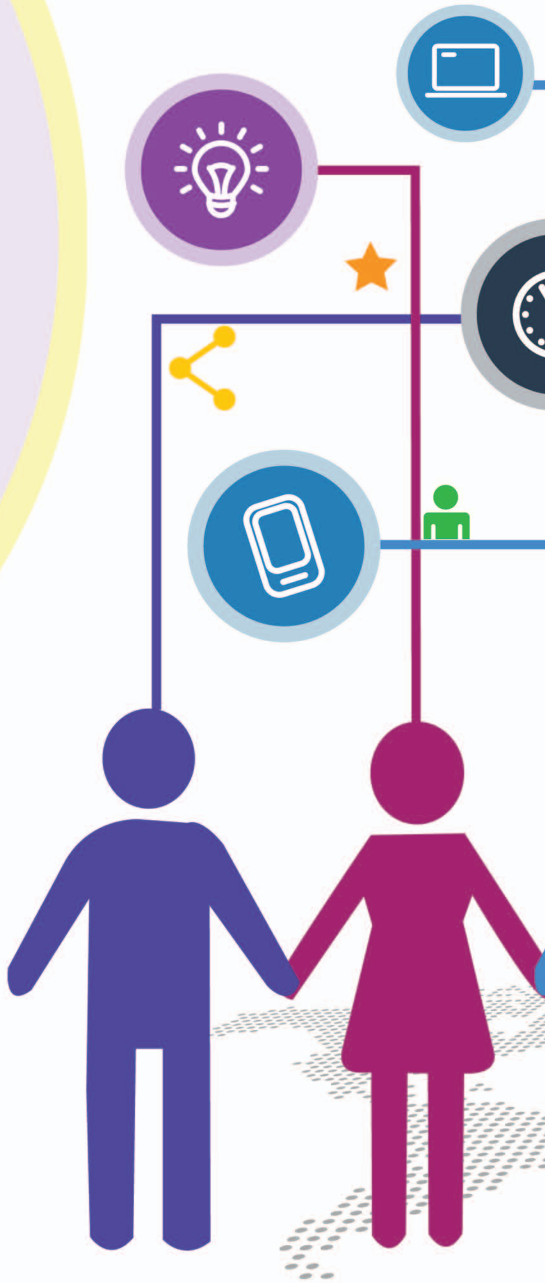
A Society of Devices

By Koen Kok and Steve Widergren



Integrating Intelligent Distributed Resources with Transactive Energy

SECURE, CLEAN, AND EFFICIENT ENERGY IS ONE of the great societal challenges of our time. Electricity as a sustainable energy carrier plays a central role in the most effective transition scenarios toward sustainability. To harness this potential, the current electricity infrastructure needs to be rigorously re-engineered into an integrated and intelligent electricity system: the smart grid. Key elements of the smart grid vision are the coordination mechanisms. In such a system, vast numbers of devices, currently just passively connected to the grid, will become actively involved in system-wide and local coordination tasks. In this light, transactive energy (TE) is emerging as a strong contender for orchestrating the coordinated operation of so many devices.

The Gridwise Architecture Council (GWAC) defines TE as "a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." We identify two key parts in this definition. One is "using value as a key operational parameter," which defines what makes the approach "transactive": operational decisions are made through an exchange of value-based information captured in transactions between participants. The other, "across the entire electrical infrastructure," declares this approach feasible across the entire electricity system, from the transmission level with its bulk generation

