Taming the wild edge of smart grid

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Taming the wild edge of smart grid – Lessons from transactive energy market deployments

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ABSTRACT

For two decades, transactive energy practitioners have been gaining experience with using market-based approaches to coordinate the flexible operation of customer electric assets. While the benefits anticipated from this distributed decision-making approach have been well explored, the practical aspects of implementing such systems and their suitability addressing real-world problems are just beginning to emerge. This report surveys 24 field-deployment programs and offers observations from interviews with experts instrumental in these deployments. The results of the survey and interviews reveal the diversity of designs and applications. They highlight the technical promise of the approaches as well as challenges with system integration, sustainable business strategy, and regulatory policy obstacles. Insights from the survey offer considerations to direct future effort and investment.

1. Introduction

The energy transition forces stakeholders in electricity production, delivery, and consumption to rethink the current top-down coordination of the electricity grids and wholesale markets and move towards more bottom-up coordination where energy resources in the distribution grid can participate on a local operational level as well as on a regional/wholesale level. Transactive Energy (TE) is an energy management approach combining (local) systems control with market-based interactions to realize more bottom-up coordination. Parties in a transactive energy system coordinate their actions through automated software agents who act on their behalf to negotiate transactions based on an exchange of value, where “value” acts as a key operational parameter GWAC (GWAC, 2019). In the past decade, many TE system studies have been conducted, illustrating the ability of small-scale consumers to participate in wholesale electricity markets (Jin et al., 2020) while also addressing local distribution operating issues (Pinto et al., 2021).

For example, in one study, a TE system requires market participants to send bids to the distributed system operator, placing a combined bid into day-ahead, intraday, and balancing markets (Farrokhseresht et al., 2020). Another example is a TE system that allows consumers to participate in the balancing markets via a local peer-to-peer market (Zhou et al., 2020). These studies, however, are based on simulations and models that cannot re-create real-life conditions and situations. To gain real-world, practical experience, the development of TE systems must cycle between research based on simulations and models to real-life field experiments. As the frameworks outlined in these simulation-based studies have gained traction, progress has been made in adopting transactive energy systems in a real-world context.

GridFlex Heeten is, for example, a field experiment in the Netherlands that demonstrated a TE system where consumers were able to provide flexibility and shift consumption/production by following dynamic network tariffs GridFlex (GridFlex, 2020). In the United States, the Brooklyn Microgrid project used blockchain technology to allow market participants to sell and buy solar energy within their neighborhood (Brooklyn, 2019). These field experiments demonstrate the possibilities of TE systems in real life and can therefore provide valuable information for future TE research.

However, to date, accessing information about field experiments has

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been challenging. Ideally, the findings from these programs would be made widely available, allowing researchers to apply new learning to future research, implementations, and methods. However, our literature review indicates that little information about field experiments is available, and what is available lacks important details. Furthermore, learned experiences such as methods for addressing practical deployment and operational challenges are left unknown. Additionally, many projects release information as a news bulletin, which is therefore, not peer-reviewed, and potentially untrustworthy.

Making this information available can support the development cycle between simulations and real-life progress. Field experiment information will help future research by providing significant insights into the performance of TE systems under real-life conditions that are difficult to recreate in a simulation. These insights could steer future research to further advance TE system designs. Naturally, these deployments are conducted by organizations that cannot always share all of the details as some information may involve intellectual property. However, collecting as much information as possible, verifying the details of this information where possible, and publishing the verified data in peer-reviewed documents is essential.

Some work has already been done to collect and publish information from field experiments. One study looked at the current state of nine local energy market experiments in German-speaking European countries and provided an analysis of and comparison of these experiments (Weinhardt et al., 2019). Another study reviews significant policies that drive microgrid development in the United States and discusses several methods and market interactions of seven field experiments (Feng et al., 2018). These papers; however, have a different or limited scope, do not provide the detailed information required for researchers, and do not provide the learned experiences of these field experiments.

This study aims to find detailed information on a broad range of TE field deployments and determine the lessons learned by uncovering detailed information on a broad range of TE field deployments. It involves uncovering detailed information on a broad range of TE field deployments, categorizing characteristics of these deployments, and speaking directly with people involved in developing and operating these TE systems. These interviews helped corroborate and clarify the published information and, importantly, filled unpublished gaps in deploying these systems. The contributions of this paper are: .

- A full literature review of completed and ongoing TE field deployments.
- Systematic gathering of implementation details of TE field deployments through a comprehensive questionnaire-based survey and follow-up interviews.
- Presentation of lessons learned and best-practice recommendations based on an analysis of the gathered TE field deployment details.

The process involves, first, a literature review to collect available information on TE field experiments from peer review and non-peer-reviewed sources. Second, identifying and contacting people involved in developing these TE systems to ask them to verify and provide additional information via a survey. Finally, the collected information is compared and analyzed using a strengths, weaknesses, opportunities, and threats (SWOT) analysis to identify and articulate the learned experiences. An step-by-step overview of the process can be found in Fig. 1 in Section 3.

2. Transactive energy landscape

Market-directed dispatch is not an new concept in the electricity sector. In both the United States and Europe, centralized markets have organized dispatch at the bulk generation and transmission system level for decades. However, consumers have been largely insulated from these price swings by system regulators. Although wholesale markets can inform real-time system operation decisions, these control signals generally remain centralized. An important characteristic of a TE system applied at the edges of the power system is the reliance on local intelligence and automation to first negotiate operational actions, then control local equipment based on the negotiated agreement.

This separation of concerns and responsibilities is a fundamental property of a TE system that enables scaling to great numbers of interacting parties. The approach decomposes the complex system problem into many subproblems that can be processed in parallel. However, like any community, effective interaction requires an organizational structure with well-defined roles and responsibilities and rules for engagement.

The electricity system is a complex socio-engineering structure. While the purpose and goals of power system operations are the same across the globe, the way communities and electric companies are organized vary greatly. Clarifying the roles and responsibilities of electric system stakeholders is important for designing TE systems and managing their operation.

2.1. Stakeholders

Many different entities are actively investigating and implementing new TE programs. Focusing on the distribution system and retail electricity level, these entities include:

- **Customers**: These are the end users of electricity and the reason for having electric power systems. Nearly all customers purchase, own, and operate the electric devices and systems used in their premises, although the arrangements can be complicated (such as own, lease, and sharing agreements with others). Many other entities claim to represent customers (e.g., distribution system utilities, aggregators, and policymakers). TE initiatives may interview customers, but there was no direct participation of customers in the survey.
- **Distribution system utilities**: These organizations have the responsibility to deliver power to retail customers and manage the distribution system. They may exist in many legal forms as part of larger electric utilities that also operate transmission and wholesale generation systems, local municipal electric providers, or rural co-operatives. They may also be public or private (regulated for-profit)

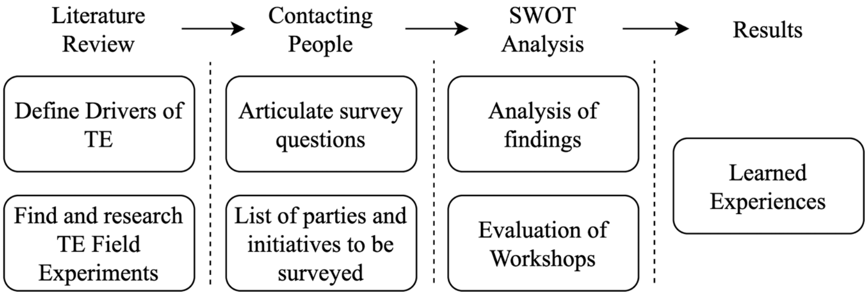

Fig. 1. The investigative process from literature review to the study's findings.

entities. Different aspects of distribution utility business include the following:

  - **Load serving entities**: This term refers to the distribution utility's responsibility to serve its customers by arranging for adequate supply and delivery mechanisms.
  - **Distribution system operations**: This aspect focuses on the operation of the distribution infrastructure to deliver electricity reliably and safely
  - **Retail market operators**: This area concentrates on the operation and maintenance of local energy market systems. While relatively new, they are an important function for TE systems. Survey examples: American Electric Power, Southern California Edison, Avista, Southern Company, Green Mountain Power, Ameren, Holy Cross Energy Cooperative, Alectra, Hydro Ottawa, Alliander, Centrica.
- **Aggregators**: Aggregators interact with customers and their electric equipment to present a combined package of electricity generation, storage, and end-use for interaction with distribution system utilities. Even if such a package is presented to a wholesale market, the coordination is still required with a distribution system utility for the safe and reliable operation of the system. For the sake of the survey, the function of aggregating customer resources was done with technology solution provider platforms; however, aggregators exist in many legal forms in practice.
- **Policymakers**: This stakeholder group includes regulators, legislatures, and government agencies. Survey examples: Public Utility Commission of Ohio, California Public Utility Commission, California Energy Commission, New York State Energy Research and Development Authority, Ontario Energy Board.
- **Technology solution providers and system integrators**: These organizations develop and deploy information and communications technology platforms for hosting TE systems. In some cases, they may operate these systems, but from the surveyed initiatives, they were operated as governed by the distribution system operator. Survey examples: Opus One Solutions, TeMIX, LO3, IBM.
- **Research institutions**: Universities, national laboratories, and other research organizations provide novel ideas and the scientific basis for TE system design. They may also play a role to test and evaluate the performance and impact of a TE initiative. Survey examples: Pacific Northwest National Laboratory, Oak Ridge National Laboratory, SLAC National Accelerator Laboratory, TNO, Eindhoven University of Technology, University of Toledo.

2.2. Drivers for adoption

As variable renewable resources from wind and solar energy become cost competitive, market operators will need new strategies for integrating these technologies. Subsequent social and legislative policy decisions to address climate change and sustainability issues further increase the use of variable renewable resources and electrification of energy-consuming processes such as transportation and building heating and cooling systems. These changes strain traditional forms of power system operation and further drive interest in unlocking the value of distributed resource flexibility.

Classical schemes of utility-directed demand response and load control run into challenges with energy service providers and customers alike. Distribution system utilities working within customers' premises assume responsibility and liabilities for equipment operation and safety. The cost to monitor and maintain the equipment is significant, and the regulatory model can make it difficult to target customer classes that may enhance program effectiveness. Customer challenges can include privacy concerns from others entering their premises, impact of controlling equipment at inopportune times, and data privacy and cybersecurity concerns for supporting the information flow with service providers. In addition, past programs have offered little choice when it came to the control equipment, equipment being controlled, and the customer preferences for control.

TE approaches are designed to be agnostic to the type of equipment participating in coordinating flexibility. They reflect the customer's preference for operation and sensitivity to economic factors in energy bills and technology purchases. By establishing agreements that describe the service to be performed (e.g., scheduling a quantity of energy use for a stated price), customers can choose the amount of flexibility they wish to offer at different times. They have the freedom to determine how to fulfill the agreement by selecting the equipment and control technologies to meet the stated performance of the service. The service requester need not know how the service was performed as long as the result can be verified by measurement. This performance-oriented aspect preserves the privacy of customer choice in technology and operation.

Aspects such as carbon intensity or other ecological concerns can also be incorporated into the incentives through sanctioned valuation structures in the system. For example, a sanctioned price per quantity of carbon dioxide or water usage can be layered into the valuation of electricity production.

The operational objectives for using this flexibility in managing the electric system are often reflected in the names of the programs utilities offer to customers. These objectives include the following: .

