Chapter 4
Transactive Energy Applications of eIoT

The previous chapters have situated the development of eIoT within an ongoing transformation of the electric power grid. In response to several energy-management change drivers, the grid periphery will be activated with an eIoT composed of network-enabled physical devices, heterogeneous communication networks, and distributed control and decision-making algorithms that are organized by well-designed architectures and standards. When these factors are implemented together properly, they form an eIoT control loop that effectively manages the technical and economic performance of the grid. This control loop is most consonant with an emerging concept of transactive energy (TE).

Definition 4.1 (Transactive Energy [607]) A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter. ■

TE is commonly viewed as a collection of techniques to manage the exchange of energy in business transactions [47]. A utility, or any other private jurisdiction can implement TE between its various customers in industrial, commercial, and residential environments to manage DER technologies. TE applications incorporate the new eIoT-based activities for utilities, and industrial, commercial, and residential consumers. The result is better management of resources, successful integration of renewable energy, and increased efficiency in grid operations [47]. In many ways, TE is seen as an effective way to manage the technical and economic performance of various grid operations at all levels of control—commercial, industrial, or residential. As such, eIoT technologies directly support the implementation of TE applications.

This chapter discusses how aspects of the eIoT control loop from Chap. 3 are reflected in various TE applications across different layers of the electricity value chain:

- Section 4.1 discusses the role of TE in future grid applications and highlights some of the proposed TE frameworks.
- Section 4.2 presents a few motivational use cases for TE frameworks.

S. O. Muhanji et al., *eIoT*, https://doi.org/10.1007/978-3-030-10427-6_4

- Section 4.3 addresses the role of the utility and distribution system operators within the TE framework. This section also recognizes some of the challenges and opportunities presented by the implementation of TE.
- Section 4.4 examines several customer applications for TE and eIoT in commercial, industrial, and residential settings.

4.1 Transactive Energy

Transactive energy (TE) was a concept introduced by the GridWise Architecture Council (GWAC) to unite demand-side influences with wholesale markets, retail markets, and system operations [14]. GWAC is an organization that seeks to guide policy and facilitate the exchange of information in order to integrate information technology and e-commerce with distributed intelligent networks and devices [607]. A careful inspection of GWAC's definition of TE reveals that it is entirely consonant with the eIoT control loop. Not only does TE encourage dynamic demand-side energy activities based on economic incentives, it also ensures that the economic signals are in line with operational goals to ensure system reliability without resorting to override control [14]. It is this techno-economic nature of TE that makes it suitable to deal with the growing number of DERs and the current dynamic nature of consumer demand and energy market operations [14, 607].

TE is expected to offer increased efficiency to the power system and help maintain much needed reliability and security [607]. TE is, further, enhanced by its ability to engage both the technical and economic objectives of the grid in order to solve multi-objective control and optimization challenges [607].

As the grid evolves to accommodate more DERs, traditional grid control approaches must change to engage new grid stakeholders with more interactive control. DERs such as intelligent loads, storage, and distributed generation require more sophisticated control approaches than conventionally non-networked loads [607]. As more DER assets and their owners participate in the operational, economical, and semantic aspects of the grid [607], their activities must be optimally coordinated to align values and incentives among all stakeholders [607].

TE frameworks provide a systematic alignment of these incentives to favorably achieve grid objectives throughout central operations and peripheral additions. As a design rule, TE architectures must also account for the heterogeneity in the nature of transactions by providing the necessary definitions and guidelines. Recognizing the heterogeneous nature of operations provides the option to expand both the number and types of applications that can be added or removed from TE platforms. Consequently, heterogeneous operation includes making economic decisions that depend on local factors such as the levels of smart metering integration and DER penetration in the region [608]. Future TE development will rely on clear definitions of the transacting parties, the type of information to be exchanged, the transaction terms, what is being transacted, and the transaction mechanisms used by the system [607].

Recognizing that there is no "one size fits all" solution for interactions between the participants of the grid's techno-economic control loops [609], various groups have come forward to provide guidance in designing TE systems. The Transactive Systems Program (TSP) by the US Department of Energy aims to develop TE designs that offer "systematic, scalable, and equitable approaches for managing energy system operations [610]." The goal of TSP was to test existing TE designs to find an approach that is best-fit for the grid's multi-objective optimization problem. The program provides test cases and data sets for evaluating TE applications. It also outlines the criteria and procedures for measuring the performance of TE systems focusing on critical system behaviors such as scalability, optimality, and convergence [610]. Transactive mechanisms are key building blocks to energy exchanges, since each mechanism describes a value-based negotiation for energy flow between entities [610].

Recognizing the inter-timescale and multi-layer couplings of various grid operations, TSP analyzes mechanisms across varying timescales and layers of the energy system [610]. In addition, this program emphasizes the importance of creating the necessary interfaces to allow for communication, and interactions between various TE platforms as well as distributed control platforms [610]. It also stresses the need to clearly define any given TE platform to facilitate the transparent identification and comparison of TE frameworks [610]. TSP serves the key role of ensuring that TE platforms are assessed based on their value and overall contribution to the performance of the energy industry.

Another TE framework is the transactive energy market information exchange (TeMIX). TeMIX is a non-hierarchical methodology to support automation in energy transactions and decentralized control for the smart grid [47]. It is a subset of the Organization for Advancement of Structured Information Standards' (OASIS) for TE [47]. Essentially, TeMIX is a general marketplace for parties to interface in energy and energy transport transactions, with call and put options for both. Uniform information exchanges across DER component types occur in a TeMIX network for quotes, tenders, and transactions [47]. TeMIX allows for involved parties to carry out transactions without the intervention of any central authority thus removing any hierarchies. Transactions of energy and energy transport can occur between parties in retail and wholesale markets as well as between parties in different wholesale markets, a factor that is enabled by the standardized information exchange among all parties [47]. This simplifies interactions significantly by allowing exchanges across all parts of the electricity value chain. It is important to note that TeMIX is most useful in a smart grid context where customers are assumed to have smart meters, smart HVAC, and smart PEV charges [47].

Overall, TeMIX is a framework for automated interactions with the grid-periphery, consumer devices with distribution grids, transmission networks, and central generation and storage [47]. It simplifies the billing and settlement process for all consumer classes and DERs. Frameworks, like TSP and TeMIX, are important when planning transactions, since any modification to existing structures should undergo scrutiny from the perspective of holistic grid functions [609].

In addition to these TE frameworks, there have been several implementations and demonstrations of TE at the grid periphery in the past few years that have helped validate the TE framework for smart grid control. These demonstrations include the Olympic Peninsula Project, the American Electric Power (AEP) Ohio gridSMART® project, and the Pacific Northwest Smart Grid Demonstration (PNWSGD).

