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The challenges of implementing transactive energy: A comparative analysis of experimental projects

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ABSTRACT

This study examines the results of field experiments of transactive energy systems (TESs) in order to identify challenges that occur with the integration of TESs with existing software, hardware, appliances, and customer practices. Three types of challenges, and potential responses and solutions, are identified for the implementation phase of TESs: systematic risk to existing building functions, lack of readiness of users and connected systems, and lack of competitiveness with existing demand-management systems and products.

1. Introduction

Under policy guidance that encourages improvements in load management, utilities have developed increasingly sophisticated demand-response programs to incentivize customers to align their electricity consumption patterns with the power supply. These programs include direct load control, in which customers allow the utilities access to power consumption sources such as heating and air-conditioning systems, and time-varying or time-of-use pricing, which relies on smart-meter technology that can monitor consumption in short-term time intervals. Moreover, demand response has been increasing its market share because it can help to stabilize electricity prices and to support load management. In current applications, transactive energy extends demand response programs by connecting the supply and demand for electricity through real-time transactions that include communication with the customer's appliances and/or distributed energy resources (DERs) (Pacific Northwest National Laboratory, 2020).

Much of the existing research on transactive energy systems (TESs) consists of formal models that draw on the methods of electrical engineering, software design, and economics. These studies focus on the important "internal" or technical challenges that come with designing systems that can achieve the goal of applying economic models to real-time, automated electricity transactions. However, when transactive energy is implemented in field experiments that approximate "real-world" conditions of future implementation, an additional set of "external" or implementation challenges is also encountered. This study reviews real-world experiments in TESs in the U.S. to identify leading external challenges and responses that can help to overcome the challenges.

2. Background

Although there is still some dispute over the definition of transactive energy (Kaufmann, 2018), one general definition is provided by the U.S. government's Pacific Northwest National Laboratory, which organized and supervised transactive experiments: TESs involve "smart devices that communicate with the energy market to make decisions on behalf of the consumer whether to pay higher energy costs during times when power use peaks or delay energy use to pay less and alleviate strain on the power grid" (Pacific Northwest National Laboratory, 2020). Another helpful characterization of transactive energy is that of Chen and Liu (2017:14), who describe seven central features: "distributed intelligent devices are controlled in real time; these devices are 'controlled' based on economic incentives rather than centralized commands; these devices exchange information and make transactions in a decentralized way to ensure scalability; these devices are automated to enable real-time transactions and control; these devices are controlled by their owners rather than power companies; transactive energy provides joint market and control functionality; and both supply and demand side resources are coordinated."

Transactive energy provides a variety of potential benefits such as grid reliability and demand management (Daneshvar et al., 2018; Holmberg et al., 2019; Rahimi and Ipakchi, 2012), the integration of renewable and distributed energy sources and general environmental

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benefits (Rahimi and Ipakchi, 2012; Vaahedi et al., 2017), efficient investment in local energy technologies (Holmberg and Bushby, 2018), and the potential for lower energy bills (Chen and Liu, 2017; Daneshvar et al., 2018; Widergren et al., 2014).

To assess the specific challenges associated with the implementation of TESs, research on real-time pricing, which is one of the key components of transactive energy, has provided some starting points. One group of challenges here falls under the broad category of user readiness. For example, researchers have identified the need for customer education, clear communication, and adequate feedback systems for users (Darby and McKenna, 2012:768). Another group of challenges is largely economic. For example, the benefits of real-time pricing often vary depending on household and energy consumption amount (Fernández et al., 2017; Nilsson et al., 2018), and benefits are greater for larger consumers than residential consumers (Fernández et al., 2017). Furthermore, real-time pricing increases transaction costs, which may delay wide-scale implementation (Salies, 2013).

