to transactive rates but do not participate in the market; produce bill reductions in proportion to the value derived from customer responses; and create a simpler, more transparent, and more accurate representation of the actual costs across customer classes (Pratt et al. 2022).

Implementing new utility policies can be a lengthy process, though, as regulators must assure that rates and markets are fair and that stakeholder concerns have been addressed. To address issues of fairness and other stakeholder concerns, significant transparency into the fundamental functions of the policies must be accessible to a wide range of stakeholders. Designed to enable granular value assessment of unique stakeholders in TE systems, the valuation methodology developed under the Transactive Systems Program at Pacific Northwest National Laboratory is well-positioned to support utilities, regulators, and stakeholders at large as we see continued evolution in utility policies and the potential for the deployment of dynamic rates and transactive energy systems (Bender and Preziuso 2021; Bender et al. 2021). The methodology employs the unified modeling language and e3 value modeling principals to depict value exchanges within a defined system (i.e., value activity diagrams) and show categorical differences between systems or operational scenarios (i.e., use case diagrams).

To that end, this report applies the valuation methodology to a set of representative utility rates that range from the dominant flat rates that currently permeate the landscape to TE rates that arise from a fully TE system. The goal is to model the functional differences in value exchanges that occur under the selected rates to begin establishing the transparency that will be required for TE deployment. This work creates a foundation of value considerations for deploying more dynamic rates and transactive energy systems, underpinning future site-specific analyses that will be required in practice.

The remainder of the report is structured as follows. Section 2.0 defines the assessed rate structures and outlines the assumptions made within the value model. Section 3.0 presents the diagrams created from applying the valuation methodology, and Section 4.0 offers concluding remarks including future avenues for work.

2.0 Rates

Five utility rate structures are considered within this work: flat rates, a base rate (e.g., flat rate) with critical peak pricing (CPP), TOU rates, real time pricing (RTP), and a TE rate that arises from the introduction of a retail market within a TE system. The first four rates reflect the current utility rate landscape and the increasing dynamics in rates that are likely to occur as utility policies evolve to utilize customer sited DERs. Note that for the sake of this report, flat rates, CPP, TOU rates, and RTP are considered conventional utility policies relative to a TE system and the resulting rate; additional bill adders like critical peak rebates and demand charges are not explicitly modeled in this work but are discussed alongside CPP. Although the selected rates and market structures can manifest in various ways, we have assumed simple definitions to illustrate the key differences in value accrual under each and reflect common implementations.

2.1 Flat Rates

Flat rates levy the same price per kWh regardless of the time of day or time of year that the energy is consumed. While flat rates are simple and easy for customers to understand, they offer no incentive for reducing consumption during peak periods or responding to time-dependent grid needs, forgoing meaningful benefits that DERs can generate. Prosumers[1] on flat rates, as well as CPP, TOU, and RTP, are typically enrolled in net metering; net billing; buy all, sell all; or alternative compensation mechanisms that pay prosumers at a predetermined rate per kWh based on the amount of electricity they export to the grid and, at times, on the time the energy is exported (Zinaman et al. 2017). Accordingly, a generic representation of these compensation mechanisms is implemented in the value model.

While most prosumers are currently enrolled in net metering policies in the United States, net metering is evolving, and the rate at which prosumers are compensated may change in the coming years. There are continued efforts to create compensation mechanisms that more accurately reflect the true value of exported electricity rather than using the retail rate as net metering has historically done. As such, researchers and policymakers have the nontrivial task of calculating what that cost may actually be as the factors included in those analyses have significant influence over the outcomes (Lawson 2019).

2.2 Critical Peak Pricing

CPP is a mechanism typically added to a base rate (e.g., flat rate, TOU rate). CPP increases the price per kWh that customers are charged during a number of critical peak periods each year. Most CPP mechanisms have a preset number of critical peak periods they can call each year and a total number of hours that the periods can last, often culminating in 10-20 critical peak periods that span several hours each. The periods during which CPP is applied are the most grid-strained, often during summer months when demand is projected to be particularly high, which makes the overall reduction in end-use consumption valuable (U.S. Environmental Protection Agency 2022). Customers enrolled in CPP are usually given notice that a critical peak will occur at least a day in advance to allow them to prepare and have a cap on the number of hours that they can last (e.g., four hours per day).

[1] Prosumers are utility customers with onsite generation who have the capability of exporting excess electricity back to the grid or consuming it on-site. Prosumers can be compared to consumers who strictly consume energy from the utility and do not have on-site generation.

Although not considered in this assessment, it is worth noting that CPP is similar to critical peak rebates in that latter issues rebates to customers for consuming less than what they have typically consumed during peak periods in the past. In comparison, demand charges apply an additional fee based on the maximum power a customer requires over some predetermined period of time, often the billing cycle. While the values associated with critical peak rebates and demand charges manifest differently than CPP, the similarities that exist in value flow (as these mechanisms essentially function as bill adders) allows the CPP diagram to serve as an example of how these mechanisms can be accounted for in system valuation.

2.3 Time of Use

TOU rates have designated periods throughout the day, most often in intervals greater than an hour, where different volumetric prices are charged per kWh. In many TOU rates, there is a peak period in the evening hours and an off-peak period remains for the rest of the day; however, the schedule of periods in TOU depends on the specific utility and can include more than two periods throughout the course of a day (Preziuso and Odonkor 2022). The schedule for these periods and the prices charged within them can also vary based on season, but overall, the prices charged during the designated periods remain constant over long stretches of time. This is often due to the regulatory approval cycle, and while this offers customers predictability in their costs and better aligns charges with known grid needs, it introduces a risk of rates growing stale.

2.4 Real Time Pricing

Real time pricing is a rate structure where the customer's volumetric charges fluctuate alongside wholesale prices, typically at an hourly interval (Lazar & Gonzalez 2015). While the customer may retain a monthly fixed or access charge, the bulk of their bill is based on the volumetric rate as is the case with the aforementioned rates. RTP is very dynamic and can experience large swings in price. While RTP exposes end users to the volatility in the wholesale market, safeguards can be put in place to protect customers from extreme scenarios. We assume that RTP systems operate in jurisdictions that have access to a wholesale electricity market (i.e., an Independent System Operator (ISO)/Regional Transmission Operator (RTO)) and that the wholesale market's prices are passed through to consumers. By extension, the utility functions as a wires-only utility (i.e., is responsible for delivery of power and maintenance of the network, but not power generation). We also assume that distribution system costs are fixed and do not fluctuate.

2.5 Transactive Energy Systems

In contrast to RTP rates, a TE rate is more dynamic with fluctuations more frequent than hourly. Rather than a simple pass through of the wholesale price, TE systems allow energy generation and consumption at the distribution, or even device-level, to respond to system demands and pricing through a retail TE market that is cleared by a market operator. TE systems can also be used to defer distribution system costs by allowing prices to vary at the local level (Gridwise AC 2020). Congested networks, for example, may see higher prices than uncongested ones.