The Olympic Peninsula Project (OPP) was initiated in 2004 by the Pacific Northwest National Laboratory (PNNL) to test distributed dispatch, based on energy and demand price signals with automated, two-way communication between the grid and DERs [611]. This project implemented the GridWise concept which is a TE term coined by PNNL to describe a future-looking grid management system that uses smart devices and real-time communication [611]. GridWise technologies are a part of "non-wires solutions" (NWS) that are meant to provide alternative solutions to energy infrastructure issues due to growing load without having to build new transmission [612].

The Olympic Peninsula Project was carried out in Clallam County, the City of Port Angeles, and Portland, and served municipal, commercial, and residential loads. The project controlled a 150-kW water pump capacity between two stations, 175 and 600-kW generators, and 112 DR homes with two-way communication support in electric water and space heating [611]. Monetary incentives were used to control the DG suppliers and DR households. PNNL observed the DERs in this system through a dashboard that combined the resources as a common virtual feeder [611].

The main goal of the Olympic Peninsula Project was to assert the importance of intelligence at end use; that is to show that activating the grid periphery improves both the operational and economic efficiency of the grid [611]. This goal was guided by several sub-goals that include [611]:

- Show that DERs can provide multiple benefits through economic dispatch delivered by a shared communication network,
- Understand the individual and collective performance of DERs in near real time,
- Analyze the incentives and incentive structure for DER control and customer participation.

These goals not only helped study the value of active DER participation in energy markets but they were also a test of the effectiveness of current market practices [611]. Data from the system was collected for about a year (from early 2006 to March 2007) and were fundamental to the project's findings. The data provided unambiguous evidence that DERs could bid into the electricity market as a non-wire solution, and that these technologies could be applied at a larger scale [611]. Besides ascertaining the willingness of consumers to participate in DR given price incentives, this project provided a few key lessons for large-scale implementation of TE. In terms of increasing the number of participants, this project demonstrated that user-friendliness of the DR program or ease of participation were imperative for DR. As for grid operators, the ease of use relied on the availability of visualization dashboards that were developed and tested throughout the project.

The second project is the American Electric Power (AEP) Ohio gridSMART project. It focused on the deployment of advanced DR infrastructure in Columbus, Ohio [613]. The project embarked on infrastructural renewal by deploying advanced equipment such as smart meters, distribution automation circuit reconfiguration (DACR), voltage control and optimization from volt VAR optimization (VVR), and enhanced communication for consumer programs [613]. The project spanned 3000 miles of distribution lines, 16 substations, 100,000 residential consumers, and 10,000 commercial and industrial customers [613].

Given that no AMI meters had been installed in the region prior to the project, 110,000 m had to be installed to allow two-way communication between participants [613]. In addition to AMI, this project included cyber-security and interoperability requirements that involved comprehensive system improvement for both new and legacy systems [613]. The benefits of this program were numerous and provided a lot of insight for DR programs and grid operators. First, the AMI systems allowed for faster connections, remote-service usage, and improved billing accuracy. Second, automated circuit reconfigurations and smart metering infrastructure reduced the number of outages which in turn reduced field visits and manual meter readings. Furthermore, AMI could locate potential equipment failures to preempt outages and make the maintenance process more proactive.

The most notable benefits of this project were in consumer and pricing programs. In addition to smart meter installations, the project offered six programs that provided consumers with data on their energy usage and allowed consumers to respond to real-time price signals [613]. The real-time pricing with double auction (RTPda) was an experimental pricing program that was especially successful at allowing consumers to shift energy consumption according to fluctuating energy prices. Approximately, 250 consumers successfully participated in this program.

Another noteworthy benefit of this project was in the cyber-security and interoperability efforts. As a result of these efforts, multiple advancements were made to improve the security and interoperability of smart grid devices. The Cyber Security Operations Center (CSOC) was created to monitor and test the AMI system. Threat information was also shared with peer utilities and governments [613]. The CSOC was able to secure and validate the two-way communications from utility-owned networks through to the consumer home-area networks using penetration and interface testing [613]. Additionally, consumer data was protected with extensive and dedicated resources at a high level of security [613]. The CSOC continues to pursue efforts to ensure system security as well as interoperability in future deployments.

Like most projects, this demonstration was not without its challenges, and modifications will be required for any future deployments. The key challenge was in the deployment of new equipment. It was often costly, involved multiple maintenance team trips, and suffered equipment and communication system failures [613]. Despite these challenges, the program was an overall success; especially in creating awareness through community outreach programs and education [613]. The state of Ohio hopes draw from the lessons learned in Phase 1 and move to Phase 2 deployment where communication modules will be added to smart meters to enable DR and enhanced market participation [613].

The Pacific Northwest Smart Grid Demonstration (PNWSGD) by Battelle was arguably the world's first transactive coordination system [614]. This project was deployed in December 2009 and ended in 2015, funded by the DOE [614]. This project, in particular, exceeded the other two in both extent and complexity. It spanned multiple states and utilities, and included at least 55 smart grid systems [614]. Additionally, 25 out of 55 of the participating smart grid systems contained DERs of both supply and demand [614]. The cost and amount of electricity was negotiated to meet local and regional objectives, address renewable generation intermittency, and shape consumer loads [614]. Regional response was coordinated across 11 utilities, and a highlight of the project was the wide-scale connectivity between transmission, distribution, and home-area network systems. The demonstration successfully collaborated with dynamic endpoint responses to achieve conservation, reliability, responsiveness, and efficiency goals [614].

The tests in the PNWSGD were organized into three categories meant to bolster grid functionality [614]. First, several installations were made to contribute to improved energy conservation and efficiency [614]. Second, transactive assets were installed to respond to signals from the project's transactive system [614]. Third, these systems were tested for improved reliability in the distribution system [614]. These objectives of conservation, transactive response, and reliability were often investigated simultaneously at test sites [614]. A primary objective of the PNWSGD was to create a foundation for future smart grid advancements [614]. This objective was to be accomplished by creating an interoperable infrastructure to manage DR programs, DERs, and distribution automation in a system that could be validated through analysis [614]. This infrastructure combined generation, transmission, distribution, and load assets that were owned by utilities and customers across a five-state area [614].

An important focus for the project was data collection and analysis of the demonstration's costs and benefits for customers, utilities, and regulators [614]. The findings from the data provided potentially influencing testimonies for standards and methodologies for TE systems [614]. The project worked towards a future smart grid that is secure, scalable, and interoperable in regulated and non-regulated environments across the nation [614]. The transactive system was successful in connecting diverse, dynamic endpoint assets to the transmission system [614]. The report also noted that future applications of this system may further distribute its automated control responsibilities among distributed smart grid actors and devices [614].

Despite these successes, significant problems occurred with the consistent and accurate reporting of data [614]. Battelle expressed concern for utilities' ability to handle the large quantities of data that are produced by a smart grid system [614]. Future TE applications require better tools for confirming data accuracy. Furthermore, these applications must proactively identify and correct faulty sensing equipment that can introduce bad data into the system [614].