We build on to this literature on real-time pricing and its challenges. However, TESs are a step beyond real-time pricing, and the challenges are not necessarily identical to those already identified for real-time pricing. Thus, this study addresses the following research question related to the implementation challenges of TESs: *What have real-world experiments with TESs identified as the leading types of implementation challenges?*

3. Case selection and background

3.1. Case selection

Transactive energy is not yet widely institutionalized, and to date its use outside the laboratory has mostly taken the form of experiments designed to assess how well the economic models work in field (or "real-world") settings. This study focuses on three different projects that have experimented with the implementation of transactive energy, all of which were located in the U.S.: GridWise Olympic Peninsula Project, AEP Ohio GridSMART Demonstration Project, and Pacific Northwest Smart Grid Demonstration Project. These three projects were chosen because they are considered the three leading projects supported by the U.S. Department of Energy initiative, which was implemented in cooperation with the Pacific Northwest National Laboratory (2020). Other projects in the U.S. (e.g., the Brooklyn Microgrid) were not yet completed.

There were detailed official reports of the projects, and they became the primary source of information. The documents were published by the project organizer and supported by the U.S. Department of Energy and Pacific Northwest National Laboratory. Additional background information was obtained by searching Web of Science and ProQuest under the terms "transactive energy" and "United States." For ProQuest, we used a filter for "full text only." This search yielded approximately 900 articles (Web of Science: 454; ProQuest: 438). Searches were also conducted for each project's names in Web of Science and ProQuest. The GridWise Olympic Peninsula Project resulted in 6 articles in ProQuest and 0 in Web of Science. The AEP Ohio GridSMART Demonstration Project had 12 articles in ProQuest and 1 article in Web of Science. Lastly, the Pacific Northwest Smart Grid Demonstration Project had 214 results in ProQuest and 6 results in Web of Science. Although this study used a number of different sources for background research, the articles beyond the official reports did not discuss the projects in enough depth to be able to contribute to the analysis of potential challenges of transactive energy projects. Therefore, this study has relied on official reports, which ranged from 157 to 835 pages in length.

3.2. Background on the three projects

The GridWise Olympic Peninsula Project (OPP) in Washington State started in late 2004 and was led by the Pacific Northwest National Laboratory (Hammerstrom et al., 2007). Data were collected between early 2006 and March 2007. This project developed pricing for 5-minute intervals based on projected costs to the utility at a regional level and the value of local resources to the feeder, but over time, the price also was adjusted based on customer responses. On the demand side, the following assets were in place: water pumps from a government facility that could control the level of a water reservoir, a commercial building equipped with diesel generators and a natural gas microturbine that enabled the building to be removed (islanded) from the grid, and 112 homes that could alter residential consumption of water heating and space heating (See Table 1).

The GridSMART Demonstration Project in Ohio ran from 2009 to 2013. The project was conducted in cooperation with the Pacific Northwest National Laboratory (2014), Battelle Memorial Institute (headquartered in Ohio and the manager of the Pacific Northwest National Laboratory), and the utility American Electric Power Ohio (AEP Ohio). The project was part of a rollout of smart meter implementation, and the portion of interest for transactive energy was called SMARTChoice^{SM}. The program provided real-time prices (5-minute intervals) from the utility based on the regional wholesale price and other factors. On the demand side, customers could set preferences for home energy consumption that affected the settings of their heating and air conditioning systems (Pacific Northwest National Laboratory, 2014:134).

The Pacific Northwest Smart Grid Demonstration (PNWSGD) Project was led by the Pacific Northwest National Laboratory. The project involved participation from 10 distribution utilities and the University of Washington campus, and the Bonneville Power Administration participated in the project. The project took place in the Western states of Idaho, Montana, Oregon, Washington, and Wyoming from 2010 to 2015, and it was the largest and most significant of the three test projects. Supply was defined as the load projection for the entire Bonneville Power Agency area, which was used to generate a price signal. Demand included both customer-owned distributed generation and management of consumption from residential and non-residential customers (Battelle Memorial Institute, 2015). Although the size of the demand-side electricity production and consumption was not large enough to affect the grid, it did provide an opportunity to experiment with transactive energy.

4. Results

Overall, participants reported that they were happy with the

Table 1
Description of Transactive Energy Projects.