Various market and price forming mechanisms can be used in TE systems. However, we assume a double auction mechanism for this analysis.[1] Double auctions are familiar in the electricity sector, and many wholesale electricity markets are based on similar principles (FERC 2020). For example, the Pacific Northwest National Laboratory Distribution System Operator and Transactive study uses such a mechanism (Reeve et al. 2022). Other transactive market designs, such as peer-to-peer (i.e., where buyers and sellers trade directly with each other) or order books (i.e., where a market operator matches buyers and sellers based on their bids) would have different value flows. The TEMix transactive energy demonstration in California, and the GOPACS program in the Netherlands use these market mechanisms, respectively (Cazalet 2019; Kok, et al. 2022). The wholesale market structure is assumed to be the same as in the RTP scenario (i.e., with a wires-only utility passing through purchases made through an ISO/RTO).

Many of these approaches are focused on energy cost recovery and generally roll capital costs into energy costs on a per unit of energy basis. However, other methods of recovering capital costs also exist. For example, Pratt et al. (2022) call for separate distribution and congestion charges that scale according to consumption and retail multipliers, which allow for non-energy costs to be recovered. Other cost recovery models, like performance-based regulations, allow for capital costs to be recovered through the achievement of defined performance goals (Cross-Call et al 2018).

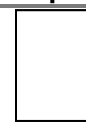
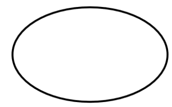
Finally, this assessment assumes aggregators will serve an instrumental role in the TE market, acting as an intermediate between households and the market operator. While aggregators are not a necessary component of a TE system, most TE pilot projects that are not situated on a microgrid utilize an aggregator (Abrishambaf et al. 2019). Thus, we assume that aggregators have a likely role to play in near-term applications for TE and provide a generic representation of one for illustrating the flow of value in such a system.

[1] In a double auction market sellers submit quantities and prices to the market operator (i.e., an ISO) and customers submit bids. The market operator clears the market at the price where these supply and demand curves converge.

3.0 Value Model

The diagrams comprising the value model, presented in the subsections that follow, rely on the unified modeling language as described in the valuation methodology (Bender and Preziuso 2021; Bender et al. 2021). Table 1 shows the key features of the value model diagrams, which readers can use as a legend herein.

Table 1 Value model notation.

Name	Description	Graphical representation
System Boundary	The system(s) being modeled, used to show the objects modeled within each system.	
Use Case	A function, or set of functions, of the system; a categorical set of behaviors in the system.	
Association	Association relationships represent an interaction or communication.	
Activity	Activities are the dynamic aspects of a system. Activities create value exchanges within the system.	
Actor	A user or other system that interacts with the system. Many actors are stakeholders.	
Information Flows (Information)	Information flows show an exchange between activities and actors. Information-specific information flows show abstract pieces of information that serve as inputs to value flows rather than tangible amounts of value.	
Information Flows (Value)	Information flows show an exchange between activities and actors. Value-specific information flows show tangible values exchanges.	

3.1 Use Case Diagram

More conventional and commonly used rates, including flat rates, CPP, TOU rates, and RTP, are categorically different than a TE system. In the former, the absence of prices formed in a retail market influenced by the behaviors of consumers and producers leave the utility as the main actor applying rates. Those rates have been previously approved by regulators or formed through the wholesale market and are passed through to customers in monthly bills. In a TE system, end users, including both consumers and prosumers, are more active in influencing the prices levied by programming DERs to behave accordingly. Figure 1 shows a system boundary defined around existing grid operations that rely on conventional utility rates. There are four use cases within that system: exporting electricity, settling monthly bills, consuming electricity, applying rates, and providing electricity. Prosumers, consumers, the utility, and generators are all active within that system. The TE system, which encompasses the system of existing grid operations, includes three additional use cases—inputting preferences to DERs to configure their behavior in the market, submitting market bids, and clearing the market—and two additional actors—the market operator and the aggregator. The actors that have associations with use cases interact with those behaviors in the systems, which manifest in accordance with the rate structure that is implemented.

In both the conventional system and the TE system, consumer and prosumers consume electricity and settle their monthly bills. The key difference between these actors is that prosumers can also produce electricity that can be exported back to the grid and accepted by the utility. Generators also provide electricity within the system boundaries. The utility applies rates and settles monthly bills with prosumers and consumers. The primary difference between the behaviors in the conventional system and the TE system is the introduction of more active participation from DERs. While consumers and prosumers may control their DERs in a conventional system, that interaction is not shown in Figure 1 because consumer and prosumer preferences, and the subsequent energy behaviors they influence, are most material in a TE system as they lead to engagement with the market. The aggregator participates in the activities required to submit bids, sitting between the customers and the TE market, and the market operator is ultimately responsible for clearing the market. Resulting prices from the TE market are ultimately called upon by the utility as they settle the monthly bills.

The use cases depicted in Figure 1 are further explored through the specific activities depicted in the value activity diagrams that follow.