Together, these three TE demonstration projects have provided key insights into the opportunities and challenges of developing and deploying TE platforms. First, it is clear that TE systems must engage secure physical and cyber technologies to enable transactions. Second, these technologies must be interoperable so that devices with different functional characteristics can connect and communicate. Given that TE engages a diversity of systems, interoperable interfaces must allow transactive systems to operate across multiple timescales and enable event-driven operations [607]. Standardized interfaces must be constructed at the intersection of exchange mechanisms regardless of whether individual devices choose to play a transactive role [610]. Third, physical devices such as metering and telemetry devices must have the capabilities to accurately record and attribute energy flow measurements for the appropriate DR compensations [609]. In accounting devices, wholesale and retail services must be compatible to interoperate, yet also separable to prevent double counting for participants in multiple DR programs [609].

Since these TE demonstration projects, "blockchain" has emerged as a new internet encryption technology that enables distributed pricing [615]. Blockchain is a distributed cyber tool for communicating unique information publicly and securely [615]. Distributed, shared data repositories are protected from interference through encryption so that there is no need for extraneous bodies to enforce security [615]. At its core, a blockchain creates a "distributed ledger" as an immutable public record of transactions in a computer network [615] and entirely eliminates the need for a middleman. Transaction rates are determined by the size of distributed data sets, or "blocks," and the time interval for which the chain of data sets is periodically synchronized [616].

TE frameworks and enabling technologies are a force of decentralization that empowers DER management across energy customers. As a technology, blockchain shows great promise in enabling decentralized and distributed exchanges in TE applications. At the moment, blockchain protocols face scalability constraints that may slow transaction rates [616]. Nevertheless, blockchain has emerged as a technology that is integral to future TE applications.

In conclusion, TE platforms and applications are at the core of eIoT deployment and adoption. In the next subsection, the techno-economic control of TE is discussed in reference to its applications in industrial, commercial, and residential domains. The components of eIoT systems complement the high-level discussion of TE applications.

4.2 Potential eIoT Energy-Management Use Cases

The potential impact of TE can perhaps be best illustrated in two theoretical use cases. In one case, members of a community collaborate to lower costs by changing a utility's point of sensing. In the other case, larger loads or producers bypass utility involvement through direct participation in wholesale electricity markets. In both cases, energy consumers are able to make money by altering their relationship with utilities. These two eIoT TE use cases demonstrate how peripheral actors can engage in energy arbitrage with the help of present and future technologies. Opportunities for generators and consumers at the edge of the grid are presenting themselves in areas where price does not accurately represent the balance of supply and demand. Technological advancements in IoT enable peripheral actors to take action and exploit these imbalances in energy market prices. With eIoT, consumers and prosumers willing to form an aggregation can be set up to engage in energy arbitrage.

As first discussed in Sect. 1.3 and illustrated by the "duck curve" in Fig. 1.6 (on page 10), distributed power generation is expected, in the not too-distant future, to drive a surplus of energy compared to consumption during the same time [4]. Solar generation, in particular, is driving this trend, since its generation is limited by the hours of sunlight [4]. A glut in energy production during peak daylight hours does not necessarily coincide with consumers' energy demand [4]. The energy available on the grid during the surplus is sold at a low price, and sometimes at no cost. Hence, as prosumers inject their electricity into the grid, the value of this electricity falls, and so does the compensation received from utilities. If an oversupply occurs, utilities may curtail generation or bar the electricity from entering the grid. In most systems today, the retail price of electricity to consumers does not reflect the turbulent pattern of electricity supply [43, 44]. However, with implementation of TE systems, consumers can take advantage of lower energy prices.

Several assumptions are made to best present these use cases and to help guide the discussion:

1. It is assumed that eIoT technologies will be installed to the extent that sensing networks may adequately measure and process local consumption in real time.
2. A flow of pricing information from the electricity market to the periphery is available for consumers to react appropriately.
3. A connection to the market for energy flow and exchange is measured.
4. A platform to coordinate power data with pricing data is available to synthesize prosumer revenues and costs.

The eIoT technology trends described in Chap. 3 make these assumptions reasonable for the near future.

4.2.1 *An eIoT Transactive Energy Aggregation Use Case*

One interesting eIoT TE use case is based on the premise of changing consumers' relationship with a utility through aggregation. Consider Fig. 4.1. On the left, a conventional apartment building with rooftop solar consists of several apartments whose tenants act *individually* as conventional consumers to the local electric utility. Electricity consumption in each apartment is individually monitored with smart (residential) meters and the utility bills consumers accordingly. On the right, two important changes are made. First, the tenants of the apartment building

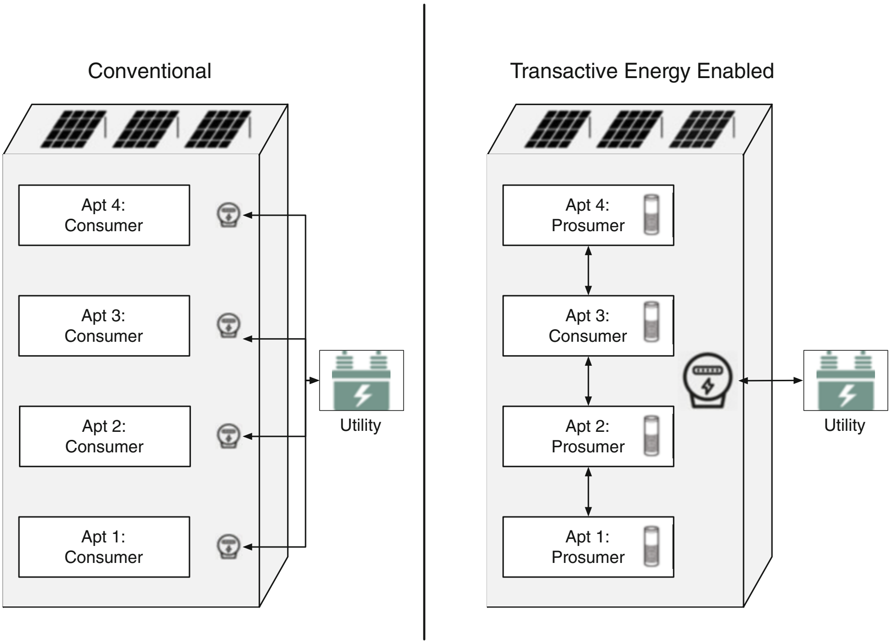

Fig. 4.1 A use case comparison between a conventional and an eIoT transactive energy-enabled apartment building

now act *collectively* as a single commercial *prosumer* to the local electric utility. Consequently, the many smart (residential) meters are replaced by a single smart commercial meter. Second, each prosumer purchases a TE-enabled smart home hub that allows each tenant to buy and sell electricity from other building tenants in real time.