Project Name	GridWise Olympic Peninsula Project	AEP Ohio GridSMART Demonstration Project	Pacific Northwest Smart Grid Demonstration Project
Demand-side resources	Municipal water pump, capacity to island commercial load, wind microturbine, and residential and commercial heating and air conditioning (Hammerstrom et al., 2007)	Residential thermostat control over heating and air conditioning system (Widergren et al., 2014).	Distributed generation and consumption from residential, commercial, and other customers (Hall, 2010).
Outcome	For grid stability and managing peak loads, the project was successful (Samson, 2009).	Reduction of short-term energy use with price increases and conversely increased energy use with price decreases (Widergren et al., 2014).	Contribution of the TES to load reduction, but some failures regarding technological limitations (Battelle Memorial Institute, 2015; Hall, 2010).

technology, but there were certain problems with transactive energy projects that need to be addressed. The analysis of the reports identified three types of implementation challenges: the generation of systematic risk or perceptions of risk, the readiness of users and connected systems, and the economic feasibility of the project.

4.1. GridWise Olympic Peninsula Project

The GridWise Olympic Peninsula Project involved the creation of a virtual feeder that treated the distributed-energy and demand-response resources as if they were located on the same feeder, and it created a "shadow market" that incentivized the use of the resources to reduce congestion. An account was created for each customer to credit and debit the contribution of the customer's energy devices to the real-time needs of the feeder. Participants had access to websites for managing their responses, which they could select on a scale from no response to maximum economy response. Additionally, participants could also override this setting at any time if they desired (Hammerstrom et al., 2007). Although the project found that customers responded to the pricing signals and that the system could relieve congestion on the feeder, the experiment also identified some challenges. The discussion is developed from the main official report, which examined the TES experiment with respect to three different types of customers: a government water department, a commercial business, and residential customers (ibid.).

4.1.1. Risk perceptions

The municipal water pumps were originally designed so that pumps came on when the reservoir level hit a designated threshold: one pump when the water level declined by one foot (30.5 cm), two pumps when it declined by two feet, and so on. Maintaining the water level at a specified threshold was important because of the emergency function that the reservoir had for the water department. The TES set up the station to bid higher prices as the water level declined. If the pump bid price did not exceed the market price, the pump or pumps did not turn on. Because the water department was not comfortable with having the water level fall by more than a few feet, the first settings were too conservative to have a measurable effect, but they were modified after subsequent negotiation. However, the water department frequently used the override option. The reluctance of the users indicated that although the system functioned technically, the TES generated a perception of supply risk to the water managers.

In the case of the commercial building, again, the TES worked technically, and the building was able to activate a diesel generator system and natural gas microturbine to reduce system demand. However, the successful operation of the TES generated risk that affected full implementation of the TES. The diesel generators could have been run economically for a longer period and therefore could have made a greater contribution to load management for the utility; however, their use was limited for environmental reasons. This restriction did not apply to the building's microturbine, which ran on natural gas. Another limitation for the diesel generators was that they could not cycle on and off frequently because doing so would create risk to the longevity of the machines because they were not designed for frequent on-off cycling. In short, two types of risk (environmental and machinery longevity) were identified for the TES.

For the residential portion of the experiment, perceptions of risk also created some implementation challenges. For those who participated in the project, systemic risk appeared to emerge in only one instance (Hammerstrom et al., 2007). At one point, the water-heater portion of the project encountered a control problem. The problem was rectified, but users disabled the systems and did not show willingness to use the system with aggressive control choices.

4.1.2. User and system readiness

For the residential portion, more significant challenges involved user and equipment readiness. It was difficult to recruit customers with large households, and the utility concluded, "Participant recruitment goals were not easily met and the recruitment period lasted longer than expected despite the possibility of financial rewards" (ibid.). This report and others pointed to the need for investments in educational materials and a sales force if such a project were to be implemented on more than a test basis; it also suggested that the economic incentives in the TES models (as developed in the tests) might be inadequate to motivate opt-in. The recruitment process also revealed that residents sometimes lacked basic knowledge about their appliances, such as whether their homes used gas or electric power (Hammerstrom et al., 2007:3.2). The project also discovered a range of technical barriers caused by the lack of readiness of the home technology for transactive energy. Examples included Internet connectivity problems; technical limitations of the previously installed smart meter for real-time, two-way communication; homes with multiple thermostats and thermostat location that did not enable Wi-Fi communication; lack of homes with a combined heating and air conditioning ventilating system due to the cool climate; and compatibility of the home equipment with the real-time pricing system.