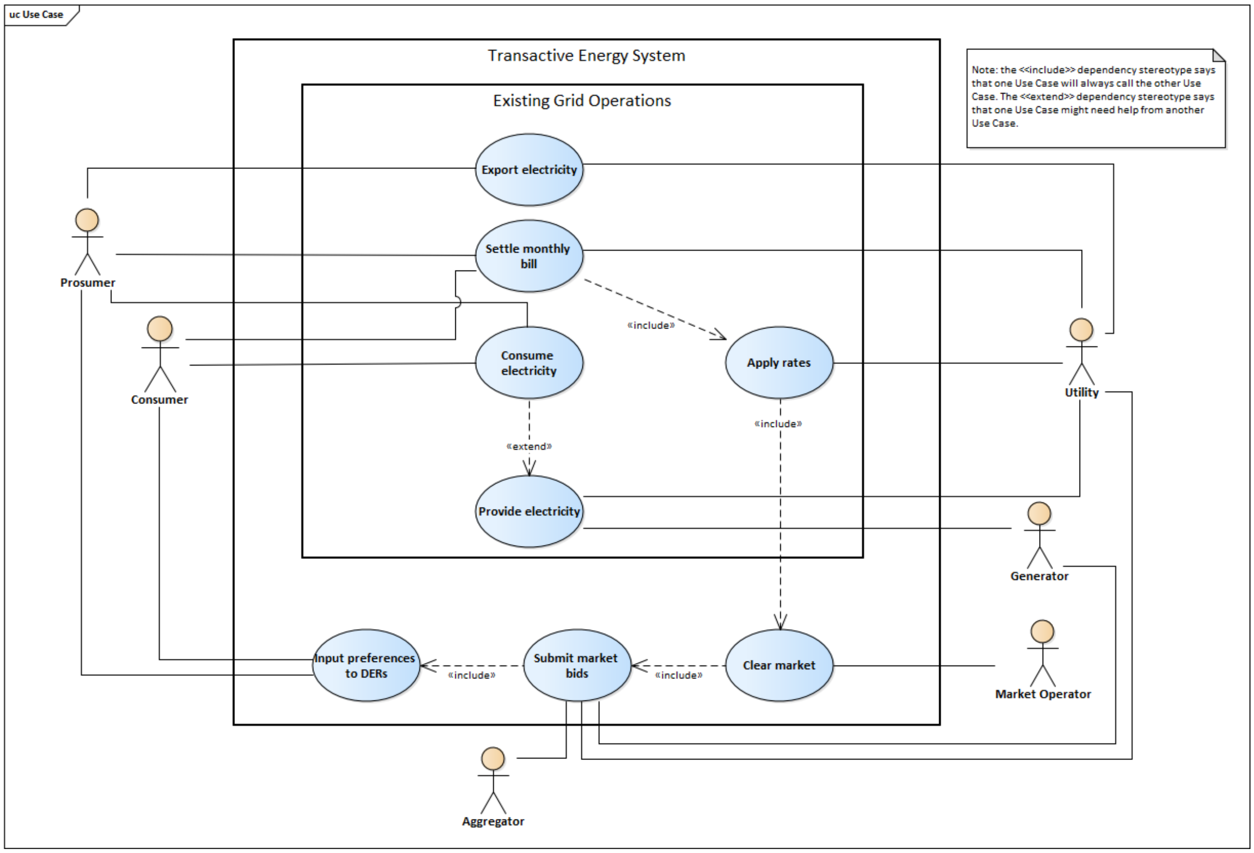


Figure 1 Use case diagram depicting the categorical differences in behavior between traditional rate structures and a transactive energy system.

3.2 Flat Rate

When a utility applies a flat rate to their customers, the primary exchange of value is a payment from a prosumer or consumer to the utility for providing them electricity as shown in Figure 2. Given that flat rates remain steady regardless of time, the activities that occur are also simple. Since prosumers also produce electricity, they can consume that electricity on-site if their compensation mechanism allows or export the electricity back to the utility. When exported, the utility accepts that electricity and credits the prosumer accordingly, which comes through on their monthly bill. While generators are not depicted in this diagram, it is assumed that generators provide electricity through the utility. The generators are part of the wholesale market, which is depicted in the RTP diagram in Figure 5. While the wholesale market exists in all the rates within this assessment, it becomes most relevant in the RTP and TE scenarios because it has a more visible impact on the prices customers are charged for consumption in those situations. The analog for the flat rates, CPP, and TOU rates would be regulators approving the volumetric rates that the utility then applies. The regulator is not depicted in the diagrams as that process would not need to be considered in the simulation of such a study to quantify value accrual.

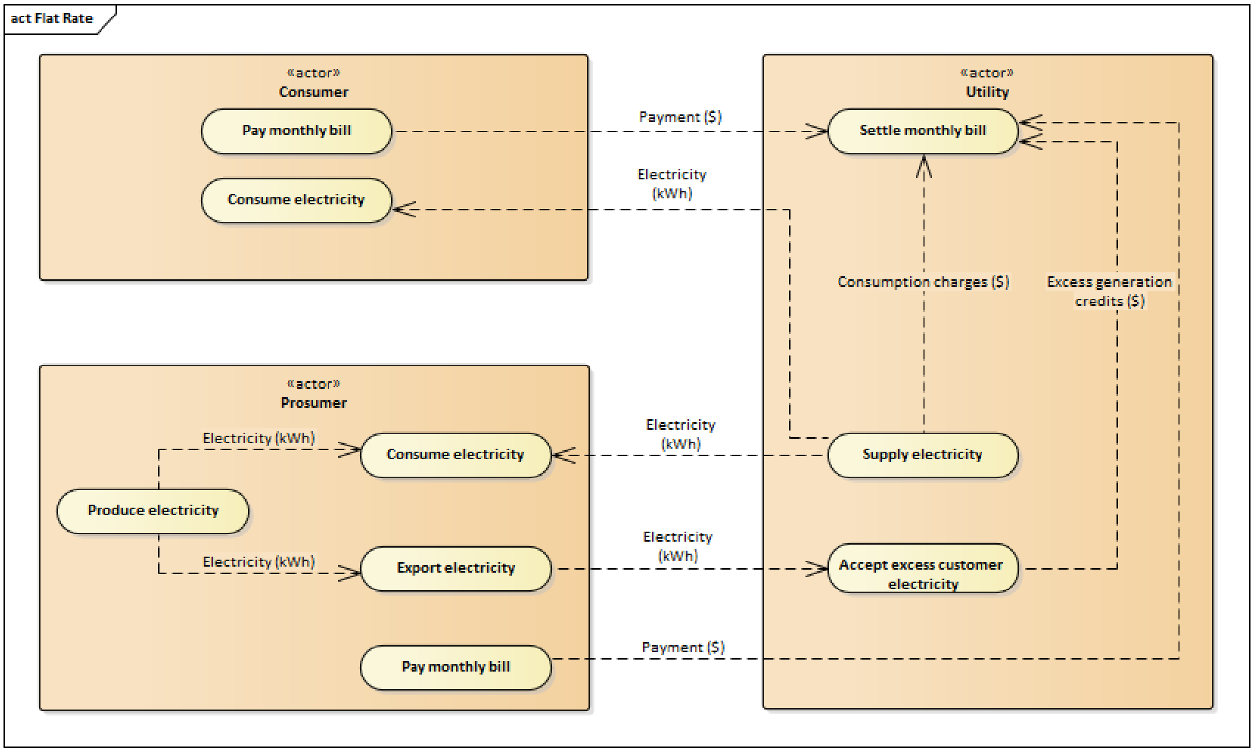


Figure 2 Flat rate value activity diagram.

3.3 Critical Peak Pricing

Under CPP, consumers and prosumers continue to consume and produce electricity in accordance with their base rate (e.g., a flat rate). The key difference in value exchanges under CPP and the flat rate depicted in Figure 2 occurs during the critical peak periods. Figure 3 shows that when customers consume and produce electricity during critical peak periods, the utility levies different charges against them to reflect the strain currently on the system. The charges are higher per kWh of consumption during those periods, and the export rates for prosumers also have the potential to deviate from the standard agreement. Knowing the changes in policy occur during peak periods is critical knowledge for both end users and the utility. End users need to know when those peak periods will occur to adjust their energy behaviors, and the utility needs to track those behaviors to charge and credit their customers accordingly. Outside of those CPP charges, the payment interactions remain the same between the utility, consumers, and prosumers, with monthly payments including all costs and credits.

If we were to instead consider critical peak rebates in this context, additional activities within the utility would need to compare the consumption of the consumers and prosumers within the critical peak period relative to historic consumption. These activities would also factor the rebate into the monthly bill. In comparison, the critical peak period activities depicted in Figure 3 would not be relevant for a demand charge. Demand charges would allow consumers and producers to continue their consumption under their base rate, reflecting the volumetric portion of the monthly bill, with demand charges calculated separately by the utility and applied to the monthly bill based on the peak consumption under that rate.