- **Peak shaving**: The objective is to reduce the draw of electricity from the system during high-use periods. These types of programs started out as a handful of critical peak times but can become more frequent as variability of supply and amount of resource flexibility increase. An outcome of these programs is to shift energy use to adjacent periods. Program designs need to be careful to avoid moving the peak problem to another time.
- **Flexibility for generation following**: The objective is near-term balancing with wholesale market. It can involve smoothing the load curve or shifting the load curve to follow inexpensive generation patterns, such as higher photovoltaic generation mid-day. A signal to accomplish this can come from the wholesale market.
- **Congestion management**: The objective is to economically relieve power flow bottlenecks that may occur from time to time. Bulk system flow constraints are reflected in locational marginal prices that drive response from flexible resources in a transactive system. Local constraints on distribution feeders from situations like high production from rooftop solar or simultaneous charging of electric vehicles can drive the use of flexibility to increase or reduce energy usage using transactive techniques.
- **Efficiency and loss reduction**: The objective is to operate the supply and delivery of energy in the electric system. At the bulk system level, locational marginal prices usually include incentives to manage losses as well as flow constraints. Distribution system losses can also be incorporated into transactive signals as markets seek system efficient operating points.

Drivers for evaluating TE concepts include the following:

- **Cost alignment and equitable allocation**: Customer resource flexibility programs design incentives that align with the costs of running the electric system and ensuring that customers' billing is fair. Transactive approaches allocate savings to those who provide system operational benefits. Project designs may be driven to investigate the effectiveness of transactive rates to fairly compensate customers in various demographic classes.
- **Proof of concept for flexibility coordination and multiple technologies integration**: Projects may be designed to evaluate a specific transactive approach to see the effectiveness of the rates, the communications technology, and the performance of the flexible resources themselves.
- **Customer behavior and acceptance**: As a relatively new approach with customer participation, TE program providers have many questions about customer acceptance. The customer experience

depends on many factors, including the program design, rates, range of customer preferences offered, and amount of flexibility available from customer equipment. Questions may cover the experience with registering and configuring customers, incentives to sign up, satisfaction with the trade-off of comfort versus economic savings, and simplicity of interaction (including ability to override or update operational settings). These can contribute to understanding overall customer satisfaction with the program, customer retention, and what could be done to improve the program.

3. Field projects reviewed

The projects identified in this paper represent an extensive (though not necessarily comprehensive) list of transactive field programs in Europe and North America. We include only projects that feature two way communication between end users, and the grid operator. Advanced demand response or real time pricing programs that exclusively feature top down communication were considered out of scope, and not included. However, some projects featured here experimented with these sorts of mechanisms alongside transactive controls. In order to ensure that the respondents would have learned experiences to report on, we limited our search to those who began testing no later than 2020. As a result, some more recent projects are absent from this analysis.

In order to develop a list of projects for inclusion, the authors began by identifying projects with which we had direct experience. This list was supplemented with a comprehensive review of both academic literature, as well as industry press releases, and a general, but thorough, internet search using drivers found in Section 2. We focused our search on projects in North American and Europe. However, we did include projects in Asia, Africa, and Australia when they were discovered organically through this process. After completing the literature review, we vetted our findings with industry colleagues, and asked them to recommend any additional projects for inclusion. Despite our efforts to present a comprehensive landscape of transactive energy field programs, some projects may have been inadvertently excluded.

Tables 1 and 2 summarize the field projects that were canvased along with their location, project dates, and a few key attributes. Projects highlighted in bold are those who responded to the survey. 24 projects covering three continents are represented in this analysis. A step-by-step overview of the process of the investigation can be found in Fig. 1.

3.1. European projects examples

Several European projects have experimented with transactive energy. These programs are quite diverse, ranging from peer-to-peer energy markets to market frameworks focused on alleviating congestion and involving both DSO and TSO. A few are highlighted below.

3.1.1. Quartierstrom Walenstadt

In the Quartierstrom project, a local energy market was piloted in the Swiss town of Walenstadt from 2019 to January 2020. It included 37 participating households, including 27 prosumers with a total combined PV capacity of 280 kW and a lithium-ion battery storage capacity of 80 kW h (Ableithner et al., 2019; Nicholas, 2020; PV Europe, 2020). Peer-to-peer trades of solar energy were made within the neighborhood using blockchain technology, enabling participants to buy and sell locally-produced solar electricity. The pilot aimed to determine the technical feasibility of a local market and to test the participation and willingness-to-pay of consumers/prosumers.

The local energy market allowed participants to change their electricity purchase and selling price. The market is decentralized on a mesh of prototypical smart meters, which were supplied to participants for this study. A price slider was implemented using the smart meter with which consumers and prosumers set a maximum purchasing and

Table 1

Organizations and Projects Responding to the Survey.

Project name	Abbreviation	Organization	Location	Start/End
Brooklyn Microgrid Project	**(BMP)**	**LO3**	**NY, USA**	**Apr. 16/ong.**
Buffalo DSP	**(BDSP)**	**National Grid**	**NY, USA**	**Dec. 16/Sep. 19**
Cornwall Local Energy Market	**(CLEM)**	**Trillema Consulting**	**UK**	**2017/2020**
D3A	(D3A)	Grid Singularity	Germany	Nov. 16/ong.
Electric Access System Enhancement	**(EASE)**	**Opus One**	**CA, USA**	**Jul. 20/ong.**
Energy Collective	(EC)	DTU	Denmark	Jul. 17/ong.
EV Blockchain	(EVB)	SWITCH Energy	ON, Canada	Nov. 20/Nov. 23
FUSION	**(FUSION)**	**SPEN**	**Scotland**	**2021/Dec. 23**
GOPACS	**(GOPACS)**	**Tennet/Alliander**	**The Netherlands**	**ongoing**
GridExchange	**(GE)**	**Alectra**	**ON, Canada**	**2018/2021**
GridFlex Heeten	**(GH)**	**ESCOZON)**	**The Netherlands**	**2017/2020**
Illinois Transactive Energy Marketplace	**(ITEM)**	**Opus One**	**IL, USA**	**Mar. 19/ong.**
InterFLEX	**(IF)**	**Enexis**	**The Netherlands**	**Jan. 17 /Dec. 19**
Isle au Haut	(IaH)	Introspective Systems	ME, USA	Jun. 18/ong.
LAMP	(LAMP)	Karlsruhe Insitute of Technology	Germany	Jun. 17/Dec. 19
LO3 Hedge System	**(LHS)**	**LO3**	**TX, USA**	**Apr. 18/ong.**
Micro Transactive Grid	**(MTG)**	**PNNL**	**WA, USA**	**Jul. 20/ong.**
Ohio GridSMART	**(OGS)**	**PNNL**	**OH, USA**	**Dec. 11/Fall. 13**
Olympic Peninsula Demonstration	**(OPD)**	**PNNL**	**WA, USA**	**Early 06/Mar. 07**
P2PQ	(P2PQ)	Wien Energie	Austria	Aug. 18/Aug. 20
Pacific Northwest Smart Grid Demonstration Project	**(PNSGDP)**	**PNNL**	**OR, WA, ID, WY & MT, USA**	**Dec. 09/Jun. 15**
Pebbles	(PEBBLES)	Pebbles Consortium	Germany	Mar. 18/Mar. 21
Quartierstrom	**(QS)**	**ETH Zurich**	**Switzerland**	**Oct. 18/Oct. 20**
RegHEE	**(RH)**	**TU. Munich**	**Germany**	**Mar. 19/Feb. 22**
Retail Autmoated Energy Systems	**(RATES)**	**TeMix**	**CA, USA**	**Jun. 16/Jun. 19**
Smart Neighborhood	**(SN)**	**ORNL**	**GA & AL, USA**	**Oct. 16/ong.**
SoLAR	(SLAR)		Germany	May. 18/Apr. 21
South Africa Blockchain Project	(SABP)	Cenfura	South Africa	Feb. 20/ong.
SSEN Transition	**(SSEN)**	**Opus One**	**Oxfordshire, UK**	**2021/ong.**
Tokyo Energy Project	(TEP)	Tokyo Tech	Japan	Apr. 21/ong.
Transactive Campus	**(TC)**	**Uni. of Toledo**	**OH, USA**	**Jan. 17/ong.**
Transactive Energy Service System	**(TESS)**	**SLAC**	**CO, USA**	**Oct. 19/ong.**
Vermont Green	**(VG)**	**LO3**	**VT, USA**	**Nov. 19/ong.**
VPP	**(VPP)**	**Uni. Wuppertal**	**Germany**	**Mar. 17/Feb. 22**

Table 2
Organizations and projects responding to the survey.

Abbreviation	Strategic orientation	Blockchain	Price formation mechanism	Value proposition	Costumer segment
(BMP)	Active program	yes	Order Book	Green energy trading	Res/Com
(BDSP)	Financial model develop/ demonstrate	no	Double auction	Ancillary services	Com
(CLEM)	Field Trial	yes	Double auction	Variability mitigation	Res/Com
(D3A)	Proof of Concept	yes	Tested pay as offered, double auction, market clearing price		Res
(EASE)	Simulation/Proof of concept	no	Order book	Ancillary services	Res
(EC)	Proof of Concept	yes	Consensus price matching		Res/Com/Ind
(EVB)	Proof of concept	yes		Self-sufficiency	Com
(FUSION)	Field Trial	no	Double auction	Reduce infrastructure upgrades	Res/Com
(GOPACS)	Active Program		Order book based on intraday congestion spread	Congestion management	Com/Ind
(GE)	Field trial	yes	Double auction	Reduce infrastructure upgrades	Res
(GH)	Field Trial	no	Optimization algorithm	Reduce infrastructure upgrades	Res
(ITEM)	Simulation/Field trial	yes	LMP plus distribution value	Improved DER integration	Com
(IF)	Field Trial	no	Single buyer auction	Reduce infrastructure upgrades	Com
(IaH)	Active program	no	Top-down scarcity pricing	Transmission deferral	Res
(LAMP)	Prototype Implementation	yes	Two-step merit order		
(LHS)	Active program	yes	Bilateral peer-to-peer	Market price hedge	Com
(MTG)	Value maximization experiment	no		Ancillary services	Com
(OGS)	Field trial	no	Double auction with prices based on PJM LMP	System efficiency, reduced congestion	Res
(OPD)	Proof of concept	no	Double auction	Distribution deferral, ancillary services	Res/Com/Ind
(P2PQ)	Field trial	yes			Res
(PNSGDP)	Simulation/Proof of concept	no	Double auction	Reliability improvements, ancillary services	Res/Com/Ind
(PEBBLES)	Proof of concept	yes	Merit order		Res
(QS)	Field trial	yes	Double auction		Res
(RH)	Proof of Concept	yes	Double auction		Res
(RATES)	Proof of concept	no	Order book against long-term subscriptions	efficient operations, lower costs	Res/Com
(SN)	Field trial	no	Iterative negotiation/consensus	Co-optimize cost, comfort, 0environment, reliability	Res
(SLAR)	Field trial				Res
(SABP)		yes		System reliability	Res
(SSEN)	Field Trial		Experimenting with different market mechanisms	Flexibility, Congestion management	Res/Com/Ind
(TEP)	Field trial	yes	Consensus price matching	Variability mitigation	
(TC)	Field trial	no	Testing double auction, peer-to-peer and hierarchical	Peak management, variability mitigation, ancillary services	Com
(TESS)	Field trial	yes	Double auction	Variability mitigation	Res
(VG)	Proof of concept	yes	Auctions with counter-offer option or set utility rate	Renewable integration	Res/Com
(VPP)	Proof of Concept		Optimization algorithm	Optimization of trading	Res/Ind

minimum selling price. The framework allowed users to indicate a willingness to purchase local electricity from neighbors on top of the purchase and sale prices. Every 15 min, the smart meter creates a bid based on the user's preferences and current electricity consumption. An order book collects the bid. In this market, bids are ordered from lower to higher sell prices and higher to lower buy prices. Trades are cleared and allocated on a 15-minute basis, and blockchain technology was used to validate transactions and settlements.