4.1.3. Economic feasibility

The third main group of challenges was economic. On the customer side, the central comparison was between customers who selected the time-of-use arrangement versus real-time pricing. Whereas the TES system used real-time (five-minute interval) pricing, the alternative time-of-use pricing was based on off-peak, peak, and critical peak usage, and equipment could be set to respond to these prices. The experiment found that the average savings was greater for time-of-use pricing, but the median savings was higher for real-time pricing. The difference was caused by a small number of participants in the real-time group who chose the most economical setting. Furthermore, both real-time and time-of-use groups affected electricity consumption on the feeder, and the time-of-use group had the higher reduction of total energy consumption. Thus, from both the utility and consumer perspective, time-of-use could be favorable to real-time pricing. However, once the implementation challenges for real-time pricing are addressed, it should be able to achieve its potential even outside the range of large institutional customers.

A report from the Bonneville Power Administration also pointed out that from the utility perspective, "Overhead may be high to manage a large force of contractors at work over a wide geographic area" (Hammerstrom et al., 2007: 8.5). The feasibility of the program was also dependent on the use of the Internet, which could undergo outages, and on ongoing repairs of equipment failures. These limitations indicated that the use of transactive energy for residential customers might generate excessive overhead costs for the utility. In summary, from both the customer and utility side, the cost-benefit proposition was likely to be weak in comparison with an alternative time-of-use arrangement, at least in the current economic configuration.

4.2. AEP Ohio GridSMART Demonstration Project

The American Electric Power (AEP) Ohio GridSMART Demonstration Project (AEP Ohio) was part of a larger implementation of smart meters and testing of various new technologies and programs. Within this broader project, the SMARTChoice^{SM} program involved an experiment with transactive energy based on real-time pricing (five-minute intervals) for residential homes using their heating, ventilation, and air conditioning (HVAC) units. Customers could set the thermostat to indicate the minimum temperature, the maximum temperature, the preferred temperature, and a position along a slider bar between the extremes of more comfort or more savings. The system then automatically calculated the bid price. These preferences were aggregated within a circuit to form a demand curve to buy power, and the corresponding supply curve was developed to represent the utility's offer to sell power (Pacific Northwest National Laboratory, 2014: 133–134). Although the

SMARTChoice[SM] project was a success, in the sense that it reduced demand during peak load, the experiment nevertheless identified challenges. Although the report did not identify systemic risk as a problem, it did identify challenges based on user and technological readiness and economic feasibility.

4.2.1. User and system readiness

The project identified the need for additional customer service representatives to handle the high call volume, and the utility had to make multiple trips to homes to install the systems and to maintain their functionality (Pacific Northwest National Laboratory, 2014: 125, 167, 348). The implementation of the program required resources allocated to “education” and “buy-in” (ibid., 334). Moreover, on the utility side, the experiment showed that legacy back-office systems were not adequate to handle real-time pricing and would need to be updated (ibid., 167).

4.2.2. Economic feasibility

The identification of readiness barriers also indicated that implementation costs for the utility would be higher than originally envisioned if the TES were to be implemented at scale, and again the challenge of broader economic feasibility became salient. The combined cost of the installation of the system, its maintenance, and cellular communication “was too costly for the utility to absorb without some cost recovery mechanism such as in the tariff, through an additional rider, or by increasing the pricing in the tariff” (Pacific Northwest National Laboratory, 2014: 167). Likewise, on the customer side, a survey indicated overall high satisfaction, but it also found that 49% of the customers responded that the project resulted in either no change to their electricity bills or an increase (Pacific Northwest National Laboratory, 2014: 140). If consumer savings is expected to motivate participation in the system, the perception that there is little or no gain may reduce consumer willingness to participate. In contrast, other programs offered by the utility “had greater financial value to the consumer and utility” (ibid., 167).

4.3. Pacific Northwest Smart Grid Demonstration Project

This five-year, $178-million project involved 11 different sites of study. The main final report is a compilation of the different site reports and is paginated by section numbers (e.g., 14.5.2) rather than pages (Battelle Memorial Institute, 2015).