The financial impacts on the utility and the tenants can be calculated. If the building as a whole consumes 2000 kWh at a rate of 0.1$/kWh and it generates from solar 1200 kWh which are sold back to the grid at $0.08/kWh, then the utility's total revenue for the conventional case is

$$\begin{aligned}\text{Utility Revenue} &= (2000\,\text{kWh}) * (0.1\$/\text{kWh}) \\ &\quad - (1200\,\text{kWh}) * (0.08\$/\text{kWh}) = \$104 \qquad (4.1) \\ &= \$200 - \$96 = \$104 \qquad (4.2)\end{aligned}$$

Collectively, the tenants spend $200 on electricity consumption and receive a $96 credit for their solar generation. In contrast, in the transactive energy case, the tenants with rooftop solar offer their solar generation at an average rate of $0.09 kWh to encourage their neighbors to shift their electricity consumption to daylight hours. Consequently, no solar generation is exported back to the grid. The utility's total revenue for the transactive energy case is

$$\text{Utility Revenue} = (800\,\text{kWh}) * (0.1\$/\text{kWh}) = \$80 \tag{4.3}$$

Consequently, the transactive energy case shows a $24 reduction in the utility's revenue! Even more interestingly, the tenants now spend only $188 as opposed to $200:

$$\text{Tenant Payment} = (1200\,\text{kWh}) * (0.09\$/\text{kWh}) \tag{4.4}$$

$$+ (800\,\text{kWh}) * (0.1\$/\text{kWh}) = \$188 \tag{4.5}$$

Finally, the tenants with rooftop solar now receive $108 as opposed to $96:

$$\text{Solar Tenant Credit} = (1200\,\text{kWh}) * (0.09\$/\text{kWh}) = \$108. \tag{4.6}$$

While this specific case may appear ideal, it is illustrative. In the TE case, the presence of solar generation provides an incentive for greater competition that ultimately benefits all the participating prosumers while simultaneously eroding the utility's billable energy. Because the tenants have collectively agreed to interact with the electric utility through a single commercial meter, the utility simply sees a decrease in the total amount of electricity purchased.

The eIoT TE aggregation use case above shows net social benefits due to several enabling factors:

1. The presence of prosumers with local solar generation that is, at times, inadequately compensated by utilities encourages the emergence of a transactive energy marketplace.
2. The solar generator's value proposition leaves local consumers at times over-billed by utilities.
3. The transactive energy marketplace is likely to be strengthened if there is a strong sense of community within the apartment building.
4. There exist nearly ubiquitous measurement, communication, and decision-making capabilities within the building to support the transactions. It provides price and quantity information for rational decision-making. The user-friendliness of these information technologies encourages greater adoption.
5. There exists a sparsity of measurement, communication, and decision-making capabilities between the building and the utility.

Naturally, if any of these factors is undermined, then the value proposition of the use case weakens. Of the five, only the last is directly within the utility's scope. Utilities and their associated regulators, for example, may choose to offer real-time retail electricity prices as a means of encouraging greater competition. In such a case, they would be encouraging TE at the distribution system level and not just at the building level. The alternative is that other TE buildings can emerge at the grid periphery. Furthermore, if such a trend were to take root, then large communities such as compounds and bounded neighborhoods might choose to do the same. In that case, a large enough TE microgrid could effectively form which bypasses a utility's services whenever it is convenient.

The application of the eIoT TE aggregation use case is already well suited for residential areas. Collaborations, such as the Brooklyn Microgrid project, embody aspects of this example and, in many ways, showcase the viability of peer-to-peer energy transactions [617, 618]. The Brooklyn Microgrid is a project that has brought consumers and prosumers to a virtual trading platform powered by blockchain to carry out energy transactions among themselves [619, 620]. This project, launched by LO3 Energy, provides a platform for consumers and prosumers to trade among themselves with the help of smart meters and blockchain technologies. A similar application is Power Ledger, a startup that was started in Australia, allows consumers to buy and sell renewable energy among themselves using blockchain [621]. In addition, Power Ledger intends to launch an asset-backed crypto token that will enable consumers or groups of consumers to share in the benefits of having renewable energy assets through trading in this token [621]. This approach would open the renewable energy market to a diversity of consumers and investors, hence, encouraging the growth of renewable energy systems [621]. Around the world, more and more people are starting to recognize the potential of peer-to-peer (P2P) energy transactions with some notable successes in Bangladesh, Germany, and New Zealand [619, 620, 622–624]. Beyond peer-to-peer applications, blockchain technology continues to support a growing number of applications in the energy industry. Recent studies have shown potential applications in cyber-security [625–627], multiple IoT applications [628–632], data privacy and security [633], and as a storage system for critical data [634]. Going forward, favorable regulatory measures might help advance peer-to-peer energy transactions such as those of the Brooklyn Microgrid. In customer applications such as this, TE implementation is primarily motivated by monetary incentives and the individual motivation to be more sustainable. Besides aggregation, energy usage can be modified at the source by adjusting times of use and consumption patterns.

4.2.2 An eIoT Economic Demand Response in Wholesale Electricity Markets Use Case

The second eIoT use case is based upon economic demand response (DR) as it is currently implemented in wholesale electricity markets. Consider Fig. 4.2. On the left is the same conventional apartment building. On the right is the same TE-enabled building which now acts as a single economic DR participant.

The building's conventional load profile is shown in Fig. 4.3a. For simplicity, assume that the building is relatively small compared to the peak load of the wholesale electricity market. Consequently, the building acts as a price taker because its bids have little effect on the locational marginal prices (LMPs) that clear the wholesale electricity market. Figure 4.3b shows the hourly LMPs for the full day. They are assumed to closely follow the trend of the "duck curve" mentioned earlier in Sect. 1.2.

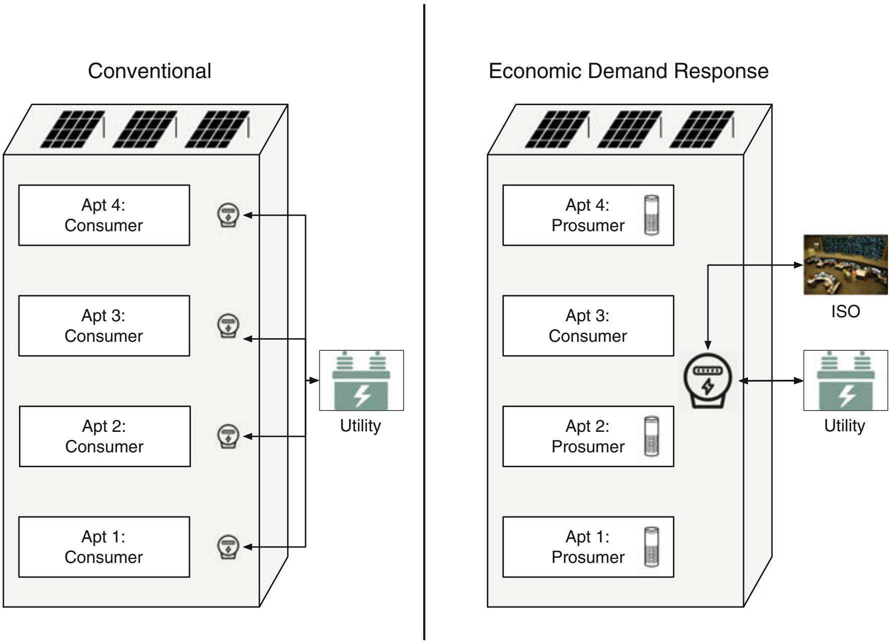

Fig. 4.2 A use case comparison between a conventional and an eIoT economic DR apartment building