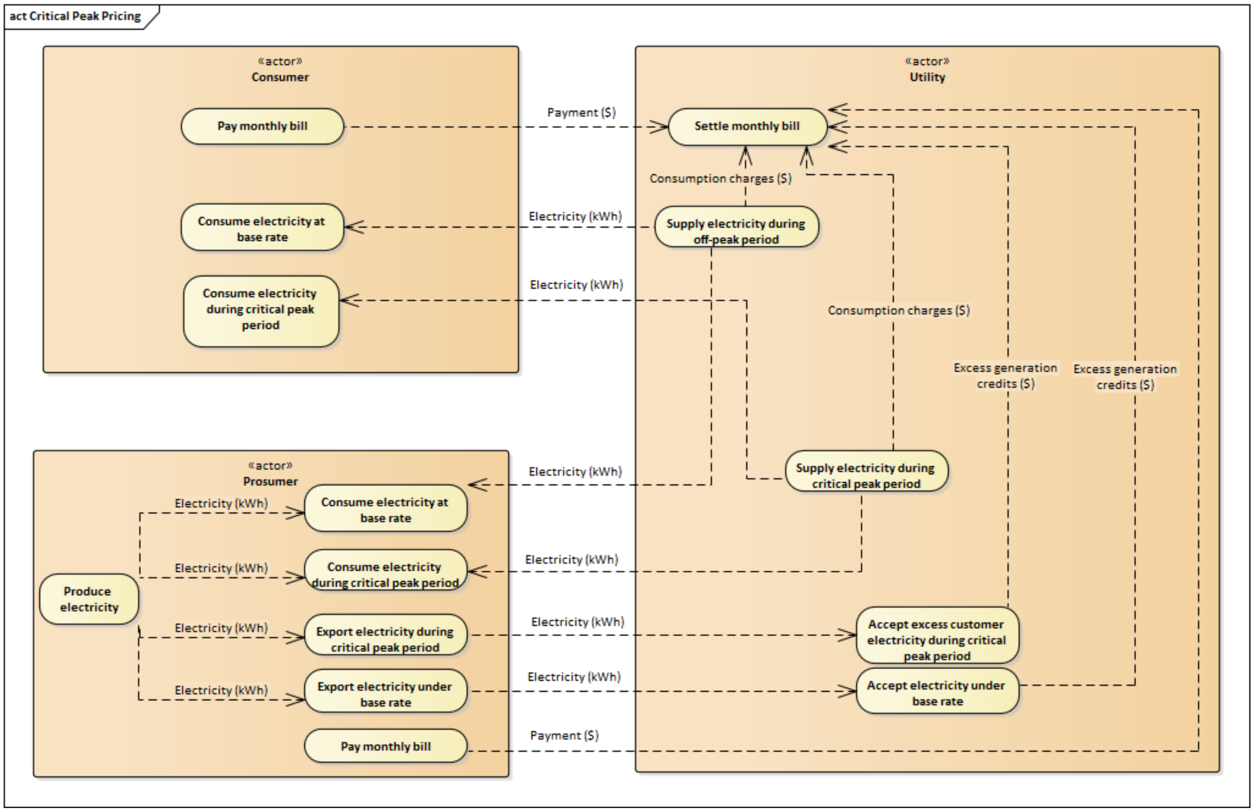


Figure 3 Critical peak pricing value activity diagram.

3.4 Time of Use Rate

Figure 4 shows the function of value exchanges under TOU rates strongly resembles that of flat rates and CPP; the utility remains the primary actors for implementing TOU rates. The largest difference in this rate scenario lies in the timing of consumption. Rather than having only a few periods in the year that levies a different price per kWh for consumption, as is the case with CPP, volumetric consumption charges under TOU vary based on periods of the day. Most often, there is a peak period and an off-peak period in TOU rates, but schedules can have additional periods over the course of the day. For example, some TOU rate schedules have peak, off-peak, and super-off-peak periods. Regardless of the number of periods, the value exchanges remain the same: the utility applies unique volumetric prices during the designated blocks of time throughout the day. TOU rates increase in temporal coverage compared to CPP as consumers and prosumers are not just expected to engage with grid needs a few times a year but may instead create more habitual changes in their energy behaviors to benefit from the daily pricing scheme.

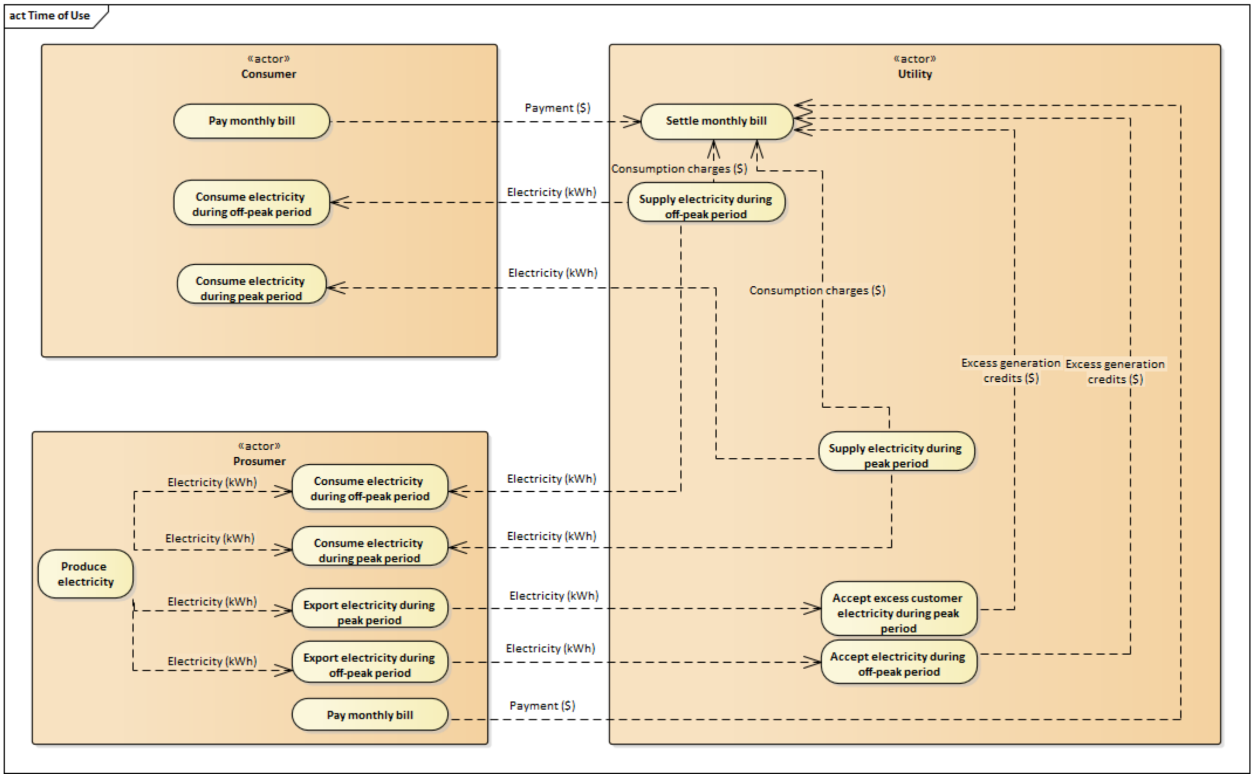


Figure 4 Time-of-use rate value activity diagram.