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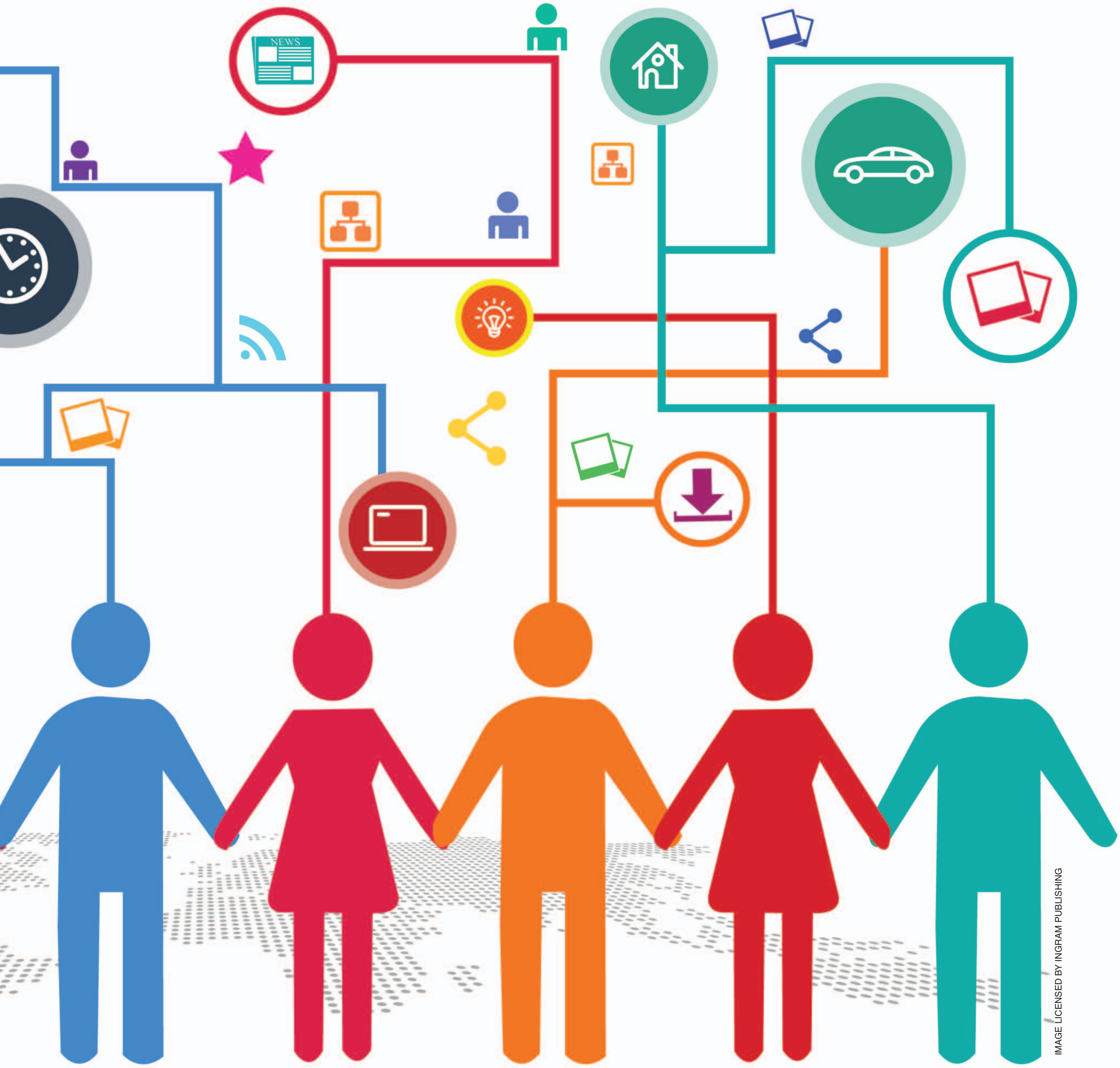

and transport of electricity down to the distribution system and the variety of connected customers.

In large parts of the world, electricity markets exist on the transmission level of the infrastructure. Here, markets and energy transactions are already used to influence system operation, and, thus, aspects of TE are arguably already in place at that level. Because of this, the distributed, collaborative decision-making nature of how market mechanisms work at the transmission level in modern power systems is already well understood. The big challenge for the smart grid is how to coordinate an ever-growing number of intelligent devices, each with their own objectives and value perspectives, into a resilient, secure, and efficient system that balances the trade-offs among the objectives of the many participants and has the flexibility to evolve with the changing mix of resources over time. This frames the opportunity for introducing TE concepts across the *entire infrastructure* and specifically into the distribution-level of the electricity grid.

This article focuses primarily on the application of TE as a scalable coordination approach to electricity distribution systems operations by reviewing and contrasting the way a TE system works and its advantages with competing control and coordination approaches. Several field demonstrations are summarized both in Europe and the United States, where first-generation TE systems have been shown to improve the balance between local consumption and production and, by doing so, improve the integration of renewable generation and mitigate congestion (i.e., local power flow overloads) in distribution systems.

Classifying Distribution-Level Energy Management Approaches

In a distribution-level TE system, mid- to small-sized electricity consuming or producing devices automatically negotiate about their actions with each other, with devices in the physical network, and with dispatch systems of energy suppliers through efficient and scalable electronic market algorithms. To debate the advantages of this approach, and to classify different approaches, the "smart energy management matrix" has been introduced. This matrix classifies smart grid energy management approaches into four main categories. The vertical matrix axis distinguishes if an approach makes decisions on local issues either locally or centrally. The horizontal axis plots whether the approach uses one-or two-way communications. Figure 1 shows this matrix with four general classes of energy management approaches filled in: top-down switching, price reaction, centralized optimization, and transactive control and coordination.

Top-Down Switching

This quadrant contains the classical demand-response programs where, typically in a certain grid area, one device group is switched simultaneously following a broadcasted signal. This is the simplest demand-response approach, and it has been used successfully for decades in different parts of the world. In the typical setup, a signal sent out through the power grid by the local utility company switches off systems such as water heaters, and air-conditioning systems during peak load periods. Although the approach is simple and effective, it does not unlock the full response potential of devices, as the device state is not taken into account. The expected system reaction is only known by using statistics, and as a result the operation is based on worst-case scenarios. Most of all, the method ignores the consumer altogether. It does not take user preferences into account and interferes with the autonomy of energy consumers.