The local energy market was only accessible to participants. If energy demand could not be supplied locally, the energy was acquired via a utility company (Ableitner et al., 2020). During the project period, the purchase of locally produced solar power almost doubled. The 37 households covered 33 % of their electricity demand with solar power produced in the neighborhood. The participating households were actively engaged in the program and perceived the electricity market as green, local, and fair. Finally, in a questionnaire, users indicated that they support the general concept of P2P local energy markets and have recommended the concept to others.

3.1.2. *FUSION*

FUSION is a local market pilot for large consumers-producers that is currently ongoing in East Fife, Scotland. FUSION is based on the Universal Smart Energy Framework (USEF) (de Heer et al., 2021), a flexible market architecture that integrates prosumers, aggregators, and distribution system operators in the existing wholesale electricity markets. FUSION is focused on alleviating congestion by activating flexibility bids, reducing the need to upgrade grid infrastructure, and uses high-level forecasts of the SP network to inform congestion pricing (Mian and Versmissen, 2020;SP Energy Networks, 2020). The goal of the program is to extend the regular (green) operational mode of the power grid by managing capacity through local prosumer flexibility (the yellow regime), following the USEF operating regime definitions (de Heer et al., 2021).

Bids are based on the USEF framework and use USEF's D-programs as a bidding platform. D-programs are prognosis profiles that take grid topology into account and do not have to be balanced. These D-programs can be contractually arranged or can take on the form of free bids called FlexOrders. D-programs are determined iteratively. First, D-programs are submitted at 11:00 am the day before with a 30-minute settlement period. Next, the list of congestion points is determined. Finally, the D-programs are updated, and the process repeats.

FUSION does not allow participants to join the TSO's balancing markets but alleviates grid congestion by implementing the green and yellow operating regimes determined by USEF. The pilot focuses on larger parties too small to participate in the existing markets individually, rather than smaller residential customers.

3.1.3. GridFlex Heeten

GridFlex Heeten is a local energy market field experiment that operated from 2017 to 2020 in the Dutch town of Heeten GridFlex (GridFlex, 2020). The project included several project partners, including Dutch DSO Enexis and the University of Twente. As investing in grid infrastructure is expensive and the extra capacity often remains unused, the project's goal was to alleviate congestion by shifting consumption to moments with less consumption. The pilot included one community of 47 households, of which 100% participated in the pilot. The field experiment tested two different network tariff models and included sea-salt batteries in a real-life scenario.

The market managed congestion persuading participants to shift consumption with a congestion-based price signal. Two different network tariffs were used. One only varied the networks transport tariff (not the networks connection tariff), while the other set a fixed price of 20.5 cent per kWh on excess solar energy sold within the community. Participants received a tariff prediction for the next 24 h, determined by running simulations. The pilot also allowed excess energy to be stored in the sea-salt batteries.

Several important lessons learned from the pilot identified the need to involve partners from the start, the importance of testing in real-life (the simulation had to be tweaked during the pilot), and that participants' behavior can only be partially predicted. Finally, they found that altering transport tariffs alone will not profoundly adjust consumer behavior, though an effect was still noticeable, as transport tariffs are just a small portion of the energy bill of residential prosumers in the Netherlands.

3.2. North American project examples

Programs within North America are geographically disparate, covering both coasts, the Midwest, and the Southeast United States. They also span a variety of electricity market types, appearing in both deregulated ISO/RTO markets, vertically integrated utility markets, municipal and cooperative utilities, and on campus facilities. Most programs trade electricity that is physically delivered in scheduled periods. A few projects were designed to trade the financial value of energy in a time period (such as the use of energy from a rooftop photovoltaic site), but did not model or manage the actual flow of energy through the electrical infrastructure. The following sampling of surveyed projects highlight their variety.

3.2.1. RATES

The Retail Automated Transactive Energy System (RATES) project (Edward and Michel Kohanim, 2020) was supported by the California Energy Commission and hosted by Southern California Edison as the distribution system operator in the area deployed. The project received California Public Utility Commission approval for an experimental dynamic pricing tariff that included a paid subscription to an energy load shape for each customer. Roughly 100 residential homes connected to a distribution substation participated. The pilot was operational for about a year with project updates to technology and customer software agent logic continually being improved.

The novel subscription approach established a nominal energy pricing point against which customers bid to buy or sell energy in hourly, 15, and 5-minute markets. This protected customers from high volatility exposure and allowed the distribution operator to layer distribution delivery costs and congestion (scarcity) prices on top of the locational marginal price for energy rate established by the system operator. These price changes allow intelligent device software agents to determine operational trajectories to improve their owner's financial position against their purchased load shape. Software agents were developed for HVAC units, batteries, electric vehicle charging, and pool pumps.

The RATES project demonstrated effective operation of flexible resources in response to the dynamic pricing situations. Customer billing impacts appear to vary greatly based upon the amount of flexible resources available, the time of the year, and the behavior of their non-responsive loads to their subscription. The performance of the flexibility device software agents to react beneficially to the systemic price signals was well demonstrated. Lessons learned included the need for more robust communication interfaces (a frequently expressed issue), the need to engage greater numbers and types of flexible equipment, and a fully instituted dynamic pricing tariff for customers to truly engage and invest in technology appropriately.

3.2.2. gridSMART RTP-da

American Electric Power, Ohio (AEP), a mid-west utility, demonstrated the use of innovative smart grid technologies in their gridSMART-TM program from 2011 to 2014 (Widergren et al., 2014). The real-time pricing double auction (RTP-da) project implemented a second generation transactive design based on the Olympic Peninsula project (Hammerstrom et al., 2007). AEP selected four residential distribution circuits with homes equipped with HVAC units to study the the effectiveness of using the resource flexibility to respond to regional price changes and distribution capacity constraints. Savings from shifting or avoiding high prices or mitigating distribution capacity issues was be shared with customers through a real-time tariff reviewed and approved by the Public Utilities Commission of Ohio.

The tariff was a function of the wholesale locational marginal price of energy in 5 min intervals with retail adders for distribution delivery infrastructure and management. Having regulatory interest at the onset of the project was important. To gain regulatory approval of the tariff required its design demonstrate fairness, equity, and customer protections.

The technical approach used cellular communications between distribution operations and a home management function in each of about 200 homes that were equipped with smart thermostats that displayed the real-time price as well as smart meters to measure and communicate the energy used in the market intervals. HVAC agents in the homes exchanged price/quantity bids curves every 5-minutes for double-auction price clearing on each circuit.

Results indicated the overall responsiveness of the aggregation of the population of resources, while corroborating the breadth of reaction from individual devices based on building status and customer preference. Household bills analysis indicated an average 5 % reduction compared to a control group. Customer surveys indicated very good satisfaction.

3.2.3. University of Toledo transactive campus

The transactive campus project (Raker, 2022) at the University of Toledo, a mid-west university, started in 2017 and was ongoing in 2022. It emphasizes flexible and efficient operation of automated buildings in a campus environment. This allows researchers to experiment with the flexibility in complex building systems that deliver heating, cooling, ventilation, and lighting services to the occupants. A battery energy system (125 kW/130 kW h) and a 1 MW photovoltaic solar array were also integrated in the TE system.

Operational scenarios were experimentally tested on the campus. The scenarios included utility to campus TE markets for addressing system peaks, as well as TE markets within buildings that coordinated device agents' flexibility in heating-cooling zones. The device agents exchange a time series of price/quantity energy bids with their electrical neighbor agents and iterate until prices and quantities delivered converge across the network. Flow constraints of each connection are honored in the process.

Key to successful deployment, the facility manager supports the project objectives of applying better building controls to reduce energy expenses to the campus. Ensuring that the communications message bus platform addressed cybersecurity concerns was important for buy-in.

The integration with existing building control technology is problematic. In some cases, building control systems need to be upgraded for adequate control of devices. Different building communications protocols (e.g., BACnet and LonWorks) are used by the various building automation system that need to be integrated. Underscoring interoperability issues is the significant effort needed to decipher tables of control and status points mapped to the equipment unique to each building automation system.

The first phase of project was installed in 8 buildings. The technology is migrating to 5 buildings on the main university campus, which provides a richer set of building loads and operational situations.

3.3. Comparison between North American and European implementations

The following sections describe some insights on similarities and differences between North American and European experiences with TE deployments.

3.3.1. Program design and development

Field projects for TE have been envisioned in the United States and Europe since the early 2000s. The Olympic Peninsula Demonstration Project is generally regarded as the first TE program deployed in the field. Projects in Europe may have taken a bit longer to come into effect. However, potentially due to their regulatory structure and the prevalence of distribution system operators, European projects quickly were able to establish strong business frameworks, while many North American projects remain in a pilot or research stage. Though larger-scale TE programs are beginning to gain a foothold in the US, European programs like GOPACs have been able to integrate themselves into standard utility operations more efficiently.

3.3.2. Regulatory and market structures

The overarching regulatory and market structures also differ substantially between and within the two regions. The EU has an almost total separation of generation, transmission, distribution, and retail companies, with retail competition being common (Prettico et al., 2021). Distribution system operators (DSOs) ensure the reliability of the distribution system and are a key investor and operator of smart grid technology. The unique roll of these entities provides a relatively straightforward pathway for TE programs to expand.

The United States, on the other hand, does not see the same degree of market restructuring. While wholesale and retail markets are separately regulated in many states, others are vertically integrated in one regulated framework. In most cases, the retail utility owns and operates the distribution system. In vertically integrated states, the utility controls all aspects of the electricity system: generation, transmission, distribution, and retail sales. The rules set by regulators may incentivize distribution company capital investments or the selection of certain technologies.

While utilities of all varieties have developed TE programs, they may not possess the same organizational incentives that a stand-alone DSO may have to optimize the use of the distribution system seeking reduced customer costs or supporting retail competition. A DSO may have greater appreciation for the agnostic nature of technology solutions inherent in the exchange of value signals in a TE system. This perspective can lead to expanding TE program deployments. However, as Fig. 2 shows, pure electricity retailers are growing, especially in states like Texas and the Northeast EIA (EIA, 2018), potentially providing a mechanism for DSOs to grow in popularity in the United States.

3.3.3. Forcing functions - Grid operations challenges

Combating climate change through decarbonization of the energy system and electrification of transportation and industrial processes are similar policy drivers in Europe, the United States, and globally. Both Europe and the United States experience regionally different drivers for integrating flexibility resources with system operations. For example, increases in the type of renewable generation resources correlate with beneficial wind and solar conditions.

Time will tell, but as of this writing, the desire to quickly reduce the reliance of European countries on Russian fossil fuels may bring more attention to speeding the implementation of renewable resources and integrating flexible resources including storage to respond to variable generation and delivery constraints. While energy prices are rising in the United States, energy remains relatively inexpensive compared with Europe. The economic savings drivers for integrating flexibility resources may therefore appear greater in Europe than many parts of the United States.

4. Survey methodology

The effort to solicit feedback from project participants we used a survey followed by individual interviews to clarify and better characterize the approaches.

4.1. Survey design

Following a literature review, we developed a survey process to begin to fill the knowledge gap surrounding TE programs. A representative from each project was identified and sent a survey, which they were asked to complete. We sent a total of 30 surveys and received 24 total responses. We received some response from 80 % of identified projects (some responses covered multiple projects). In total, 24 deployments are covered in this survey – 10 in Europe, 13 in North America, and one in Australia.