3.5 Real Time Pricing

Real time pricing makes a noticeable departure from the rate structures discussed through this point. Figure 5 illustrates how values will flow in the system under this rate. The largest difference stems from the inclusion a wholesale energy market in the form of generators and the ISO. The changing values of generators' cost basis and the wholesale market price outcomes will influence the temporal variation of real time prices, in a way that is not present in flat, TOU, and CPP rates, all of which have their values determine well ahead of time. Flat and TOU rates, for example, are predetermined whereas real time prices lack a prescribed schedule and value, varying on an hourly or sub-hourly basis. As in the case of the previously modeled rate structures, this case does not include a regulator. However, regulatory questions, such as how best to design real time prices, and whether and where price caps should be instituted (and how the costs associated with those caps will be recovered) can be examined through the design of real time prices, and in bill settlement.

Figure 5 shows that generators with different marginal costs, and thus energy prices, all submit bids into the wholesale market. The bids that generators submit are not tangible values but are instead flows of information that influence the tangible values that are ultimately exchanged under RTP. Similarly, the ISO takes demand projections from the utility and uses this information to clear the market, typically on an hourly basis. The demand projections are also information-specific flows rather than value-specific flows in this case. As different generators have different available capacity at different times, and demand varies temporally, the cost of electricity will fluctuate each time the auction closes. In an RTP scheme, the utility uses this information to develop retail prices that vary in line with the wholesale market. RTP typically includes additional charges related to the operations of the network that do not vary temporally.[1] In the TOU structure, customers made the choice to consume during on- or off-peak times; here customers can decide whether to vary their consumption based on pricing variation throughout the day. Device automation can be used to simplify this exchange for customers.

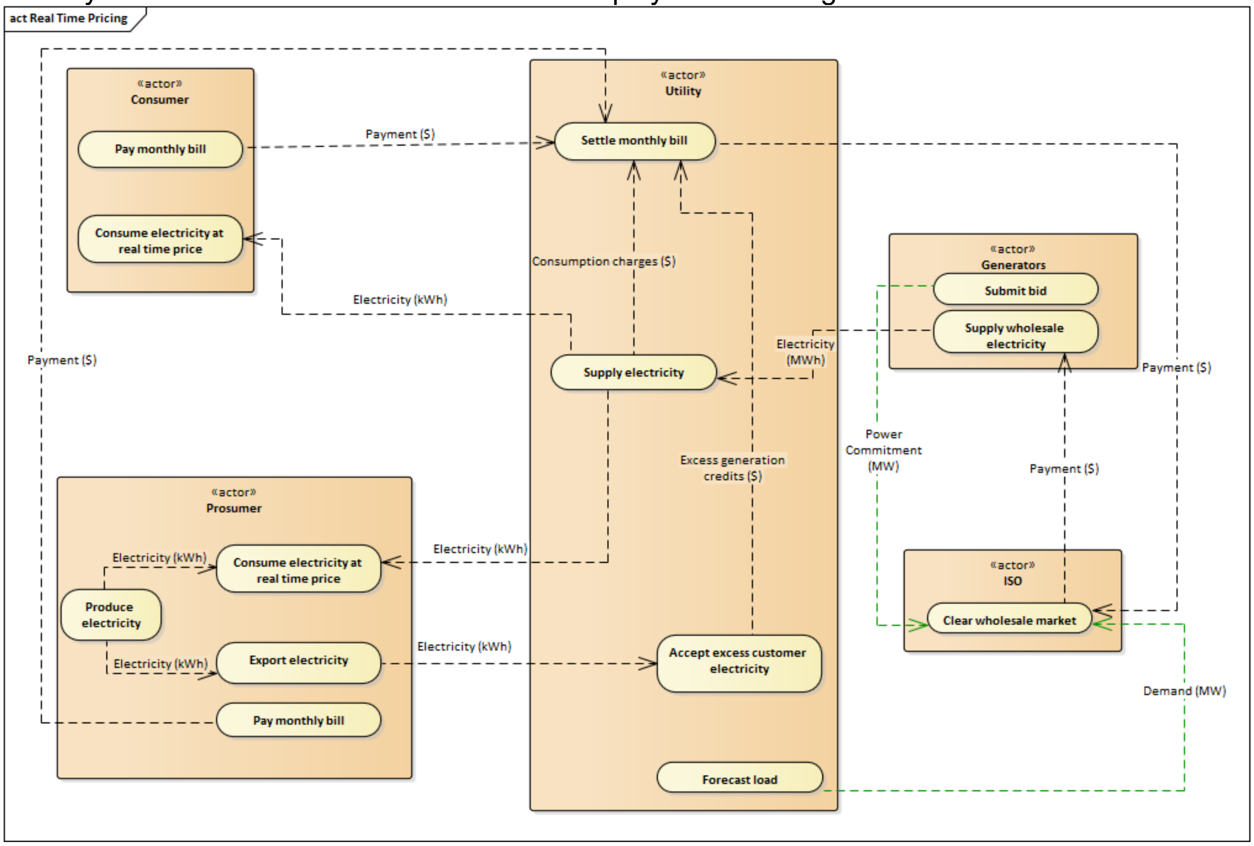


Figure 5 Real time pricing rate value activity diagram

3.6 Transactive Energy

TE prices are more dynamic still and more directly influenced by consumers and prosumers as they can now actively participate in the TE market. As Figure 6 shows, the TE system has a wholesale market that functions similarly to the RTP case, but additional market activity is introduced on the customer's side. TE prices vary alongside the wholesale market price for electricity, but within a TE system, customer activity can directly influence pricing as well. Customers are able to program their devices to reflect their preferences (e.g., temperature, time to run appliances) and commit power through aggregators. These commitments, shown as information-specific flows, can come in the form of demand response or through the sale of distributed generation. Aggregators then compile these commitments and bid them into the TE market.

TE systems can be designed with many goals in mind including congestion relief and renewable integration, and the value of these services will depend on their ability to address these system goals. The market operator then settles the market based on the total demand needed by the system and any distribution system constraints with the associated prices for these services

[1] Charges for the distribution and transmission systems are often included as a flat per kW or kWh adder to the customers' volumetric or demand charges, or included in the monthly portion of the customer bill.

flowing to the utility as information-specific flows, who in turn incorporates those values into the monthly bills that are settled. It is again worth noting that the role aggregators will play in a TE system is still evolving, so the depiction of their activities in Figure 6 shows a simple representation of how they may function but is not intended to be prescriptive. Furthermore, existing policies such as Federal Energy Regulatory Commission (FERC) Order 2222, which promotes the participation of DERs within the wholesale market, indicates how aggregators may function outside of a TE system as well (see Appendix A). While RTP bills see charges related to the wholesale market vary based on market conditions, here network charges can vary as well, as this style of dispatch can influence both wholesale and distribution level prices.