4.3.1. Risk perceptions

One type of frequently mentioned risk was that because many of the vendor companies were small and immature, the utilities could not count on vendors to remain in business throughout the duration of the project, and even vendors who remained in business often failed to deliver products or maintenance. Another form of systematic risk emerged (again) with connections to hot water heaters. Portland Energy noted that it was only able to recruit 20 residential customers on its demonstration feeder for the hot water project, and the load control devices for the heaters “were removed early when the utility became concerned about potential malfunction due to the safety of these devices” (Battelle Memorial Institute, 2015: 16.7). Some of the reports also mentioned the need to invest in greater security if the experiments were implemented at scale.

4.3.2. User and system readiness

Problems associated with the readiness of users and connected systems also appeared in the reports, but the focus was on technological readiness, and there was little information on user readiness. An exception was the report from the Northwestern Energy Services utility, which serves 400,000 customers. This report indicated that recruitment was difficult because customers were not familiar with smart-grid technology, and it was necessary to contract with a third-party installation company that had expertise with recruitment (Battelle Memorial Institute, 2015: 14.5.2). According to Robert Pratt, a program leader, "We needed to create a no-lose value proposition ensuring that residents and businesses understood that they had nothing to lose and could only gain from their participation" (Samson, 2009).

With respect to technological readiness, interoperability of communication systems presented a significant challenge; however, even where systems could communicate, the existing systems often were not technologically capable of being integrated into the TES. For example, some smart meters could not communicate in intervals of less than one day, and some utilities could not collect and process real-time data or provide real-time information on load outages (Battelle Memorial Institute, 2015: 2.39). Real-time pricing on the supply side was also complicated by lack of accessibility of real-time information, and the TES had to model the real-time supply price from seasonal trends for a simulated price. Because of the use of a simulated electricity supply price, the system could not be integrated with actual supply.

4.3.3. Economic feasibility

The project also identified a range of costs associated with project implementation, including software licenses, software upgrades and integration, overhead costs of maintenance, security costs, and installation labor (Battelle Memorial Institute, 2015: 4.2). In one case, a utility noted that it “badly underestimated staff time it would take to participate in PNWSGD” (13.6). Another utility concluded, “When in doubt, overestimate costs” (16.7). Several of the site reports indicated that residential customers reduced consumption minimally in comparison with the baseline, thus raising a question of cost effectiveness of the TESs for the utility. For example, in Pullman, Washington, the use of thermostats resulted in “very, very small conservation,” and the use of a home energy portal resulted in “small but statistically insignificant conservation” (7.13). Although effects on customer bills were not discussed, the minor levels of conservation suggested that the TES might not bring significant cost savings to customers.

5. Discussion

The TES experiments discussed here were a technical success in the sense that they showed that real-time, automated pricing could reduce customer demand to meet real-time changes in modeled electricity supply. However, the evaluation reports also revealed three main types challenges that occur with real-world implementation (See Table 2).

Table 2
Challenges Identified in the Three Projects.

Type of Challenge:	Olympic Peninsula:	AEP Ohio:	PNWSGD:
Generation of systemic risk	Risk to water-supply system; environmental air-quality risk from diesel generators; hot-water heater safety risk.		Vendor failures; hot-water heater safety risk; need for investments in security.
Lack of readiness of users and connected systems	Recruitment difficulties; need for education; Internet connectivity; domestic equipment not compatible with the TES.	Need for education and greater customer service; back-office systems not equipped to handle real-time pricing.	Recruitment difficulty; participant dropout rate; smart meter compatibility; system connections; back-office systems; real-time supply data.
Lack of economic feasibility	For customers and utilities, time-of-use pricing might be economically favorable.	Competition from other systems.	Staff time costs higher than anticipated; minimal reduction of residential consumption.

TESs generate perceptions that they create risks that were not intended by the designers of the systems. Even if the perceptions of risk are not valid from an engineering or equipment functionality perspective (for example, even if the control problem on the hot water heaters can be fixed or an override is permitted for the pump station); the perception of risk may remain for the users and may affect willingness to use the TES. Implementation of the projects at scale could also cause systematic risk to the utility if the system failures (such as vendor failures) were to cause the project to fail technologically or economically. There was no survey data on reasons for non-participation, but other reports on public concern with or opposition to smart meters indicated that perceptions of risk included perceived threats to privacy, security, and health (Hess, 2014).