Survey questions revolved around practical aspects of program management and program design. The project team's primary interests were identifying challenges and successes for TE programs, and common

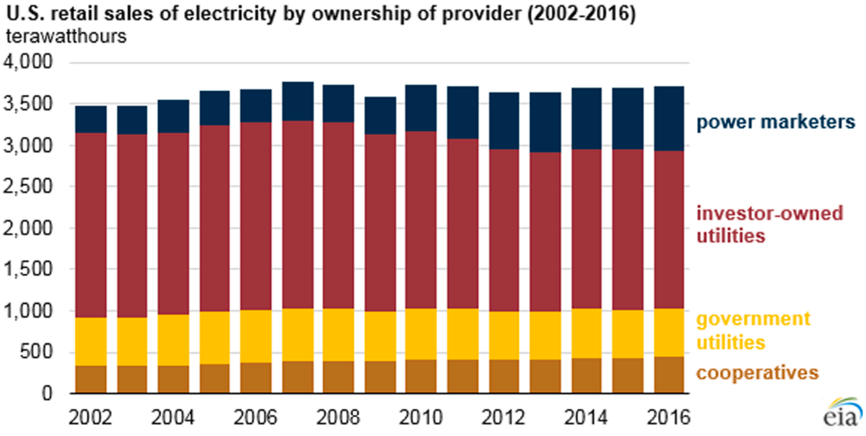

Fig. 2. Growth of Retail Electricity Providers (Power Marketeers) in the United States (EIA 2018).

threads and divergences between projects. Though questions were primarily backward looking and specific to the program in question, we also asked about ways to position TE programs for the long term, and industry-wide challenges that researchers could address.

The survey was delivered via Survey Monkey. The team worked to identify a point of contact for each pilot uncovered by our literature review, using personal networks, referrals, and online searches. We generally provided one survey per organization or pilot, though some organizations submitted a single survey with notation as to project specific replies (responding organizations, and their associated projects are listed in Table 1). The survey included 30 questions and spanned six sections (Programmatic, Technology, Regulatory, Economics, Business, and Respondent Information). The survey questions are provided in Appendix A. The survey included a mix of open ended and multiple-choice questions, depending on the context. Respondents were not required to complete each question, and some responses automatically generated follow ups. For example, if a respondent answered “yes” to the question “is blockchain being incorporated into your program,” they were asked the question “what features of a blockchain platform are being used?”.

In general, responses and completion rates were good, and respondents did not exhibit confusion about the context or questions themselves. Ninety one percent of respondents completed the survey, and only 24 questions in aggregate were skipped (an average rate of slightly over one question per respondent). Despite this, some responses did require follow up or clarification. For example, some respondents indicated that they were unfamiliar with price formation terms. Issues like these were clarified through interviews.

4.2. Interviews

In addition to the survey process, the authors also conducted structured interviews with a subset of respondents. The goal of the interview process was twofold. First, we aimed to clarify any ambiguities and correct potential errors found in the individual’s survey responses. Next, we looked for opportunities to draw out insight on key points raised in the survey. We paid particular attention to strategies for scaling their program, partnering organizations, and market readiness. We also asked for more general opinions on technologies like blockchain, and best practices and lessons learned. We completed a total of seven hour-long interviews, which covered the majority of the North American projects. All interviewees were also provided the opportunity to comment on early versions of this report, and correct any content.

4.3. Workshop

Many items in the SWOT analysis originated from a workshop with a diverse group of experts from key stakeholders in the electricity system. The participating matter experts represented two system operators, an energy regulatory body, an energy trade & supply company, an energy research & innovation funding body and a research & education institute. In the workshop, preliminary outcomes of the survey were presented and discussed, and a joint SWOT analysis was performed. The analysis focused both on improved transactive participation in wholesale and ancillary-service markets and on improved transactive coordination in distribution networks.

5. Survey results

The following sections summarize the results of the survey, the implications for the future of TE deployments, and a discussion of differences in the European and North American field projects.

The survey responses find that TE implementations are diverse, working toward different goals, addressing different markets, and using different technologies. In general, these deployments see TE as a broad coordination approach able to provide a number of distinct value streams, rather than focusing on one or two operating strategies. Though not universal, many of these implementations aimed to prove out TE as a concept, rather than use transactive systems to solve specific challenges within the energy sector. In general, respondents cited challenges related to the regulatory situation, technology standards, and business models. However, most respondents rated their project as successful, and found that the software agents behaved as expected in the transactive environment.

5.1. Technology and participation

The transactive projects we evaluated used a wide variety of technologies to achieve a number of operational objectives. Most projects used at least three different DERs throughout the project period. As Fig. 3 shows, virtually all respondents reported that solar PV was used in their program, while most used batteries and heating, ventilation, and air conditioning (HVAC) load, and many used vehicle charging systems. Most programs also treated load and generation similarly (i.e., the only difference being a sign change), with only 14 % of respondents indicating that they were treated differently. In terms of participants, all but four of our respondents indicated that their programs were targeting residential customers. Roughly half included commercial customers, while a much smaller amount (23 %) included industrial customers in their programs.

In terms of operational objectives, most respondents indicated that their projects aim to address several challenges. Most programs aimed to improve system operations flexibility and manage network congestion, which were seen as pathways to create long-term value (Fig. 4 and Fig. 5). In particular, these operational objectives were being deployed in order to add more DERs to the system, limit the need for future infrastructure investment, and improve resilience. Operators (driven by investigative research) were also extremely interested in proving out TE as a concept. Interestingly, respondents broadly indicated that their primary concerns were technical, not economic. This may be related to some of the reasons why programs have cited issues with longevity. Though proving that transactive systems technically can work in real world environments is essential to their success, ultimately these programs have to demonstrate economic value to justify their deployment. Indeed, GOPACS (a platform for coordinating DER flexibility), which has transitioned from a pilot to one of the largest active transactive programs in the world, has cited using “market-pull thinking, instead of technology push” thinking as a key factor for its success GOPACS (GOPACS, 2022).

Finally, several questions in the survey and during the interview process dealt with the use of blockchain. A third of the respondents indicated that their program used blockchain technologies, though use of its featured differed considerably. Notably, very few programs used blockchain for bids, settlement, and price formation. The most common way that blockchain technologies were used were as a public record of a finalized transaction. In interviews, some respondents indicated that they began developing their program with blockchain in mind but

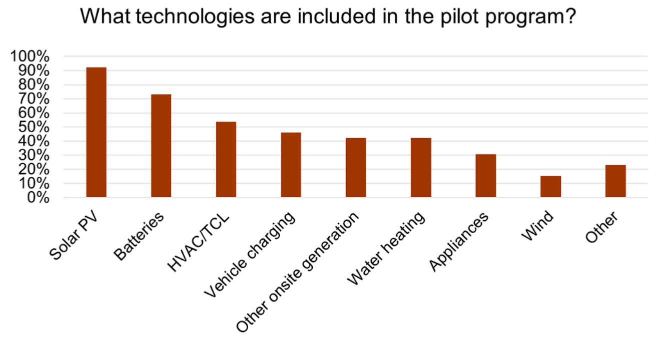

Fig. 3. Technologies Used in TE Programs.

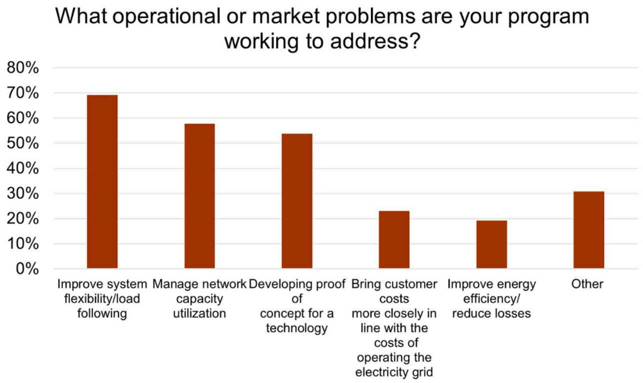

Fig. 4. Technologies Used in TE Programs.

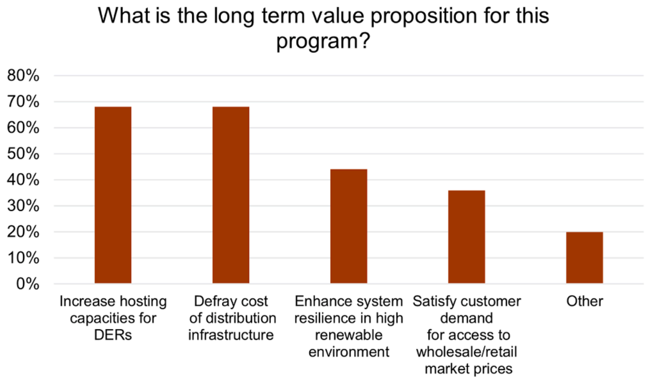

Fig. 5. Technologies Used in TE Programs.

transitioned away from it over time. Difficulty hiring technical staff and the amount of computer resources required to support the proof of work process were cited as challenges to blockchain deployment.

5.2. *Market design and business models*

As previously mentioned, most of the programs we analyzed were focused on technical efficiencies, rather than economic efficiencies. However, a number of programs experimented with different market and dispatch strategies. Fig. 6 shows the price forming mechanisms used in each of the programs. This refers to the way the market is designed that results in a price for the traded quantity of electricity - a transaction. Appendix C provides an overview of these mechanisms.

Several respondents expressed confusion regarding these market design options. Many of the responses falling into the “other” category were clarified and reclassified. The survey focused on transactive markets that result in an exchange of a quantity of electricity for a price as opposed to price-reactive programs that broadcast electricity prices to participating customer sites with the expectation of a change in consumption or production. One program claimed to experiment with several price forming mechanisms but did not express a clear preference for one method or another.

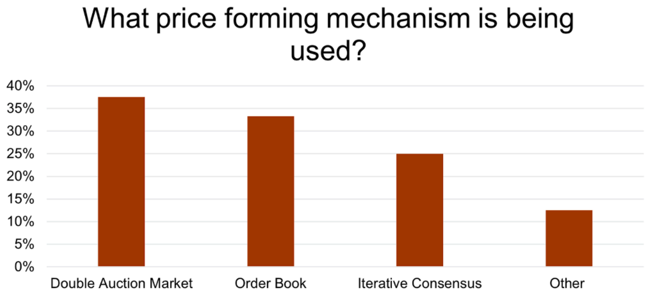

Fig. 6. Technologies Used in TE Programs.

Generally, these markets transact scheduled energy, though a small subset of projects traded ancillary services and power capacity. As Fig. 4 shows, scheduling energy was used to meet several different operational objectives. Relatively few respondents indicated that they had identified a single operational objective for their project and generally were relying on multiple value streams.

Respondents also had difficulty estimating the costs and level of effort required to scale the program, with some reporting that their program could be scaled with no additional investment, and other estimates exceeding thousands of dollars per customer. However, when we solicited strategies for scaling TE programs to a broader market in the survey, most respondents suggested targeting regulatory and rate design changes or improved standards for device communication, rather than market or business model improvements.

The long-term use of TE markets was also a point of divergence that became apparent during our interview process, with some projects indicating that the transactive market design was their preferred option long term, while others began transitioning to programs that feature more centralized dispatch strategies. This was largely due to feedback from their customer base (primarily investor-owned utilities), who expressed a preference for direct control.

5.3. *Customer participation*

Despite notable challenges, the respondents claimed that program participants responded well to the transactive environment. As Fig. 7 shows, few customers habitually override the program controls. In general, participant engagement was rated as very high, with only one respondent indicating that engagement dropped over time. Further, the project reporting the highest override rate was a very early pilot that reported other operational and programmatic challenges. While customer participation was strong, the projects relied on device automation to facilitate the transactive market. Despite these potential caveats, the fact that customers did not override controls and had strong levels of engagement is highly encouraging for the future of TE.

Consumers in general participated as expected by the program operators, though many stressed that clear and effective communication was essential. Fig. 8 shows how respondents rated consumer engagement in their programs, with only 15% indicating the customers did not respond as anticipated to the price signals. Despite this, many respondents indicated that there were challenges with customer acquisition and education.