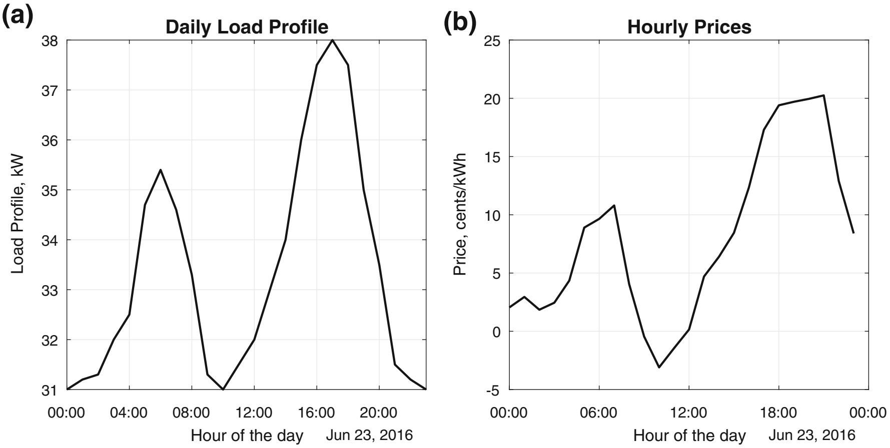

Fig. 4.3 eIoT Economic DR in wholesale electricity markets use case data: **(a)** On the left, the daily net load profile of the prior to demand–response incentives. **(b)** On the right, the hourly locational marginal prices (LMPs) experienced within the wholesale electricity market

The financial benefits for the transactive energy-enabled building can be calculated. As stated previously, the building's tenants pay $200 when exposed to the retail rate. However, simply by entering the wholesale electricity market, they would pay \$162 without shifting their behavior. This is because, on average, wholesale electricity rates are lower than retail rates. In such a case, the tenants have saved \$38 but the utility naturally has lost all \$200 because the TE-enabled building has effectively "cut out the middle-man." Now, imagine that the TE-enabled building is able to shift its loads so that it is no longer exposed to evening peak pricing and, more importantly, it makes use of negative LMPs during peak sunlight hours. A perfectly flat load curve would mean that the tenants now pay \$134 for a savings of \$66. In this case, as well, the utility has no access to the associated revenue. A flattened load curve could be achieved in multiple ways. Significantly sized loads, like a fleet of EVs or factory production, may have the required flexibility. In residences, eIoT-enabled home appliances (for example, dishwashers, washers, and dryers) can be timed to shift load during the day. In commercial buildings, HVAC units and hot water heaters can be controlled to curtail energy consumption during peak hours. Residential and commercial applications may be relatively small scale, but they have the intended impact with load aggregation. Industrial loads may not need aggregation, and examples include water pumping, desalination, and factory production. In all cases, eIoT devices and infrastructure enable the TE applications.

Again, this specific case is illustrative although it may appear ideal. The ability to aggregate so as to have access to wholesale electricity rates provides a financial benefit to the building's end consumers. Furthermore, the ability to participate in that market through economic DR allows the building to fill the troughs and shave the peaks of the duck curve. In both cases, this is financially beneficial [635]. Filling the troughs of the duck curve provides access to cheap and perhaps negative electricity prices. The peak shaving was not apparent in the case described above because the building's impact was small relative to the electric power system peak load. However, if economic DR were to become prevalent in the wholesale electricity market, then peak prices could come down and end consumers would benefit during these times as well. eIoT technology can enhance response to economic signals, and can ease coordination of production and consumption especially within an aggregate. The resulting direct participation in wholesale markets may bypass utilities; at least partially.

In the drive towards decarbonization, eventually carbon, economic, and physical accounting will align. If negative prices for renewable energy such as solar become the norm, then there is an economic opportunity to shift patterns of electricity consumption behavior. As the market adjusts to prices, and demand shifts to meet the imbalance of supply, duck curves will eventually begin to smooth. While this prediction relies on future eIoT implementation, it is nevertheless consonant with existing wholesale market practices. As the electric power system's market structures evolve to accommodate TE, it is clear that market facilitators will be required to coordinate new market procedures and entrants. Looking ahead, the question of who will take on this role remains an important component in the success of TE.

4.3 Applications for Utilities and Distribution System Operators

As seen in Chap. 3, the eIoT control loop is an electric power application that has the potential to transform the landscape of energy services for both consumers and grid operators. Furthermore, TE applications help create an empowered consumer base that is capable of making economically informed energy decisions that directly engage in energy markets. These factors put pressure on utilities to re-evaluate their approach to handling DERs and more likely reconsider the nature of their role in consumer applications. The two use cases discussed in Sect. 4.2 illustrate scenarios where utilities may face a future where consumers bypass their services partially or potentially altogether. This future scenario is not too hard to imagine especially with the DER innovations that are pressuring utilities to change their business-as-usual operations and increasing the accessibility of energy markets to consumers. The transition to transactive systems provides plenty of opportunities for utilities to take on energy-management services for customer DERs as well. However, there is no certain future for the overall transformation of the electrical power system especially regarding the role of utilities in consumer operations. Several questions are yet to be fully answered:

1. What will the transformation of utilities look like?
2. Will utilities take on the role of implementing TE?
3. What energy-management solutions for consumers will persist?

Concern for utility viability is not unique to today. The term "Death Spiral" once described the circuitous pattern utilities experienced in the 1980s of raising prices to cover costs, only to lose demand and make less profit [636–638]. Concerns about losing customers to distributed generation has revived the term, in that raising energy rates would lose profits for utilities by providing incentives for customers to generate their own electricity [637, 638]. While financial investors have found that this serious concern may be exaggerated, disruptive DER technologies and increased competition in energy markets have diminished utilities' abilities to seek rate increase in response to adverse economic environments [636, 638]. As a result, utilities may need to change their long-term strategy, as they did in the 1980s to deal with this potential "Death Spiral." The challenge of adjusting to disruptive eIoT technologies while simultaneously re-imagining their position in increasingly competitive markets makes the task for utilities much greater [637, 638].

The change drivers originally discussed in Sect. 2.1 are manifesting themselves into timely and pressing calls for action on the part of regulators and grid operators. For example, utilities in California are facing regulatory pressures to transform their businesses to accommodate DERs [4]. In the summer of 2016, the California Independent System Operator (CAISO) received federal approval for a Distributed Energy Resource Provider (DERP) tariff that allows aggregation between 500 kW and 10 MW of distributed energy to be submitted to the day-ahead and real-time energy markets as well as the ancillary services markets [639, 640]. This initiative not only poses technical challenges to CAISO but also calls for greater collaboration with utilities and any new market players willing to take on the role of managing DERs.