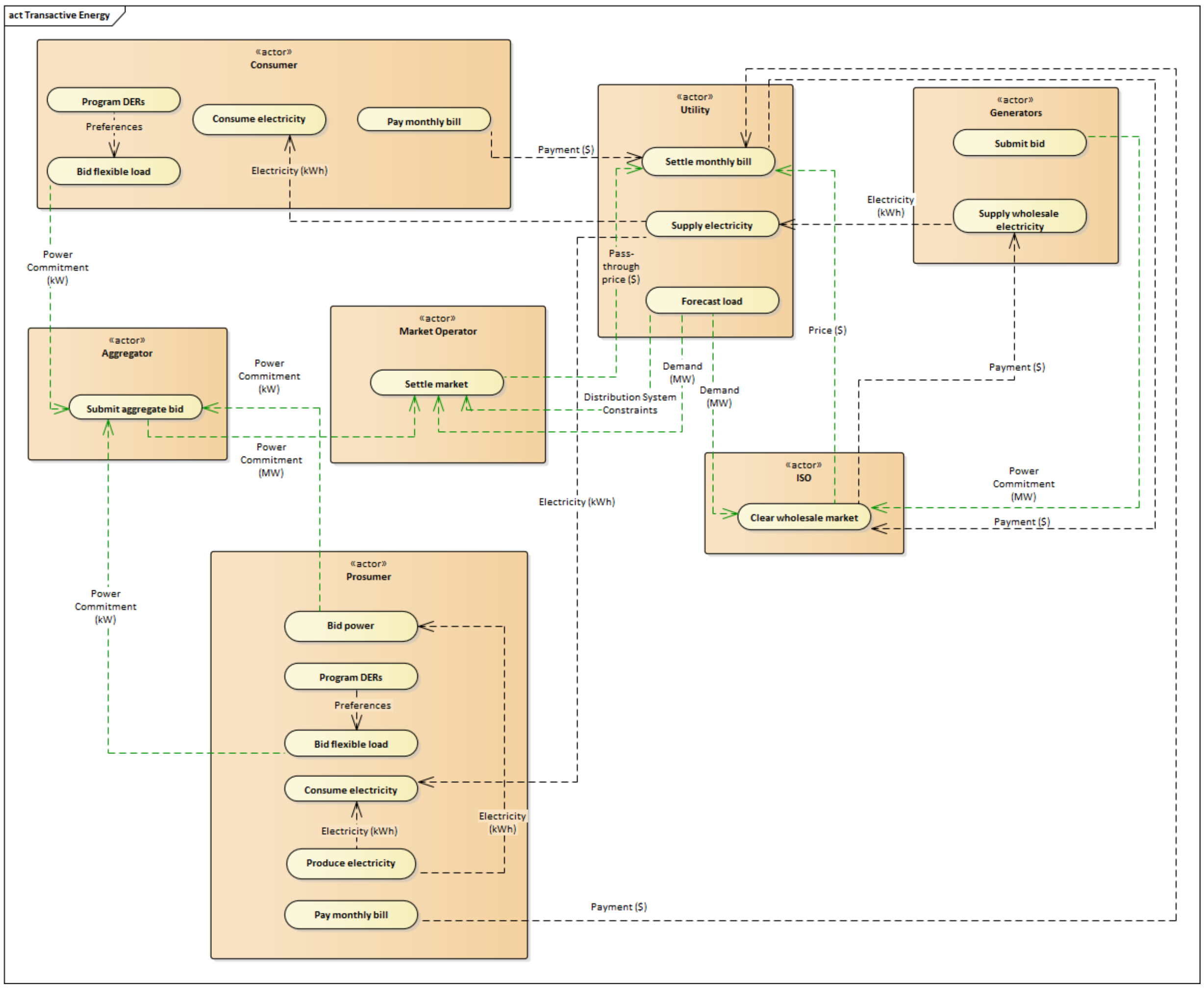


Figure 6 Transactive value activity diagram

4.0 Conclusions and Future Work

As the value model presented in Section 3 progresses from simple, flat rates through to more dynamic rates like RTP and up through a fully TE system, the valuation methodology offers increased transparency into the system to bring stakeholders together in a collective understanding of who might be affected by changes in utility policies and how. The differences from rate to rate may not be obvious otherwise, exacerbating knowledge gaps and complicating decision-making processes.

While the flow of value presented here shows little differentiation among distribution system actors, the behaviors of those actors within the depicted activities is nontrivial in determining the magnitude of value that accrues. For example, there is likely to be significant variation in consumer behaviors due to differing preferences for their electricity system that influences their consumption behavior (Ganguli, Boff, & Somani 2022). Under more dynamic rate structures, they will have a greater opportunity to exercise these preferences and amass different quantities of value. These preferences could also vary by demographic group, with customers of different races, classes, or levels of education having different demand for renewable, reliable, or local power. Though potentially significant, most models only focus on aggregate demand. As these groups may cluster geographically, demographic variance could have a significant impact on particular feeders or networks.

Likewise, while this work illustrates how values flow through the system, it does not detail how changes among rate classes impact system outcomes. For example, if a customer group has inelastic demand or low willingness to accept demand response tariffs, the dynamic effects of real time rates may be limited, and system planers may look towards building excess capacity or storage. If the inverse is true, the system may be able to use its existing infrastructure more efficiently. Scenario analysis could inform system planners on the potential magnitude of these effects if their goals for rate design extend beyond cost causation. Supporting valuation work, including class diagrams (see Appendix B) and a simulation integrated with the value model can increase the impact of such an analysis.

Additionally, while this work maps value flows between stakeholders, further attention could be paid to how value flows within them. For example, analysis has found that low consumption customers (who are more likely to be low income) generally lose money under a RTP scheme (Horowitz & Lave 2014). In California, low-income customers are more likely to live on feeders with limited hosting capacity (Brockway, Conde, & Callaway 2021). Under a TE system with pricing related to network constraints, these customers could face increased bills and be directed to shed load more frequently than other customers. More concretely extending analyses like these, which consider the order, frequency, and duration of activities, to various rate structures and to a greater number of customer groups would allow system operators and decisionmakers to better understand the distributional effects of this transition (Tarufelli and Bender 2022).

This sort of analysis could be expanded to help policymakers understand potential corrective measures. More detailed modelling using valuation diagrams could help answer questions such as if excess gains can be transferred from winners to losers or if system-wide savings can be reinvested to improve outcomes for vulnerable communities. If a TE system were to lead to a more efficient outcome by dispatching fewer high-cost peaking resources, those savings could be reinvested in networks in low-income areas, limiting the potential congestion impacts to those customers.