With respect to the readiness of users and connected sociotechnical systems, the reports referred to the difficulties in recruiting participants and to the lack of knowledge about home energy systems. User readiness could improve with time and familiarity, but increased knowledge could also lead to increased concerns with privacy and security vulnerabilities. Assuming that users could be enrolled at scale after sufficient marketing and education, various problems of readiness also occurred with the technologies because the connecting systems often were not configured for real-time pricing.

With respect to economic feasibility, the experiments indicated that the demand for TESs might not be strong from the utilities due to high overhead costs for residential customers and that there may be a lack of strong economic incentives for the participants and in some cases even increases in monthly electricity bills. Together, the questions raise an overall issue of economic feasibility of the TESs when positioned in a competitive market of other demand-management systems such as more standard time-of-use systems that do not rely on real-time pricing.

It is possible that in the immediate future TESs will not be economically viable for residential customers with current technological limitations of connecting systems and current levels of user readiness and perceptions of risk. However, the cost-benefit proposition may be different for large commercial customers, which was also the case for real-time pricing (Fernández et al. 2017). Furthermore, with changes in the pricing incentives and improvements in education and technology, there is ongoing potential for TESs to achieve the important goals of energy efficiency, load management, and renewable-energy integration at scale. Moreover, in the long term the integration of renewable energy sources and distributed energy will benefit from sophisticated demand management that TESs could bring.

In summary, the three challenges identified in the TES experiments share some similarities with the challenges proposed by the real-time pricing literature (i.e., economic feasibility), but this study also points to some new challenges that also have emerged.

6. Conclusion

This study provides two main contributions to the literature on electricity policy. First, it provides an introduction and overview of transactive energy as a development of demand management, and it suggests some challenges that occur as TESs are implemented in field conditions that approximate future use. The study shows how this next generation of demand management involves the significant integration of software design and economic models to enable automated pricing where customers set general preferences that guide real-time price bids. TESs can also integrate customer-supplied reductions in energy consumption and increases in distributed generation to help solve problems of load management that have become complicated by the growth of distributed generation and renewable energy. Second, the study also shows that when implemented in field conditions, TESs face various challenges, which are especially evident for residential customers. By identifying these challenges, it may become possible to develop new strategies for more successful implementation of TESs.

The analysis of the different challenges provides the basis for several policy recommendations. These recommendations would include prior elimination of high-risk sites (e.g., water-supply control systems) in order to reduce the problem of user acceptance based on risk perceptions of system failure. To improve customer and technological readiness, it is important to evaluate back-office systems and existing smart-meter devices for compatibility prior to implementation and to provide substantial consumer awareness and listening tours. To reduce the overhead costs to the utility and general economic feasibility challenges, it would help to prioritize large commercial sites that are already familiar with demand-management programs. There should also be extensive prior evaluation of potential customer costs and benefits in comparison with existing demand-management programs, and economic incentives should be restructured accordingly. Additionally, various price responsive controls such as critical peak pricing should also be tested as well as real-time pricing and time-of-use pricing to determine the optimal pricing mechanism and to provide additional assessment of the challenges of user and system readiness.

Declaration of Competing Interest

The authors have no conflict of interest associated with this research.

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References

Battelle Memorial Institute, 2015. Pacific Northwest Smart Grid Demonstration Project Technology Performance Report Volume 1: Technology Performance. US Department of Energy. https://www.smartgrid.gov/document/Pacific_Northwest_Smart_Grid_Technology_Performance.html/ (accessed 1 April 2020).

Chen, S., Liu, C., 2017. From Demand Response to Transactive Energy: State of the Art. J. Mod. Power Syst. Clean Energy 5 (1), 10–19.

Daneshvar, M., Pesaran, M., Mohammadi-ivatloo, B., 2018. Transactive Energy Integration in Future Smart Rural Network Electrification. J. Clean. Prod. 190, 645–654.