At present, CAISO has access to the transmission–distribution interface, while utilities own and control data between consumer-level metering and the distribution system [639]. As a result of this information gap, CAISO's DERP plan requires active collaboration with utilities. In addition, CAISO requires extensive network upgrades to address any operational concerns that may arise from this integration. If not planned carefully, it is possible that DER participation may not lead to reliable operation of the distribution system. Furthermore, without distribution data, CAISO may have to worry about larger effects aggregating up into the transmission system [639]. It is clear that the challenges described above span the technical and economic layers of grid operations. With the right investments, utilities could embrace new approaches that encourage the dynamic development of the grid and increase revenue in the process.

DERs create many new responsibilities for "distribution system operators" (DSOs) such as managing consumer data, and deploying new infrastructure such as advanced metering infrastructure, distributed storage systems, and EV-charging infrastructure [30]. With DERs, the role of utilities in operating the distribution grid becomes more complex because new suppliers and demand aggregators can emerge. Naturally, favorable regulations and tariffs are needed to promote the growth and adoption of DER technologies throughout the electric grid [30].

In addition to the production and investment credits for renewables, there have been new regulations favoring effective DER integration in market operations. In April 2016, the Federal Energy Regulatory Commission (FERC) put forward a Notice of Proposed Rule-making (NOPR) that required regional transmission organizations/independent system operators (RTO/ISOs) to revise their market rules to allow effective integration of electric energy storage into wholesale markets and the recognition of distributed energy aggregators as wholesale market participants [69].

The NOPR recognized that it was important to accommodate the operational characteristics of these DERs to allow them to participate competitively in wholesale markets [69]. This proposition was put in place in order to improve competition and encourage fairness in market rates by removing any potential barriers that hindered the effective integration of DERs [69]. As is currently the case, DERs may be hindered from participating in electricity markets due to the fact that the current market rules were specifically designed for larger more controllable thermal generating plants. Allowing the aggregation of DERs to participate in markets is a step closer to promoting DER development.

North American grid operators can also draw upon the approaches taken by European electricity markets as recommended by the Smart Energy Demand Coalition (SEDC) [30, 641]. The SEDC noted that favorable regulation and market rules, in addition to promoting DR programs, were key to the successful integration of variable energy resources in the European electric power industry [30, 641].

North American utilities have a chance to take on the additional roles created by DERs to maximize their returns as well as ease the integration of DERs. Traditionally, the interaction between utilities and consumers has been limited to maintaining the distribution service, responding to the occasional call whenever supply is interrupted and providing metering/billing services [30]. However, as more DERs are installed on the distribution system, utilities have the chance to expand their services beyond network upgrades and potentially assume the role of a DSO and control services such as DR and curtailment. Furthermore, DERs offer many flexibilities that could be leveraged by utilities to reduce system and operational costs [30]. For example, an increase in distributed solar PV systems could result in operational challenges that could be mitigated by enabling inverter control to regulate both the quality and quantity of PV power sent to the distribution feeders [30]. Additionally, distributed energy storage could support solar PV production, thus significantly reducing the need for system and network upgrades [30].

However, it is important to note that at current battery costs, network upgrades might be more affordable compared to installing new energy storage infrastructure. As for assuming the role of DSOs, favorable regulation is necessary to ensure a level playing field for all DERs and enable any new stakeholders [30, 69]. A revision of market rules to allow DERs to participate in markets competitively would be necessary as well as ensuring transparency in the ownership and control of DER operations [30].

Of course, the effective control of DERs requires strictly laid out guidelines on the eligibility, metering, telemetry, and operational coordination between RTO/ISO's, DER aggregators, and distribution utilities [609]. It is likely that new stakeholders will step up and assume the role of controlling and easing the integration of DERs. At the moment, however, distribution utilities are well placed to undertake these additional responsibilities given their awareness of both generation and the consumption flexibility of consumers and DERs [642].

Proper management of DERs and TE frameworks would result in a dynamic distribution system that is centered on energy products, regulation products, and time-responsive prices that help stabilize the grid through the provision of energy balancing, line congestion management, and voltage control [30, 643]. As in the case of European power markets, utilities may need to assume the role of the DSO. This would constitute a tremendous change in the utility business models and current regulatory structures [30].

The question of whether utilities need to be deregulated to allow for this transition must also be considered. For a long time, utilities have enjoyed a natural monopoly status that needs to be unbundled to allow for competition in the markets and encourage the presence of DER aggregators at the distribution level [643]. Assuming utilities take on the role of a DSO, their relationship with consumers must transform into a partnership where the utilities, such as DSOs, engage with prosumers to achieve the common goal of the partial supply of services [643]. This symbiotic relationship between consumers and utilities is best summarized in Fig. 4.4, where a smart home with several DERs interfaces with the grid to provide and receive services as necessary. As a DSO, a utility can serve as an intermediary

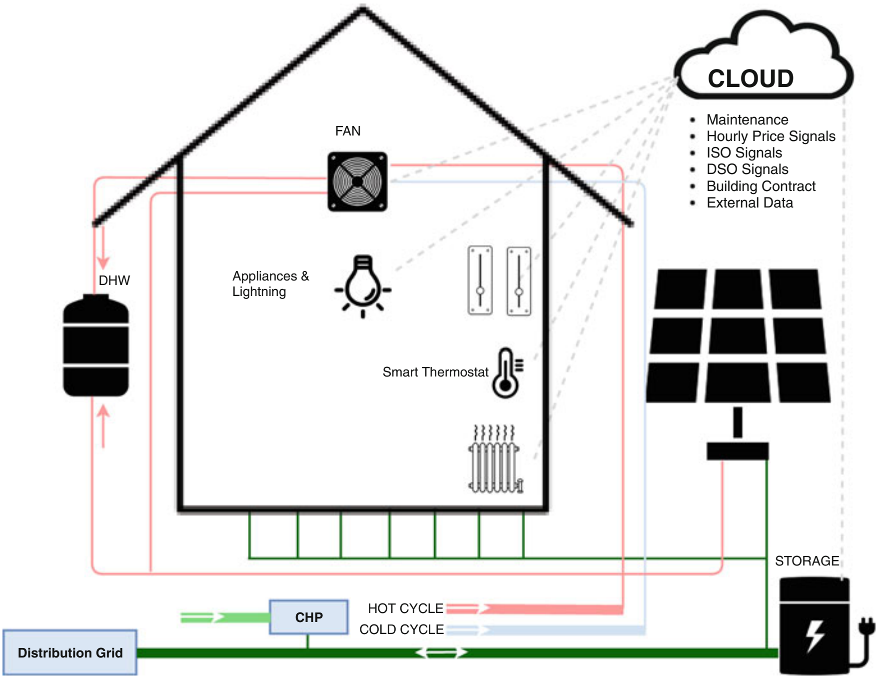

Fig. 4.4 An example eIoT-enabled smart home: DERs are connected to the grid through a cloud-based framework (adapted from [30])

to balance the supply and demand of power while correcting for any surpluses and stability issues quickly and reliably [643].