Finally, there are several emerging rate structures that we do not cover in this report. Subscription based rates, common in some deregulated retail markets, allow for greater experimentation in rate design. These plans can be tailored to the demands of specific customers. In such an arrangement, customers would survey different suppliers and choose a plan that fits their needs (much as they would when shopping for a cellular phone plan). In retail choice markets, like Texas, suppliers offer unique plans, such as flat monthly bills, and bills that provide for free consumption at night. The value flow for these scenarios may be different than those modeled in this report.

With the continued deployment of more dynamic rates, the valuation methodology offers a systematic and transparent way to evaluate the impact different rate structures can have on the range of stakeholders within the energy system. The value model presented in this report provides a foundation for future simulations that can help inform decisionmakers in creating rates that meet the evolving needs of the grid and fairly compensate those who engage with it.

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Appendix A – FERC Order 2222

Under FERC Order 2222, aggregators can help utility customers participate in the wholesale market by committing their power in aggregate. The role of the aggregator under FERC Order 2222, imagined under a RTP scheme in Figure A1, is similar to that of an aggregator under the TE process in Figure 6. However, the TE system is comparatively less complicated given that all payments for the customer are made to and come from the utility in their monthly bill. Under FERC Order 2222, the customer can see tangible monetary flows with both the utility and the aggregator. In the TE system, the customer only exchanges money with the utility with the aggregator existing in the background, accepting and aggregating bids to participate in the market.

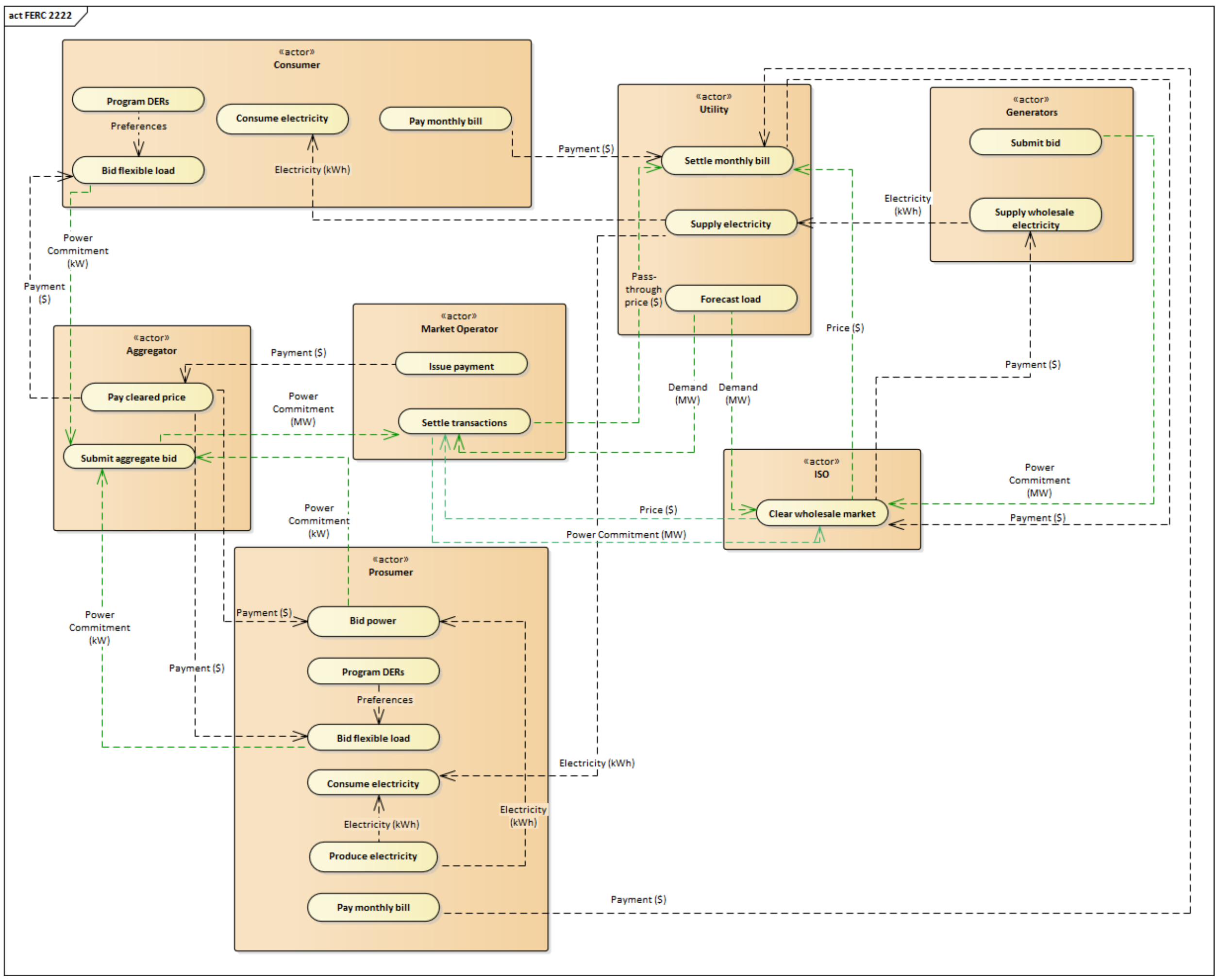

Figure A1. Activity diagram for a RTP scheme with consideration to FERC 2222.

Appendix B – Class Diagrams for Energy System Agents

Class diagrams show classes (i.e., a template for an object), a class's attributes (i.e., their characteristics) and operations (i.e., their functions), and the relationship between classes. Class diagrams can supplement the value model presented in this report and further connect these efforts to any accompanying simulation. Actors are often presented as classes within the valuation methodology and serve as a way to define different agents within the energy system. This is particularly useful when considering the various behaviors that an actor might display and any characteristics that may influence that behavior. For example, consumers and prosumers can be defined with demographic information, which can be linked to energy behaviors within a model.

The class diagram in Figure B.1 shows key attributes and operations a future simulation could consider when quantifying the value flows assessed in the value model presented in this report. Classes are depicted as a list of attributes followed by a list of operations that are separated by a horizontal line. Note that the arrow from prosumer to consumer in Figure B.1 indicates that a prosumer will inherit all attributes and operations that a consumer might has in addition to the attributes and operations in the prosumer class. Any simulation will be limited by data availability and also tailored based on study objectives and target areas of interest (e.g., the impact that TOU rates have on low-income populations). Thus, the class diagram below is not intended to be prescriptive or exhaustive but offer a foundation for future areas of work.