Customer acquisition costs and incentives in general were high, with some programs paying upwards of $750 to sign on a new customer. Many also cited challenges in communicating TE to potential customers. Both TE in the abstract, and the reasons why their devices were dispatched were often unfamiliar to residential customers and required clear and concise communication from program managers. Some of the

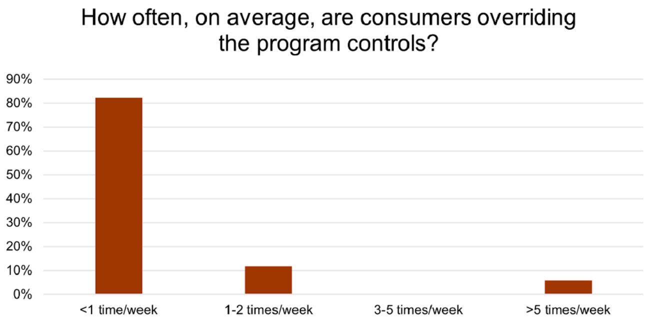

Fig. 7. Technologies Used in TE Programs.

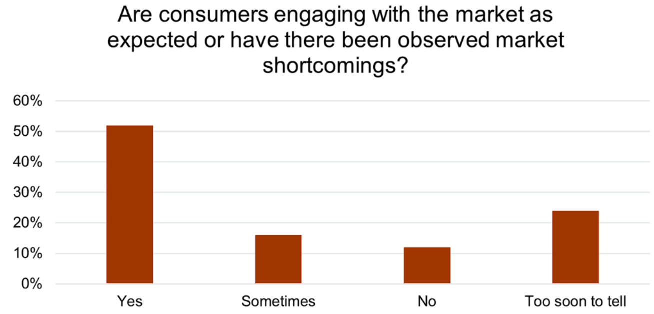

Fig. 8. Technologies Used in TE Programs.

more successful programs highlighted the importance of customer education and having dedicated support staff to field customer inquiries. Interview discussions indicated that the pilot nature of most of the projects surveyed contributed to the high customer acquisition costs. Full-scale rollouts would likely address many of these issues more efficiently.

6. Implications- SWOT analysis

The results of our survey, interviews, and workshop show that TE is in a growing, but challenging stage of development. Having proven itself as a technically viable concept, TE deployment initiatives must now grow and mature to become competitive approaches in the flexibility integration marketplace. The following SWOT (strengths, weaknesses, opportunities, and threats) analysis shows the ways that TE could develop in both the United States and Europe. In general, this analysis did not find a dominant driving value proposition for TE in the near term. Scaling TE deployments will require a more nuanced understanding of flexibility marketplace challenges and opportunities.

6.1. Strengths

A key TE field experience highlight was that the software control agents largely behaved as anticipated in the transactive environment. The transactive systems were able to coordinate the flexibility from several different types of equipment. Customer participation was rated as strong, and few opt-outs occurred. Program managers relied on automation to achieve these high rates of performance. If a goal of a pilot was to understand if customers and their resources will function appropriately in a transactive environment, then many would be rated as successful. This narrative can be useful as new programs arise, and existing programs can serve as models and best practices for consumer engagements.

The programs that have successfully expanded beyond the pilot stage also demonstrate the strength of transactive systems. Most of these systems were located in Europe, whereas few active and full-scale programs were sited in the United States. The GOPACS project in the Netherlands, for example, has over 500 participating software agents representing large-scale energy consumers and producers in the grid - and traded over 140,000 MW h in 2021 (GOPACS, 2022). This energy has been coordinated successfully to limit network congestion on higher voltage levels. For at least this specific use case, TE significantly alleviated adverse grid conditions, potentially at a lower cost than network upgrades. However, in most cases, it is used as a temporary option while grid expansion is prepared.

Greater consumer privacy was also cited as a strength, and many respondents indicated their programs provided substantial opportunities for consumers to control access to their data. Though less present in our survey and interview process, other consumer-focused aspects of TE are clear strengths. Consumers have a greater degree of autonomy then they would have under a direct control or demand response program. Similarly, the decentralized data management systems that keep more customer data local and support consumer privacy can also help protect the electricity system from cyber attacks (Zhang et al., 2019). Because less information is exchanged across nodes, a smaller security surface is needed to protect the system.

Likewise, transactive protocols can scale linearly. Once a program is established, the communication and processing infrastructure can be expanded on a customer-by-customer basis (Kok, 2013). This stands in stark contrast to central optimization approaches, which have higher communications bandwidth and upfront configuration and maintenance costs. Finally, transactive rates can be modified to incorporate policy goals. As an example, carbon fees can be attached to fossil fuel-based power plants, while incentives can be provided to low carbon resources.

6.2. Weaknesses

In US deployments, in particular, respondents identified regulation and standards related to interoperability as major challenges. Correcting and managing these issues can help transactive programs expand. In terms of interoperability, many cited issues with behind-the-meter device coordination, as well as analyzing meter data on short time intervals. Difficulty coordinating with vendors and understanding which communication protocols were used by each device were common. Many expressed a desire for clear and greater harmonization between standards that could coordinate across different devices, noting that such technical standards could reduce integration and administrative costs and make it easier to sign on new customers. High customer acquisition costs, in general, were cited as a concern, though this is not unique to TE programs, and is common for novel customer participation programs.

Regulations were also cited as a key barrier, with many respondents comparing the US regulatory environment unfavorably to that of Europe. Resistance to real-time pricing and an uncertain role for non-wires alternatives were commonly cited regulatory barriers. The presence of independent distribution system operators (which are more common in Europe) were likewise seen as an enabling factor for TE. In interviews, many stressed that greater education on the benefits of real-time pricing for engaging flexible energy use with appropriate protections for customers could help alleviate these issues. The Texas blackouts of 2021, which resulted in some customers on real-time pricing plans receiving monthly bills in excess of $9000 (Ivanova, 2021), were front of mind of some respondents. Showing how transactive markets can address grid operational concerns more effectively while protecting customers from extreme price events could help ease some of this regulatory concern.

In Europe, regulatory pathways for non-wires alternatives have also been perceived as a boon to TE. The United Kingdom, for example, has taken considerable steps to create markets for flexibility products, and pushed utilities to consider non-wires alternatives more aggressively than the US (Ofgem, 2017). Whereas in the US, non-wires alternatives are denied roughly 60% of the time in favor of infrastructure investment (Wood Mackensie, 2020). Regulatory support to weigh these investments more carefully in cost-benefit analyses could also be a boon for US TE projects.

Respondents also acknowledged that some decision-makers expressed discomfort with distributed decision-making. As an inherently stochastic process, TE systems can be perceived to have greater uncertainty than direct-control programs. Increasing the familiarity of these sorts of processes could help improve decision-makers' comfort-level with TE, as would increasing the number of transactive programs. Likewise, some stakeholders acknowledged concerns regarding unintended consequences from an increased reliance on flexible resources. Expanding these sorts of programs at a larger scale, could help expose potential issues and solutions stemming from an increasingly flexible system.

6.3. Opportunities

The key opportunities for TE are described in greater detail in Section 2.2. This confluence of technology trends is helping to create a growing market for TE. The growth in renewable energy, distributed flexibility resources, and smart technology make the case for coordinating distributed resources using TE more apparent. With these trends, distribution utilities desire for more operational flexibility is expected to grow. The growth in transactive programs themselves represents an opportunity. Program operators can learn from their peers and develop best practices for program design. Such collaborations can also help to standardize operational strategies and identify strong methods for communicating the benefits of TE. That said, advocates for TE must be sure to align their programs within key market needs, and ensure that past mistakes are not repeated, to maximize their potential for success.

The growth of dynamic rates also provides an opportunity for TE. As many regulators and utilities become comfortable with simpler dynamic rate structures, like time of use or critical peak pricing, they may become more willing to experiment with TE. As of 2020, 43 % of US utilities offer a dynamic rate for residential customers, and the EU mandated in the Clean Energy Package that utilities in the EU must offer dynamic rates, which indicates that many entities are gaining familiarity with more advanced rates (European Commission, 2016;EIA, 2021;IRENA, 2019). One respondent felt that municipal utilities and cooperatives could be prime candidates for TE programs, providing they gain experience with reactive pricing. These entities have a much more streamlined regulatory process, when compared to investor-owned utilities, and could rapidly build on their experiences with simpler price-responsive programs.

6.4. Threats

Though these programs offer substantial strengths, the advancement of TE is not without threats. Less technology-intensive methods of demand response, including time-of-use and critical peak pricing demand response programs, can offer immediate benefits and are more established. A preference by utilities for centralized optimization and dispatch programs, which can be more complex and less resilient than TE, could crowd out future programs due to ease of understanding and perception of a lower risk choice.

Indeed, at least one technology solution provider interviewee indicated that requests from utility clients resulted in their organization switching much of their product design focus to a centralized dispatch algorithm. Revised Text: Another interviewee expressed the opinion that TE programs should target residential customers, as they felt that commercial customers were already well served by existing demand-side management programs. This could speak to regional differences within electricity markets, as the EIA reports that in the US, residential customers provide greater amounts of energy savings through demand response than commercial customers, both in absolute terms, and relative to market share (EIA, 2021).

This idea is aligned with disagreement over the best ways to scale TE, namely, whether implementers should be focused on increasing participation or increasing flexibility. Navigating these tradeoffs will require clear communication about the additive benefits of TE and its simplification for integration and operation for utility decision-makers become highly reliant on direct-control programs. Additionally, price-reactive programs (e.g., time of use or critical peak pricing and one-way real-time prices) can be deployed more quickly and easily and are preferred as a first option in some jurisdictions, including the EU. TE advocates may consider strategies that build on successes and familiarity from these programs, as regulators, utilities and customers become more comfortable with dynamic pricing.

Concerns about equity also need to be addressed by TE advocates. At least one respondent indicated that there is some perception that TE is only accessible to higher-income customers who have access to technologies like batteries, solar PV, and higher-end HVAC systems. However, by lowering system-costs, TE needs to demonstrate benefit for all electricity customers, even those who do not participate in the program. Strong communication around these strengths as well as clear best practices for program design that allocate savings equitably could help counteract this threat narrative. Additionally, programs like community solar and weatherization assistance can broaden the number of eligible program participants.

7. Lessons to enhance adoption

The TE practices survey reveals opportunities and challenges for advancing TE deployment. For those working to accommodate increased DER integration and nurture coordinated operation with the electric power system using TE approaches, the following topics may be worthy of consideration.

7.1. Defining value propositions

As stated in Section 5.2, many of the programmatic goals of these deployments were to prove out TE from a technical perspective. As a result, the business aspects were not as well emphasized, leading to difficulties for many of these deployments to exit the pilot or demonstration stage. GOPACs, one of most mature and active TE programs, worked specifically to fill a market niche (congestion management). Identifying applications where TE can deliver more immediate benefit could help the technology-related aspects diffuse into the market. This section details potential pathways to identify and evaluate these value propositions.

7.1.1. Demonstrating value to electricity system operators

System operators will need to understand the efficiencies and operational advances that TE can provide to electricity systems. Contextualizing these gains within the broader operational constraints of the network could help demonstrate the value of TE to these stakeholders. TE program managers could utilize cost-benefit models and approaches that are already familiar to this audience to show how TE can help system operators meet their operational goals. These could include tools and models such as production cost, capacity expansion, and power flow models. Analyses need to carefully trace cost and benefit flows to all potential stakeholders, including both program participants and non-participants, and even the electricity system and society at large.

Interested parties could also look to existing best practice documents for DERs, such as the National Standard Practices Manual (Woolf et al., 2021) when considering valuation standards for TE programs. For transactive systems themselves, much work has been conducted to trace value flows and potential benefits from TE (Makhmalbaf et al., 2017). Continued use and refining of such methodologies could help system operators better understand the underlying value of TE.