The transformation of the grid is already underway and it puts pressure on utilities to adapt to the competition and become an integral part of the future grid. Competition at the distribution level is set to increase with the presence of DR aggregators and peer-to-peer electricity trading platforms [644]. Although the distribution system has not been as observable as the transmission system, smart meters and remote terminal units (RTUs) are quickly closing this gap [107, 645]. As a result, the role of utilities is set to transform to a more active one that is very similar to the role of transmission system operators (TSO) [646, 647]. Utilities, such as DSOs, would potentially serve as neutral market facilitators to guarantee system stability and power quality while ensuring technical efficiency and fair prices for all parties involved [646].

The adoption of eIoT and TE management platforms for grid monitoring and control will result in large quantities of data that requires management [645, 648]. Needless to say, neutrality, transparency, and non-discriminatory data management are highly necessary to ensure a level playing field for all market participants [648]. The European Union serves as a great example for the creation of DSOs and the adoption of eIoT. Organizations such as the SEDC [641] and EURELECTRIC have played key roles in identifying the potential challenges of integrating variable energy resources and the eIoT. Many of these lessons have applications to the North American electric grid. The strategic direction and role of electric utilities in this new landscape remains unclear and depends on the answers to several open questions:

1. Which agent will evaluate and deploy aggregated DERs? The utility? The aggregator? The RTO/ISO?
2. Which entity will manage and prioritize DER dispatch?
3. How will stakeholders address concerns about possible double compensation?
4. What level of visibility will distribution utilities and RTOs/ISOs need into the operations of aggregated DERs to reliably manage those assets?
5. Which entity pays for distribution system upgrades needed to facilitate DER participation in wholesale markets?
6. How will utilities recover costs to enable DER aggregation within their territories?
7. How will the evolving technological landscape of eIoT affect the answers to these questions?
8. How will FERC-level regulations affect the answers to these questions?

4.4 Customer Applications

4.4.1 Industrial Applications

The industrial sector consumes approximately 42% of all the electricity produced in the world [649]. Apart from being energy intensive, some manufacturing processes, such as with electrical drives and motors, demand high-quality electricity [650]. In addition, the industrial sector is facing high pressure to decarbonize from both regulation [651, 652] and corporate social responsibility [653, 654]. As a result, most industrial facilities have integrated on-site DERs and are rapidly undertaking energy efficiency measures to minimize their carbon footprint [655].

In most cases, the energy requirements of industrial facilities cannot be served by only a local utility. Hence, these facilities sometimes directly connect to the transmission lines and participate in the wholesale electricity markets. Typically, industrial electric loads are consistent, large scale, and centralized [649], making them good candidates for DR programs. In some countries, industrial base loads have been used by system operators for the provision of various ancillary services [649]. As it happens, it is much easier to control a few large industrial loads than numerous small residential loads. Furthermore, recognizing the higher (economic) utility of consumed electricity for industrial processes, it can be expected that production systems will be more willing to respond to price signals in DSM schemes to ensure steady and continuous supply.

The nature of industrial loads provides an easy opportunity to apply DSM to industrial energy systems [649]. The ability to reschedule or "shift" loads is particularly important as more solar and wind resources are added to the grid. At present, DSM applications compensate consumers based on their load reduction from a predefined baseline. However, studies have shown that the process of determining the baseline is prone to errors likely to cost more and result in other system imbalances that could propagate through various layers of power system control [250, 656, 657]. The industrial sector, however, provides many opportunities for load shifting that if scheduled and coordinated properly could improve DSM applications. Not only does load shifting increase demand flexibility, it also ensures that power quality is maintained [649]. That said, industrial processes that are not time constrained can be scheduled so that they can shift demand to help balance the electricity grid under certain demand constraints.

In the same way, constrained industrial processes could store intermediate power for use during periods of high demand. Currently, storage is being used in industry in the form of pumped hydro, compressed air, hydrogen, batteries, flywheels, superconducting magnetic energy storage, and super-capacitors [649] to support various applications. While storage increases flexibility, there is a decrease in efficiency, since transferring electricity to and from storage devices is not 100% efficient [649].

The concept of IoT is not new to industrial applications. IoT has been supporting industrial and manufacturing processes for over a decade now, with applications in business continuity management, anomaly detection as well as supply-chain management [658]. These IoT applications provide a control platform that could be used to carry out various DR functions. Obviously, equipment upgrades may be necessary to provide the connection and coordination capabilities for eIoT devices.

As discussed in Sect. 3.1.5, the main barrier to the adoption of eIoT lies in the cost of sensors, especially for small-scale consumers of electricity. However, industrial consumers are able to diffuse the energy cost management across various layers due to economies of scale for the required improvements. Additionally, most industries already monitor load data in real time and possess the necessary smart metering and data exchange equipment that will eventually reduce the investment cost in eIoT infrastructure [649]. These factors significantly simplify the adoption and application of eIoT in industrial energy-management applications. In fact, this makes the industrial consumer well suited for the use case discussed in Sect. 4.2.2. As stated in Sect. 3.2.4.6, IIoT and eIoT devices are overlapping and complementary rather than mutually exclusive. Therefore, the development of eIoT within industrial applications will go hand in hand with the current IIoT implementations.

4.4.2 Commercial Applications

The majority of electricity consumed in the USA goes to commercial and residential building energy systems [607]. According to the US Energy Information Administration (EIA), 77.46% of electricity generated in January 2018 was consumed by commercial and residential buildings [659]. Traditionally, commercial buildings have included hospitals, hotels, stores, and offices [660]. Commercial buildings come in a variety of sizes, and depending on the services the business provides, are less flexible to participate in DSM programs. For example, a hospital requires access to energy 24/7 and would be less willing to participate in an interruptible program [660].

In recent times, decabornization and sustainability concerns have driven most commercial enterprises to seek cleaner alternative sources of energy such as wind and solar. For some, this sustainable transition has been composed of a mix of energy efficiency measures and investment in renewable energy resources. Companies with large servers have shown great commitment to decarbonizing with some like Google vowing to source 100% of their energy from renewable sources by 2017 [661, 662]. As signatories of the Department of Energy's Better Buildings Initiative, various commercial corporations such as Walmart have committed to reduce over 20% of their energy consumption and as of 2018 they sourced approximately 28% of their total electricity from renewable sources [663].

eIoT is going to play a key role in ensuring grid reliability especially as more and more commercial enterprises assume the role of prosumers. In time, commercial enterprises such as Google and Walmart will become energy independent. Naturally, this implies more flexibility and freedom to directly participate in electricity wholesale markets. Without demand-side options that offer the equivalent (if not better) rewards for these corporations to trade and manage their energy, commercial enterprises will most certainly bypass utilities altogether. TE applications have an active role to play in creating platforms that engage commercial consumers at this level of the electric grid value chain. Most commercial buildings possess various eIoT capabilities in energy load management applications such as HVAC, and lighting [664]. For some commercial consumers such as grocery stores, sophisticated dynamic energy-management capabilities are necessary to maintain steady operation of their facilities. For example, department stores would prefer a positive pressure differential so that the air leakage happens outward instead of inward.