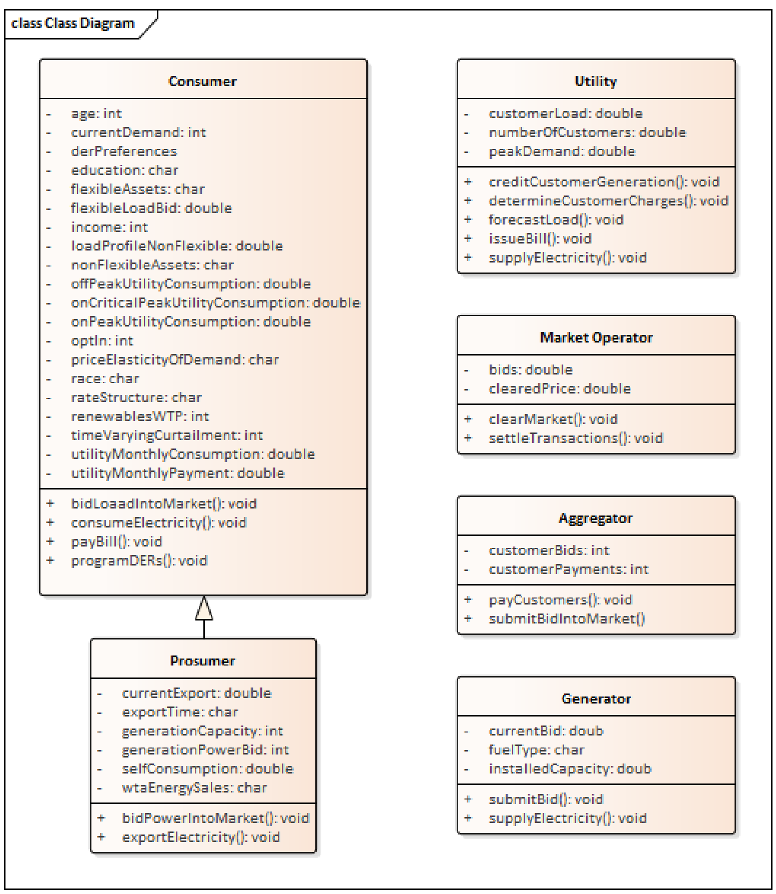

Figure B.1 Class diagram for key actors under different utility rates.

A code book to accompany Figure B.1 is presented in Table B.1. The code book provides additional information about the classes in the diagram, helping further communicate the assumptions made about each of the actors and any values associated with the assumptions. Every attribute and operation in Figure B.1 appears in Table B.1 and is associated with an actor. This is again intended to offer insights into the types of considerations that may be made in future work and is not a direct recommendation for the attributes, operations, or data types that should be evaluated.

Table B.1 Complementary code book for the class diagram.

Actor	Attribute or Operation?	Name	Description	Data Type
Consumer	Attribute	age	List of household ages	Integer
Consumer	Attribute	currentDemand	Time-stamped, current household electricity demand	Double
Consumer	Attribute	derPreferences	Household preferences for DER automation	
Consumer	Attribute	education	Highest level of household education	Character
Consumer	Attribute	flexibleAssets	List of flexible assets in the home	Character
Consumer	Attribute	flexibleLoadBid	Amount of power being bid into the market	Double
Consumer	Attribute	income	Annual household income	Integer
Consumer	Attribute	loadProfile	Load profile for forecasting	Double
Consumer	Attribute	nonFlexibleAssets	List of significant non-flexible assets in the home	Character
Consumer	Attribute	offPeakUtilityConsumption	Amount of utility-provided electricity during off-peak hours	Double
Consumer	Attribute	onCriticalPeakUtilityConsumption	Amount of utility-provided electricity during critical peak hours	Double
Consumer	Attribute	onPeakUtilityConsumption	Amount of utility-provided electricity during on-peak hours	Double
Consumer	Attribute	optIn	Likelihood of opting into a non-default rate	Double
Consumer	Attribute	priceElasticityOfDemand	Sensitivity to varying prices	Character
Consumer	Attribute	race	List of household races	Character
Consumer	Attribute	rateStructure	Rate structure to which household is subscribed	Character

Actor	Attribute or Operation?	Name	Description	Data Type
Consumer	Attribute	renewablesWTP	Household willingness to pay for increased RE generation	Double
Consumer	Attribute	timeVaryingCurtailment	List containing hour of day and price willing to pay during those hours	Double
Consumer	Attribute	utilityMonthlyConsumption	Amount of electricity consumed from the utility during the billing cycle	Double
Consumer	Attribute	utilityMonthlyPayment	Amount charged for utility-provided electricity during the billing cycle	Double
Consumer	Operation	bidLoadIntoMarket	Bid flexible load into market via aggregator	
Consumer	Operation	consumeElectricity	Consume electricity provided by the utility	
Consumer	Operation	payBill	Pay monthly bill to utility	
Consumer	Operation	programDERs	Program household DERs to reflect preferences	
Prosumer	Attribute	currentExport	Current power being exported	Double
Prosumer	Attribute	exportTime	Time (on-peak or off-peak) power is exported to the grid	Character
Prosumer	Attribute	generationCapacity	Installed capacity for on-site generation	Double
Prosumer	Attribute	generationPowerBid	Amount of power bid into the market	Double
Prosumer	Attribute	selfConsumption	Amount of power from onsite generation currently being consumed	Double
Prosumer	Attribute	wtaEnergySales	Willingness to accept for onsite generation	Character
Prosumer	Operation	bidPowerIntoMarket	Bid power into market	
Prosumer	Operation	exportElectricity	Export electricity to utility	
Utility	Attribue	customerLoad	Aggregate forecasted customer load	Double
Utility	Attribute	numberOfCustomers	Number of customers served	Double
Utility	Attribute	peakDemand	Peak system demand	Double

Actor	Attribute or Operation?	Name	Description	Data Type
Utility	Operation	creditCustomerGeneration	Determine customer credits for exporting electricity	
Utility	Operation	determineCustomerCharges	Determine customer charges for consumption	
Utility	Operation	forecastLoad	Forecast customer load	
Utility	Operation	issueBill	Issue bill to customers	
Utility	Operation	supplyElectricity	Supply electricity to customers	
Market Operator	Attribute	bids	Accepted market bids	Double
Market Operator	Attribute	clearedPrice	Price at which the market clears	Double
Market Operator	Operation	clearMarket	Clear the market	
Market Operator	Operation	settleTransactions	Issue payments to providers	
Aggregator	Attribute	customerBids	Customer bids to aggregate for the market	Double
Aggregator	Attribute	customerPayments	Payments to issue to customers	Double
Aggregator	Operation	payCustomers	Pay customers for their accepted bids	
Aggregator	Operation	submitBidIntoMarket	Submit aggregate bid into the market	
Generator	Attribute	currentBid	Current bid into the wholesale market	Double
Generator	Attribute	fuelType	Type of generator fuel	Character
Generator	Attribute	installedCapacity	Total installed capacity	Double
Generator	Operation	submitBid	Submit bid into the wholesale market	
Generator	Operation	supplyElectricity	Supply electricity	

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