7.1.2. Delivering value to customers

While TE programs need to clearly demonstrate their value to the electricity system, they must also ensure that financial benefits are passed through to customers. Transactive markets need to be designed so that customers are adequately incentivized to respond to price signals, and so customers who respond more effectively to the transactive signal are compensated appropriately.

However, the efficiency gains from TE have the potential to create economic surpluses that extend beyond the program participants. Ensuring that all utility customers benefit from these programs could help demonstrate their usefulness to policymakers and alleviate concerns related to equity and inclusion. Though some customers, due to technological, educational, or other barriers may have difficulty actively participating in TE programs, a sharing of the benefits can ensure that outcomes are not inherently inequitable.

Communicating the value delivered by TE systems in terms compelling to customers also deserves attention. Making TE-based programs attractive to customer signup is necessary for seeing that customer acquisition efforts are reasonable and ensure that TE delivers value overall. While many respondents did not report their customer acquisition costs or signup bonus, the amounts that were reported were generally high. While this is typical for demonstration projects, program rollouts that can attract customer participation with compelling value scenarios may be better able to contain enrollment costs for these deployments to scale sustainably.

7.2. Improving interoperability and system integration

Since the dawn of the initiatives that gave form to the topic of smart grid, addressing the challenge of easily connecting intelligent subsystems together and achieving reliable interoperation has been at the forefront of architecture and system design efforts (Gridwise Architecture Council, 2005).

Interoperability is achieved through alignment at technical, informational, and organizational levels of concern. While making sure communications technology can transfer messages was the early focus of interoperability, the necessity to align terminology (semantics of data fields), business processes, and governing policies (in business and regulation) has become more apparent.

These aspects have come into focus over the past three decades with business-to-business and business-to-customer automation approaches. Yet, as the survey shows, the effort to integrate the varied automated devices and systems for proper operation of a transactive system remains a top challenge to the cost of deployment and system evolution.

7.2.1. Developing best practices for regulation and business models

A significant weakness for deploying the surveyed transactive projects was the varying regulatory landscape and different business practices that make deployments unique.

Grid architecture perspectives.

Understanding the parties involved and their roles in transacting energy or other services is an important component of establishing commonly held perspectives for integrating flexibility resources. The sometimes-ambiguous roles of parties responsible for distribution system operations, transmission operations, aggregation of flexible resources, implementation of equipment and communications technology, and the customer (flexible resource owner or operator) may be able to be untangled if terminology and business processes are shared and harmonized across deployment scenarios (Taft, 2019).

Best practices for tariff design.

The various field demonstrations were designed considering the regulatory policy bounds where they were deployed. In nearly all cases, the existing rate structures needed to be changed so that retail, time-dependent pricing for energy or other services could be offered to customers. In some cases (e.g., AEP Ohio gridSMART, RATES, and GOPACS), programs and tariffs were part of the deployments' financial designs. While program and tariff design will continue to require specialization, system integration and achieving interoperability will be enhanced with greater commonality of the terminology and structure of transactive tariffs or agreements. (See Section 7.3.2 for related insights on technical assistance.).

Commonality in defining goods and services exchanged.

The survey found that while the operational objectives or value proposition drivers for deploying TE coordination were well understood by many of the program leaders (see Section 5.1) the service being transacted was less precisely stated. In most cases, the use or production of customer energy was being planned or scheduled for near-term delivery periods. In some cases, there was negotiation for forward periods. This was used to address problems such as system peak shaving or distribution system overloads.

In some cases, customer flexibility was being held in reserve to be called upon in the event of a system operational need, such as distribution congestion. Efforts to create common definitions of the goods or services being exchanged with TE systems can benefit interoperability across deployments. For example, an existing US DOE Grid Modernization Initiative project is engaging industry experts in system operations to standardize grid service terms and definitions (NAESB, 2022). The ability to parameterize the characteristics of these services (such as frequency of procurement and period of performance) may support specialization while promoting common terms and structure. Considering best practices for measuring performance to agreements may also lead to greater commonality for addressing interoperability issues associated with metering and sensing systems needed to settle the transactive process.

Machine-readable business practices.

Designing tariffs for transactive agreements involve covering a set of contract terms and conditions. While each jurisdiction does this differently, the basic components of these agreements can be structured in a common way. The Uniform Commercial Code structures the elements needed in commercial contracts in the United States. This is not federal law, but states adopt elements of the Uniform Commercial Code into their laws. With common structure and definition, greater uniformity enhances commercial transaction interoperability across the country. Based on the experience of these and upcoming projects, the elements of a uniform transactive tariff could yield similar benefits.

In addition, should something like a uniform transactive tariff come to fruition, efforts to make the terms and conditions of such a tariff machine readable would be beneficial. Machine-readable tariffs would allow those offering these tariffs to communicate them in an unambiguous way for technology solutions providers to interpret and incorporate into customer management system products, in turn enabling faster and more reliable system integration for new transactive program rollouts.

An example of an effort to provide machine-readable time-varying rates is the California Energy Commission's MIDAS program. MIDAS supports a database of rate information that can be queried with an application programming interface (California Energy Commission, 2020). Some projects in the survey have proposed using distributed ledger-based technology concerning smart contracts (or chain code) that capture aspects of the tariff design in software.

7.2.2. Interfaces to flexible resources

The other major areas of weakness cited by many of the survey respondents were the lack of standards for equipment connectivity and the high integration and maintenance costs for integrating customers. This issue is complicated by the fact that every TE deployment depends upon a communications and messaging system, commonly referred to as a platform.

The relatively small nature of the projects means that there is only one platform for every project. However, a large distribution utility-scale deployment to hundreds of thousands or millions of customers will likely involve the existence of several of these platforms. Accommodating platform diversity can help avoid vendor lock-in and support technology evolution. However, integrating with multiple platforms means that interoperability issues must be addressed between different platforms.

Device-level information communication technology standards convergence.

Platform providers and device-level integrators could benefit from standardized device-level coordination and control interfaces. Devices such as programmable thermostats, electric water heater controls, and electric vehicle charging equipment support different standards depending upon their marketplace. Buildings controls vendors use proprietary interfaces and support some standards. Often, the standards are type-of-equipment specific. Smart device standards efforts such as Modbus, CTA-2045, and Matter offer areas to help with integration at the device level. Internet protocol and Internet of Things frameworks envision smart device interaction for entertainment, security systems, and energy coordination.

A European initiative to develop an Energy Flexibility Interface (EFI) has resulted in European Committee for Electrotechnical Standardization (CENELEC) standards covering a protocol and information model for representing smart device flexibility that can be communicated to a flexibility utilization function, such as a building management system (Konsman et al., 2020). This standard guides device manufactures to communicate their equipment flexibility in a manner that eases the integration of products into TE systems.

While this device-level interoperability challenge applies to many applications, adopting a clear path forward to support integration into TE systems will help create progress in this area.

Facilities-level information communication technology standards convergence.

Most of the surveyed projects focused on integrating residential customers. These sites are dominated by unitary equipment control systems that do not interact with each other. Another approach of some projects is to integrate campuses or microgrids. These situations focus on the site-management or facility-level interface to a solution provider's platform. Commercial buildings often have building management systems that supervise the energy management of a facility. These systems have their own set of integration issues within the facility, but by separating those concerns to building managers, transactive system integrators can focus on the external, grid interface to the building management system.

With an architectural structure to organize areas of concern, topics for standardization may be clarified. The Uniform Smart Energy Framework (USEF) in Europe proposes an architectural view of organizing the areas for integration with communications interfaces. The Energy Services Interface (ESI) concept promulgated by the DOE's Grid Modernization Initiative presents another architectural vision with customer site interfaces for integration (Widergren et al., 2019). Efforts such as these look to build community alignment that can service a TE approach to coordinate resource flexibility.

Implementation profiles with certified vendor products.

Even when TE system designs use communications standards, the optionality offered by the standards requires the precise selection of features and implementation agreements that will enable interoperability. These further specifications are called implementation profiles. Such profiles allow testing and certification of products and system components so that integration more dependably results in interoperation. Efforts that encourage standards-based communities to develop TE implementation profiles with testing and certification programs will allow deployments to proceed more smoothly.

Integration best practices.

The follow-up interviews with survey responders indicate the wealth of practical knowledge gained through the integration experience of the field deployments. Though practitioners see the value of the experience, little effort has been made to formally capture the lessons learned for future projects. Other than the questions driven by the survey and the interview, sharing this knowledge is rare. Regular forums for sharing experiences and best practices can help those involved in TE deployments articulate challenges and bring focus to areas that may bring the greatest near-term benefit to system integration.

Industry forums for flexible resource integration such as standards organizations (e.g., IEEE-SA, IEC) collaboratives (e.g., SunSpec, OpenADR, USEF, LF Energy) may be worthy to consider for bringing together people with TE integration experience to identify best practices and articulate integration challenges. Government agencies and their research laboratories and institutions can serve as conveners and facilitators to organize such groups.

7.3. Promoting education, publicity and market transformation

Many respondents cited issues communicating the benefits of transactive systems to key stakeholders - both internal and external. Some respondents acknowledged that these stakeholders expressed concerns regarding potential unforeseen risks related to the technology. As a result, many program managers foresaw a need for established best practices. Alignment around best practices, when combined with outreach and consensus building could help advance and scale TE.

7.3.1. Developing trust

The issue of trust emerged as a barrier in many of our responses. Our interviewees reported that while many stakeholders expressed interested in the technical aspects of TE, far fewer trusted it to fully deliver on its financial promises. Others were uneasy about the stochastic nature of TE coordination, especially when compared to direct-control demand response programs. While experience with TE systems may help build trust over time, finding ways to ease these concerns will be necessary as TE approaches work to gain a foothold in the market.

As the first generation of TE programs reach maturity, implementers will have a greater number of successes and lessons learned to communicate. Peer exchange and testimonials can amplify and disseminate this knowledge to those who are interested in the technology but uncertain about its applications. These stories could be especially useful for risk-averse institutions who may be skeptical of a new approach. Likewise, organizations could translate these findings into tutorials for utilities, regulators, and other interested stakeholders. Providing guidebooks and roadmaps to support coordination in complex systems could help these entities more quickly and effectively stand-up programs, and more accurately compare TE to alternatives. Retail aggregators and technology solution providers would also benefit from this information and could use lessons learned to adapt their products and programs to those which have seen the greatest success in the market and have strong demand from potential participants.

7.3.2. Expanding technical assistance

Utilities, regulators, and program managers may also benefit from direct technical assistance from experts with experience in TE deployments. The sharing of best practices across a wide variety of subjects could be useful to industry stakeholders. Best practices for program design and implementation road mapping could help program managers more quickly design TE programs that closely align with their goals. Validated best practices could also help TE solution providers build trust with potential customers by showing that their programs have been substantiated by independent third parties.

Education and guidance on TE approaches, tariff design, and valuation (and other requirements to achieved regulatory readiness) will also be critical as TE deployments expand. Regulators will need standard methods for understanding the costs and savings associated with TE. Likewise, processes for allocating these costs and benefits to program participants, and the broader group of nonparticipants will benefit from standardization. Designing retail tariffs and appropriate consumer guardrails are also likely to be front-of-mind to regulators. Tariffs will need to be designed that appropriately expose consumers to the transactive price signal, but do not unfairly levy them with the costs of extreme scarcity events.

Finally, some stakeholders are likely to look for a pathway in which they can more gradually transition toward systems like TE. Providing a path for systems to transition from top-down directly controlled networks to distributed and transactive ones could help spur more incremental changes. Price-reactive systems (as opposed to two-way negotiated transactive approaches) could be useful as a bridge to TE. Developing strategies that allow system planners to understand their total need for distributed flexibility, and ways to become increasingly transactive and distributed over time, could be useful as the penetration of flexibility resources grows.