The implementation of eIoT for commercial customers will take many shapes depending on the services and type of the commercial entity. However, certain energy-management solutions such as smart metering, and price incentives could be used to advance the energy supply and control for these consumers. Net metering is expected to become a common practice in both commercial and residential buildings that want to be incorporated into utility planning and price structures. So far, 43 out of 50 US states have established net metering policies to support such engagements [665].

Unlike residential buildings, commercial building owners have a fixed decision-making structure that is most ideal for participation in demand-side programs. Usually, owners of commercial buildings are more sensitive to price incentives and most commonly have a single owner to expedite decision-making. Price incentives have encouraged the adoption of smart building management systems, where buildings are actively managing energy consumption. This means that building owners may soon become participants in real-time energy markets [666]. Requirements for this future development in energy management include automatic operational control capabilities for building subsystems, such as HVAC and lighting, and real-time communication with the grid [666].

Whether implementing DSM or individually engaging in energy pricing arbitrage, a variety of data coordination with system operators or utilities is necessary. Third parties such as energy aggregators and energy service companies are expected to use eIoT to improve energy-conservation savings [667]. This can be achieved through the installation of sensors that can monitor progress, and platforms for building management systems [668].

Recent studies have predicted a steady growth in the deployment of building energy-management systems (BEMS) for commercial as well as residential buildings. BEMS have attracted a lot of funding (more specifically $1.4B between 2000–2014) and are set to revolutionize the operations and control of commercial and residential buildings [669]. The US Department of Energy estimates that by 2020, BEMS applications will comprise 77% of the $2.14 billion US market [670, 671]. This implies an increase in sensors and internet-connected devices to manage and control building energy consumption.

Internet connectivity results in security concerns that are hopefully addressed by having cloud-hosted BEMS to relieve consumers of the need to secure their own devices or web-enabled services [672]. With time, the overall awareness and control for operators, consumers and owners will significantly improve and thus simplify the integration of renewable energy resources, energy storage, and electric vehicles. BEMS provide a key opportunity for TE-based frameworks to control, coordinate, and negotiate transactions among connected devices. For commercial customers, eIoT could be leveraged to reduce the overall energy consumption as well as improve the operation of these energy-intensive systems. As more commercial consumers adopt eIoT, they will be well placed to employ either of the two use cases described in Sect. 4.2.

4.4.3 Residential Applications

Another key TE application area is in the energy-management solutions for residential customers. Unlike commercial and industrial customers, residential consumers consume smaller loads and their energy decisions are very much comfort driven. In addition, heterogeneity in home infrastructures poses difficulties in smart energy management, since communication is required between the system, customer users, energy devices, and system operators [673]. Given the high cost of sensors, most residential customers may be reluctant to adopt new and improved sensors.

That said, the overall public opinion is shifting towards cleaner and more sustainable energy solutions. A significant percentage of the population is either producing their own electricity or opting to purchase only renewable energy.

As more residents become prosumers and sustainable, an increase in residential microgrids is expected. Naturally, TE platforms could assume the role of negotiating transactions for such microgrids as addressed in the first use case or through direct participation in wholesale energy markets in the second use case.

TE platforms for residential customers must provide an enhanced user experience and incentives that influence consumer behaviors. Consumer behaviors can be influenced through techniques such as real-time consumption monitoring, ubiquitous sensing, or contextual comparisons with neighbors [673]. However, this ubiquitous influence raises privacy and security concerns, which need to be carefully addressed especially if the data collected is to be used to gather insight on consumer behavior, build intelligent modeling tools, and support automatic grid operations [673].

As the number of smart devices in the home rises, platforms that allow interoperability among smart devices and provide a hub for consumers to customize their devices are necessary. So far, consumer apps such as Stringify and If This, Then That (IFTTT) offer options to connect similarly used devices and to create conditional statements for controlling remote devices, respectively. A key device in a residential home that is easily controlled through such applications is the smart thermostat.

As of September 2017, there were over two million smart thermostats, and a recent Navigant report predicts a four million rise by 2024 [608]. Several models have emerged for the control integration of smart thermostats including through utilities, by self-install, or in Bring Your Own Thermostat (BYOT) programs [608]. Another approach is the direct control of thermostats, which currently has an opt-out rate of 21% [608]. High opt-out rates as well as recruiting new customers, maintaining old customers, and device interoperability are key challenges [608] that still face the implementation of TE-based platforms in residential homes.

Given the high preference for comfort, privacy, and convenience, a single platform for DR and device control would work best for residential homes. Currently, utilities lack a single, all-encompassing program for DSM. About 16% of utilities offer water heater programs and 24% offer thermostat control programs, while only 9% provide behavioral programs to their residential customers [608]. However, due to reliability concerns, only half of these programs were actually called upon to provide DR in 2016 [608]. In addition, a wide range of DR options is necessary to enable more consumers to participate. As these programs evolve with real-time eIoT, DSM programs must shift from their current annual load shaping perspectives to less-than-a-minute perspectives for the provision of ancillary services. “Shape, Shift, Shed, Shimmy” is a framework built in California that incorporates timescales to better understand how to use DR.

Electric load from electric vehicles (EVs) is set to significantly increase residential loads requiring a framework to manage and control the power consumption of EVs. The power consumed by EVs is expected to reach 400 TWh annually by 2040 [608]. TE DR platforms for EVs are essential to manage this disruptive technology. Studies have shown that EVs could be used as flexible loads for the provision of ancillary services if managed properly. Currently, 19% of utilities are offering EV DR programs, while 79% are either planning or researching the DR potential of EVs [608].

Managed charging, either through utilities, load-balancing authorities, or aggregators, allows EVs to be used as storage to absorb excess renewable energy generation and smooth adverse effects on the net load [79–88]. From a technology point of view, TE platforms will require investments in infrastructure to support communication signals sent between a vehicle, other vehicles, home systems, and grid operators. Although behavioral programs could be used to affect charging times or quantity, technical integration is necessary to extract other potential grid service values in capacity, emergency load reduction, reserves, and renewable energy absorption [608]. All in all, electric vehicles offer great potential for DR that could be leveraged in a number of ways to support grid operations.

Residential TE applications stand to benefit from using behavioral DR to curb peaks, increase consumer participation and savings, and reduce the cost of engaging the large residential consumer base. Although implementation of these applications still faces many challenges, optimizing how a customer is contacted, determining how far in advance to notify a customer of an event, communicating why an event is called, how the program works and how a customer can participate, and strategically planning event calls will go a long way to ensure customer retention. Due to its analytical benefits, eIoT is likely to be instrumental in deploying behavioral demand response programs.