Darby, S.J., McKenna, E., 2012. Social implications of residential demand response in cool temperate climates. Energy Policy 49, 759–769.

Fernández, J.M.R., Payán, M.B., Santos, J.M.R., García, Á.L.T., 2017. The voluntary price for the small consumer: real-time pricing in Spain. Energy Policy 102, 41–51.

Hall, L., 2010. Pacific Northwest Smart Grid Demonstration Project. Northwest Energy Efficiency Taskforce. https://www.nwcouncil.org/sites/default/files/2010_06_17_NEET_Presentation_Smart_Grid_614draft.pdf/ (accessed 1 April 2020).

Hammerstrom, H.D., Ambrosio, R., Brous, J., Carlon, T.A., Chassin, D.P., DeSteese, J.G., Guttromson, R.T., Horst, G.R., Järvegren, O.M., Kajfaz, R., Katipamula, S., Kiesling, L., Le, N.T., Michie, P., Oliver, T.V., Pratt, T.G., Thompson, S.E., Yao, M., 2007. Pacific Northwest GridWise Testbed Demonstration Projects Part I. Olympic Peninsula Project. US Department of Energy, Pacific Northwest National Laboratory. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-17167.pdf/ (accessed 1 April 2020).

Hess, D., 2014. Smart meters and public acceptance: comparative analysis and governance implications. Health Risk Soc. 16 (3), 243–258.

Holmberg, D., Bushby, S., 2018. NIST Transactive Energy Modeling a Simulation Challenge for the Smart Grid – Phase I Report. National Institute of Science and Technology. https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2019.pdf/ (accessed 1 April 2020).

Holmberg, D., Burns, M., Bushby, S., Gopstein, A., McDermott, T., Tang, Y., Huang, Q., Pratt, A., Ruth, M., Ding, F., Bichpuriya, Y., Rajagopal, N., Ilic, M., Jaddivada, R., Neema, H., 2019. NIST Transactive Energy Modeling and Simulation Challenge Phase II Final Report. National Institute of Science and Technology. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1900-603.pdf/ (accessed 1 April 2020).

Kaufmann, K., 2018. How Transactive Energy Will Create a More Participatory Grid. Smart Electric Power Alliance. https://sepapower.org/knowledge/how-transactive-energy-will-create-a-more-participatory-grid/ (accessed 1 April 2020).

Nilsson, A., Lazarevic, D., Brandt, N., Kordas, O., 2018. Household responsiveness to residential demand response strategies: results and policy implications from a Swedish field study. Energy Policy 122, 273–286.

Pacific Northwest National Laboratory, 2014. AEP Ohio gridSMART Demonstration Project: A Community Based Approach to Leading the Nation in Smart Energy Use. Final Technical Report. https://www.osti.gov/servlets/purl/1158902/ (accessed 1 April 2020).

Pacific Northwest National Laboratory, 2020. Transactive Energy & Control. https://bgintegration.pnnl.gov/transactivecontrol.asp/ (accessed 1 April 2020).

Rahimi, F.A., Ipakchi, A., 2012. Transactive Energy Techniques: Closing the Gap Between Wholesale and Retail Markets. Electricity J. 25 (8), 29–35.

Salies, E., 2013. Real-time pricing when some consumers resist in saving electricity. Energy Policy 59, 843–849.

Samson, T., 2009. PNNL proves just how smart a smart grid can be. InfoWorld.Com, April 22. https://www.infoworld.com/article/2632166/pnnl-proves-just-how-smart-a-smart-grid-can-be.html/ (accessed 1 April 2020).

Vaahedi, E., Nodehi, K., Heim, D., Rahimi, F., Ipakchi, A., 2017. The emerging transactive microgrid controller: illustrating its concept, functionality, and business case. IEEE Power Energy Mag. 15 (4), 80–87.

Widergren, S.E., Somani, A., Subbarao, K., Marinovici, C., Fuller, J.C., Hammerstrom, J. L., Chassin, D.P., 2014. AEP Ohio GridSMART Demonstration Project Real-Time Pricing Demonstration Analysis. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23192.pdf/ (accessed 1 April 2020).

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