7.3.3. Clarifying operational objectives for flexibility resources

In the survey, interviews, and workshop, participants saw energy scheduling of flexibility resources as the primary pathway to long-term value. However, the reasons for scheduling this flexibility varied considerably. Some programs were working to minimize the need for new distribution infrastructure investment. Others sought to reduce congestion, and many had a primary or secondary goal of integrating renewables or otherwise assisting electricity decarbonization. Programs working toward meeting one of these goals can benefit from clearly documenting the total market need for integration, reduced congestion, or the maximum allowable load permitted by the current grid constraints (i.e., that which is allowable without triggering the need for infrastructure upgrades). Once the program managers understand the total resource need, they could map these to potential savings that TE can feasibly deliver. Potential savings will likely be tied to the overall size of the program, as the stochastic nature of TE allows for the delivery of sufficient change in load if it is drawing from a large pool resources.

Finally, an assessment of a potential TE program could benefit from quantifying program costs, alongside the potential benefits. Benefit-cost analysis (BCA) is an important tool that can inform whether a TE program is worth pursuing instead of other investment or operational strategies. Costs and benefits can be considered in both the short and long term. TE programs may have higher costs in the near term but benefit from the ability to scale affordably as more customers are enrolled in the program. Comparing these costs in real terms will be essential for a clear understanding of the relative benefit of different approaches.

8. Discussion

This study investigated detailed information on a broad range of TE field deployments to determine the lessons learned from project experiences. The approach entailed, a literature survey, contacting people involved in developing these projects, verifying the information available from the projects, to discover and classify lessons learned.

This was achieved by, first, diving more deeply into the TE landscape to determine its relevant stakeholders, their interests in TE, the drivers for adopting TE, and what these drivers entail. Second, by collecting and reviewing the available information on TE field deployments from peer review and non-peer-reviewed sources and creating a list of relevant TE field experiments and their details (Tables 1 and Tables 2).

With the information on TE field experiments known, the third step was to develop a survey (Appendix A) to confirm the found details and find answers to the information gaps. Next, people involved in developing these TE field experiments were contacted and asked to complete the survey. Finally, the answers to the survey were analyzed and compared to the earlier found information on TE field deployments using a strengths, weaknesses, opportunities, and threats (SWOT) analysis to identify and articulate the learned experiences.

The lessons revealed from project experiences were the importance of defining the value propositions of TE, improving the interoperability and system integration of TE, and improving the communication to stakeholders of the benefits of TE. Survey respondents were given the opportunity to look at the results and provide feedback on an early draft of the paper.

This work is limited by the contact opportunities and availability of information. The survey focused primarily on European and North-American experiments due to the authors' familiarity, available network of expertize in these regions, and literature review that indicates transactive energy projects emerging in other parts of the world. Nevertheless, there was an intention to include projects from Africa (Cenfura, 2020) and Asia (Tokyo Tech, 2021) but the developers did not respond to requests to participate in the survey and report field experience. Also, the authors are aware of projects in Australian (such as EDGE Ausnet) AEMO (AEMO, 2022), but the project is still ongoing as of this writing.

The lack of survey participation was a second limitation. With several field experiments, some of the information was available online, but, despite a significant effort by the authors, some developers were unable or unwilling to participate in the survey. Therefore, only field deployments with direct contacts were able to be to included in the final SWOT analysis.

Furthermore, some field deployments were identified, but the available information was insufficient or unavailable, making it impossible to have an screening assessment for inclusion it in this work.

Nevertheless, the authors believe that the twenty-four responding experiments used in the analysis that led to the findings were sufficient to learn from the project experiences providing credence to the findings.

9. Conclusion

This study aimed to find detailed information on a broad range of TE field deployments and determine the practical experiences by uncovering detailed information on a broad range of TE field deployments, categorizing characteristics of these deployments, speaking directly with people involved in developing and operating these TE systems, and, finally, using a strengths, weaknesses, opportunities, and threats (SWOT) analysis to identify and articulate the findings. This resulted in the following three predominant lessons:

- Clearly define the value propositions and consider the business and regulatory aspects of TE. In light of this, ESO/DSOs and regulators should be made to understand the efficiency gains and operational advances TE can provide to achieve their operational goals. Furthermore, value needs to be delivered to customers by ensuring that financial benefits are passed on to them.
- Improve the interoperability and system integration of TE by aligning technical, informational, and organizational levels of concern. The varying landscape and different business practices make TE deployments unique and challenging. This is exacerbated by the lack of standards and/or their broad adoption for equipment connectivity that is required for the interoperability of communications and messaging system technology, thus increasing the costs of integrating customers.
- Improve the communication to stakeholders of the benefits of TE. Developing trust in the financial incentives and the coordination of many processes using TE approaches is of significant importance. The sharing of knowledge and experiences about TE coordination by practitioners will benefit the adoption of TE. This includes education and guidance on technology deployment, tariffs, and valuation. Finally, clearly communicating all the benefits of TE applications (such as simpler interfaces to integrate and evolve systems and addressing operational objectives, e.g., reducing congestion) can help advance TE deployment at scale.

The field experiences in this work show that significant progress has been made and is being made in the field of TE. Nevertheless, the practical lessons listed above contain a set of challenges that lay ahead on the journey to transactive energy systems.

CRediT authorship contribution statement

Sjoerd C. Doumen: Methodology, Investigation, Validation, Data Curation, Writing - Original Draft. **Daniel S. Boff:** Methodology, Investigation, Validation, Data Curation, Writing - Original Draft. **Steven E. Widergren:** Conceptualization, Methodology, Supervision, Writing - Original Draft, Review, and Editing. **J. Koen Kok:** Conceptualization, Methodology, Supervision, Writing - Review and Editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sjoerd Doumen reports financial support was provided by Dutch Research Council. Koen Kok reports financial support was provided by Netherlands Enterprise Agency. Daniel Boff and Steven Widergren

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Appendix A. Survey Questions

1. What operational or market problems are your program working to address? (Check all that apply)

   a. Improve system flexibility/load following
   b. Bring customer costs more closely in line with the costs of operating the electricity grid
   c. Improve energy efficiency/reduce losses
   d. Manage network capacity utilization (congestion management)
   e. Developing proof of concept for a technology
   f. Other (please specify)
   g. None of the above
2. What customer segment is the program targeted to? (Check all that apply)

   a. Commercial
   b. Industrial
   c. Other (please specific)
3. How successful would you consider your pilot in meeting your program goals? (Please explain)

   a. 1–10 score
4. What markets seem ripe for transactive energy and how could your program be scaled to other customer groups/ jurisdictions?
5. What are the greatest challenges that you experienced during your pilot?
6. What technologies are included in the pilot program? (Check all that apply)

   a. Heating, Ventilation, Air Conditioning (HVAC)/ Thermostatically Controlled Load (TCL)
   b. Water heating
   c. Appliances
   d. Solar PV
   e. Wind
   f. Other onsite generation
   g. Batteries
   h. Vehicle charging
   i. Other (please specify)
   j. None of the above
7. Are load and generation being treated similarly in the program? Was this approach effective?
8. What approaches should be taken to scale technology adoption?
9. Is blockchain being incorporated into your program? (Yes/No)
10. What features of a blockchain platform are being used?
11. Have you had any interaction with regulators over the course of your pilot program?
12. What level of engagement have utility regulators provided?

    a. 1–10 Score
13. What regulatory barriers (or support) are limiting broader acceptance of transactive energy programs?
14. What regulatory changes could help to make this program more permanent?
15. What equity/consumer protection issues should regulators begin to address?
16. What price forming mechanism is being used? (Select all that apply)

    a. Bilateral Trade – Peer to Peer
    b. Bilateral Trade - Brokerage
    c. Double Auction Market
    d. Iterative Consensus
    e. Other (please specify)
17. Are consumers engaging with the market as expected or have there been observed market shortcomings?
18. What behavioral interventions have been included or observed in the program? (Select all that apply)

    a. Gaming/competition (i.e., comparing households with their peers/neighbors)
    b. Endowment effect/loss aversion (i.e., relying on penalties rather than rewards)
    c. Framing techniques (i.e., presenting choices with either positive or negative spin)
    d. Nudges/indirect reinforcement (i.e., providing small cues to push customers to a desired outcome)
    e. Other (please specify)
    f. None of the above
19. How often, on average, are consumers overriding the program controls?

    a. < 1 time/week
    b. 1–2 times/week
    c. 3–5 times/week
    d. > 5 times/week
20. Did customers receive an incentive or bonus to participate in the program? (Yes/No)
21. What types of incentives have been provided to participants? (Check all that apply).

    a. Utility bill discount
    b. Small electronic devices (e.g., smart thermostat, smart home hub)
    c. Cash signing bonus
    d. Major appliance purchase/discount (e.g., smart water heater)
    e. Distributed generation system (e.g., solar system, solar + battery)
    f. Other (please specify)
    g. None of the above
22. What is the monetary value of enrollment incentives (e.g., sign on bonus) that was provided to participant? (Please provide as payment per participant in your local currency)
23. What was the average cost of customer acquisition for this program? (Please provide as payment per participant in your local currency)
24. What level of investment would be required to sustain/expand this program? (Please provide as investment per customer in your local currency)
25. What is the long-term value proposition for this program? (Select all that apply)
26. How restricted geographically is your program?
27. How inclusive was your program to participation?
28. What type of organization do you belong to?

    a. Utility
    b. Regulator
    c. Research

   d. Nonprofit
   e. Technology solutions provider/integrator
   f. DSO/ISO
   g. Other (please specify)

29. What type of position do you hold?

   a. Engineering
   b. Program management
   c. Business development
   d. Strategy
   e. Legal/regulatory
   f. Other (please specify)

30. What locations do you operate in? (Please provide city, state, and electricity market)

B. Overview of transactive energy field projects

B.1. Brooklyn microgrid project - LO3

The Brooklyn Microgrid Project is a local energy marketplace that pairs rooftop solar generators with consumers interested in purchasing renewable energy. The program began in 2016 and allows for the peer-to-peer exchange of electricity rights, which is recorded in a public blockchain. The project features microgrids, which can island and direct power to community infrastructure when needed. LO3 Energy manages the project using its TransActive grid, while Siemens provided the microgrid infrastructure (Brooklyn, 2019;Mengelkamp et al., 2018).

B.2. Buffalo DSP - National grid

The Buffalo DSP program, aimed to integrate DERs on the Buffalo Niagara Medical Campus. The program began in late 2016 and concluded in the second half of 2019. The team utilized Opus One's GridOS platform, and facilitated transactions through a double auction, with the supply-side driven primarily through NYISO's locational marginal price. The program's participants were the medical campus itself, which comprised more than 100 businesses and 13 institutional customers. The hospital's combined heat and power facilities represented the largest participant in the program (National-Grid, 2018;SEPA, 2019).

B.3. Cornwall local energy market - Trilemma consulting Ltd

The Cornwall Local Energy Market was a pilot that aimed to improve reliability by acting as a non-wires alternative to distribution system upgrades. The program had secondary goals of marking energy trading more inclusive, lowering CO2 emissions and increasing flexibility. Over two hundred participants (split evenly between residential and commercial customers) bid into the programs market. Bids could be issued on a wide variety of timeframes, from months in advance to a day ahead and intraday markets. Settlement was tracked through a private blockchain platform (Kok et al., 2022), Atkinson (Atkinson, 2020).

B.4. Electric access system enhancement - Opus One/SCE

The EASE program is a demonstration of transactive principles on a Southern California Edison distribution feeder that began in mid-2020. The program targeted 100 residential customers with solar PV and storage systems the program used top-down price signals based on the nodal LMP to manage constraints and congestion on the local system. The SCE team partnered with Opus One and used their GridOS platform as a market facilitator. The project was funded through the Department of Energy ENERGIZE program (St. John, 2020).

B.5. FUSION - SP energy networks

FUSION is an active pilot program running in East Fife, Scotland. The program began in 2021 and is working to minimize the need for new distribution infrastructure by reducing congestion and promoting flexibility. Flexibility markets are informed by forecasted constrains of the power system. The platform uses a double-auction mechanism with a day ahead market and is targeted to larger consumers or generations that do not have access to existing wholesale energy markets (Kok et al., 2022; Mian and Versmissen, 2020).

B.6. GOPACS - Tennet/Alliander

GOPACS is an active TE program operating in the Netherlands. The platform provides congestion management by scheduling energy on an intraday market (typically at a 60 min or 15 min interval). The platform utilizes an order book price-forming mechanism, and leverages existing energy price signals, but with an added locational component. Over 500 commercial and industrial customers are participating in the market, which has transacted over 140 GWh of electricity (Kok et al., 2022; GOPACS, 2022).

B.7. GridExchange - Alectra

The GridExchange program was a TE demonstration program located in Ontario, Canada. Conducted as a 3-month pilot program across 21 households, the program used a blockchain platform to settle transactions within the TE system. Program managers used these transactions to inform how DERs can be coordinated to participate in wholesale and distribution markets. The program was also used to investigate how blockchain technologies could be incorporated into utility operations and will be used to inform how the utility can scale or commercialize transactive markets (Alectra, 2019).

B.8. Gridflex Heeten - ESCOZON

Gridflex Heeten was a TE pilot program that ran from 2017 to 2020 in the town of Heeten, the Netherlands. The program aimed to reduce congestion and the need for addition distribution infrastructure. A community of 47 households participated in the pilot, which utilized local solar PV and battery storage capacity. The transactive mechanism primarily influenced the delivery or transportation component of customer bills, and while it had only a small impact on the customer's monthly bills, resulted in a small but noticeable effect on demand and consumption (Kok et al., 2022;GridFlex, 2020.).

B.9. Illinois transactive energy marketplace - Opus One/Ameren

The Illinois Transactive Energy Marketplace is a simulation and field trial conducted at the University of Illinois, Urbana. The program began in March of 2019, and leverages Opus One's GridOS platform as an exchange mechanism, with the goal of integrating renewables and DERs. The trial took place on the university's microgrid, which includes 1 MW of natural gas generation, 250 kW of battery storage, 125 kW of PV, and 100 kW of distributed wind. Pricing is based on the MISO market's price signals, and features day ahead, 1-hour, and 15-minute markets for energy (St. John, 2019).

B.10. Interflex - Enexis

Interflex is a TE platform that has been deployed in demonstration projects in the Netherlands and France, with the goal of managing network congestion. The program relies on aggregators with portfolios of customer-sided DERs, who are able to respond to the price signal. The network operator issues congestion prices to these aggregators, who then respond based on their own availability Interflex (Interflex, 2019).

B.11. LO3 hedge system - LO3

LO3′s Hedge System is a transactive platform for commercial and industrial customers, based in the ERCOT market. The platform uses blockchain technology to allow for the trading of energy hedge contracts on a short-term scale (i.e., 15 min to 1 h). The product allows for customers with critical load to access other energy supply options, and trade in real time. The initial customer base included five commercial and industrial customers, with plans to expand to other markets St. John (St. John, 2018).

B.12. Micro transactive grid, Spokane - Avista/PNNL

The Micro Transactive Grid program is a value maximization experiment being conducted in two Washington State University buildings in Spokane, Washington. These two buildings, each equipped with solar PV and batteries, are able to trade energy as the transactive price signal fluctuates. The system will also provide backup power and resilience during extreme events. The program experimented with responses to congestion events and other forms of scarcity pricing (Ledbetter, 2020;Walton, 2020).

B.13. Ohio gridSMART RTP-da - AEP Ohio/Battelle

The gridSMART real-time pricing double auction program 2011–2014) was a TE field trial in Gahana, Ohio that was operational in 2014. It featured a real-time double-auction pricing mechanism to match supply and demand with residential customers in the state of Ohio. The program compared a non-transactive control group of households to households enlisted in the transactive program to measure responsiveness, savings, efficiency, and other program metrics. The program experimented with different congestion durations to examine how customer responsiveness can change over time (Widergren et al., 2014).

B.14. Olympic peninsula demonstration - PNNL

One of the first TE demonstration projects, the Olympic Peninsula Demonstration Project tested transactive principles, developed at Pacific Northwest National Laboratory, in 112 residential homes, two diesel generators, and four municipal water pumping facilities. Beginning in spring 2006 and conducted over a year, the program utilized a double-auction mechanism with two-way communication between software agents to transact energy on a scheduled basis. As a first of its kind project, the program worked both to demonstrate the viability of TE and improve the flexibility and efficiency of the network (Hammerstrom et al., 2007).

B.15. Pacific northwest smart grid demonstration project - PNNL

The Pacific Northwest Smart Grid Demonstration Project was a large-scale TE demonstration program that ran between 2009 and 2015. It featured over 60,000 customers across five states (Washington, Oregon, Idaho, Montana, and Wyoming) and 11 utility territories. The program was intended as a proof of concept for transactive energy and aimed to improve communication and control infrastructure, aid in the development of standards for TE, and assist in renewable integration. The program worked to quantify how TE could coordinate smart grid assets across both the normal operations of the grid and in extreme events such as weather incidents (Hammerstrom et al., 2015).

B.16. Quartierstrom - ETH Zurich

Quartierstrom was a TE pilot program that ran between 2019 and January 2020 in Walenstadt, Switzerland. The program included 37 households (27 of which had PV or battery systems) and 280 kW of generating capacity and 80 kWh of energy storage. The program used blockchain technology to facilitate peer-to-peer trading of electricity. The platform aimed to alleviate grid congestion and had the effect of doubling the consumption of local solar power (Weinhardt et al., 2019; Kok et al., 2022).

B.17. RegHEE - Technical University of Munich

RegHEE was a blockchain based TE proof of concept program, which aimed to create a peer-to-peer market for distributed generators and storage. The program included 20 consumers as well as a local municipal utility as participants (Weinhardt et al., 2019).

B.18. Retail automated transactive energy system - TeMix/CEC

The RATES program, which ran between 2016 and 2019, utilized the transactive TEMix platform to coordinate energy exchange 100 residential and small commercial customers in southern California. The RATES program used a unique combination of monthly capacity subscriptions and real-time prices to transact energy among program participants. The fixed subscription rate acts as a price hedge, protecting the customer for wild price swings, while still incentivizing them to act on the transactive market (Edward and Michel Kohanim, 2020; Cazalet, 2019).

B.19. Smart neighborhood - Georgia power/Alabama Power/ORNL

The Smart neighborhood program is being piloted in two neighborhoods in two utility territories. One site consists of 50 homes in Atlanta, GA and the other of 62 homes near Birmingham, AL. Oak Ridge National Laboratory is working with Southern Company subsidiaries Georgia Power and Alabama Power to implement the program. These programs also utilize nearby solar PV, battery, and natural gas generators, and can island as a microgrid. The program utilizes the VOLTTRON-TM platform and a uses an iterative consensus process based on day-ahead demand forecasts to schedule energy US-DOE (US-DOE, 2018; ORNL, 2018).

B.20. SSEN Transition - Opus One/Scottish and Southern electricity networks

SSEN Transition is an active trial program with the goal of promoting network flexibility in the UK power networks. The program began in 2021 in Oxfordshire. The program targets commercial and industrial customers who can provide either demand response or own a battery or distributed generated technologies. The program is experimenting with a number of different market signals and price forming mechanisms including pay as bid and pay as cleared pricing, and fixed price, auction, and peer-to-peer price forming mechanisms. The program also included detailed analysis of power systems operations that were used to inform price signal (SSEN-Transition, 2021).

B.21. Transactive Campus - University of Toledo

The University of Toledo has been working since 2017 deploying transactive energy technology on its campus. The program leverages the VOLTTRON-TM platform and includes a 1 MW PV array, a 130 kWh battery, and eight campus buildings. The program was launched in support of the University's climate goals and is being used to manage variability associated with the PV system as well as the University's peak load. The program is experimenting with different market and operational strategies and examining which are most effective in helping the University meet their operational objectives (Raker, 2022; Raker et al., 2019).

B.22. *TESS - Holy cross energy/SLAC*

A collaboration between the SLAC National Accelerator Laboratory and Holy Cross Energy (an electric cooperative in central Colorado), the Transactive Energy Service System is a transactive controls program focusing on the residential sector. The project began in four homes built by Habitat for Humanity in Basalt, CO. These homes are being leveraged to manage congestion and variability on the local feeder. SLAC is working to expand the TESS program to several hundred rural households in Maine and New Hampshire (SLAC, 2022; Arlt et al., 2021).

B.23. *Vermont Green - Green mountain power/LO3*

The Vermont Green program is a peer-to-peer energy platform built using LO3′s Pando platform in conjunction with Green Mountain Power. The program launched in late 2019 and facilitates the exchange of power between commercial and industrial customers who are interested in purchasing renewable power and rooftop solar customers who opt into the program. The exchanges are virtual in nature, in that the businesses receive the rights to the power (which can be used to meet corporate renewable goals), but not the electrons themselves (Power, 2020; Trabish, 2020).

B.24. *VPP - University of Wuppertal*

The Virtual Power Plant program was a research project conducted by the University of Wuppertal and their local utility. It featured 550 participants (primarily urban households) who participated to improve system flexibility and integrate renewable energy. Customers were sent a price signal via a digital dashboard based on the scarcity of local generation and asked to respond by shifting their electricity consumption (Weinhardt et al., 2019).

C. Overview of price forming mechanisms

There are many approaches to design markets for settling the exchange of goods or services. The following general types of approaches have been used to determine (or form) the exchange price for resolving a TE marketplace. Implementation differences exist with each of the categories.

Bilateral trade - Peer-to-Peer is a form of trading in an open marketplace. Any requestor can make a deal for a quantity of energy and delivery on a specific schedule from any provider. There are generally few barriers to participation, though participants may have to sign into the program. Sellers and buyers, people post their bids in an open marketplace, so that matches can be made. Price formation is derived from knowledge of the typical “going rate” of energy deals for that time period.

Bilateral trade - Brokerage: Functions similarly to a like peer-to-peer market but includes is a brokerage house to provide the matchmaking between buyers and sellers. Similar to stock brokerages, there are many forms that brokerage houses for TE could take, and these houses may charge commissions using different formulas. Price formation comes from the cost of energy that emerges for a specific time period and this price can fluctuate, especially in a forward market.

Double auction market: This price forming mechanism requires a market operator who takes bids for buying and selling energy at a specific period of delivery. The period could be a future period (e.g., day ahead or hour ahead) or it could be near real-time. The market operator combines supply price-quantity information and balances that with energy demand price-quantity information (hence the double auction). The market operator “clears” the market at the marginal price where supply equals demand. There are different ways to set up and run a double auction market. For example, they can run at regular intervals (5, 15, 60 min) or they can run at variable time periods depending on price changes in the bids.

Order book: In this mechanism, a market operator lists buy and sell orders for energy at specific delivery periods. The entity performing the trade is also listed. At the top of the list (order book) is the highest bid and the lowest ask prices. The history of transactions (deals between buyer and seller) is also listed. Users (traders) of the order book list usually pay a fee to get this information. They then can enter the market with their own orders and bilateral transactions. Price formation comes from the knowledge of the orders and transactions which indicate the going rate of deals being made.

Iterative consensus: Markets allow participants to trade with each other for energy at a specified delivery period. They continue to correct their trades based on new trading information in an interactive fashion until the correction between market participants is close to zero. This is the iterative aspect. Some transactive schemes only allow trading with their electrically connected neighbors. Trades can sometimes be updated as other participants react to price changes in response to system losses or congestion constraints.

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