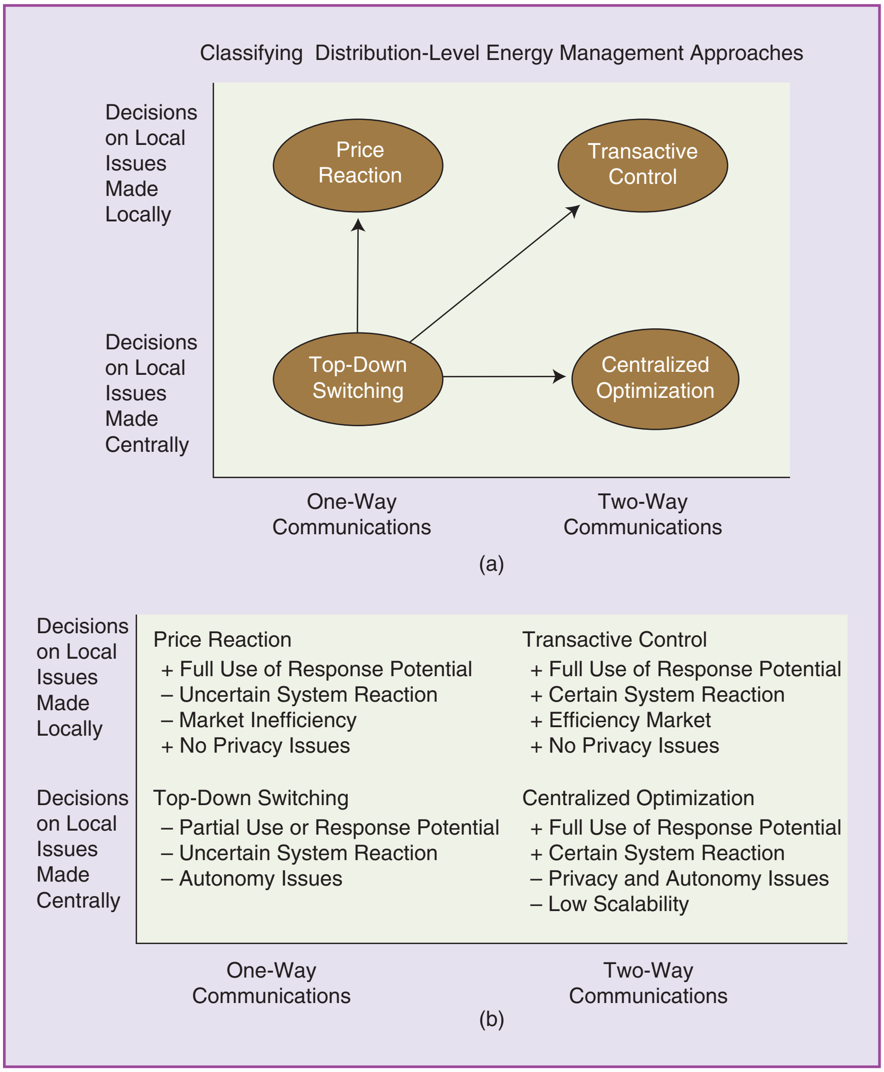

figure 1. The energy management matrix: the four main categories of (a) smart grid energy management and (b) their pros and cons.

Centralized Optimization

In the centralized optimization quadrant, local decisions are still made centrally, but communications are two way. Here, a complex optimization engine oversees all flexible demand and supply in the smart grid cluster under consideration (such as a virtual power plant or a local grid segment). Based on available information and taking into account the global and, perhaps, local control goals, the optimizer searches for the best solution for the whole system. All relevant local data need to be communicated to the optimizer, which informs the central controller that communicates control signals or schedules to the field.

Having the relevant local data available as input to the optimization, the method is able to fully unlock the response potential of the individual devices. Further, as the central system performs a direct control on the local devices, the system-level reaction of the response cluster is known when a response is triggered. The autonomy issue of the top-down switching approach remains, and a privacy issue is added as detailed local information is now communicated. Further, communicating

> Successful outcomes require acceptance by business and policy decision makers as a cost-effective, valid, equitable, and advantageous revenue/investment recovery mechanism.

all relevant local information to a central point limits the accuracy and scalability properties of the approach. When equipment changes locally, the central system must be updated as well. If the number of responsive houses, buildings, and installations becomes large, the communication and optimization times grow nonlinearly. The approach also does not respond gracefully to communications or central optimizer failures.

Price-Reactive Systems

The price reaction approach is based on a one-way signaling of a dynamic price to end users. At certain time intervals, a new electricity price or a price profile for the coming hours is sent to an automation system at the premises. This price profile is displayed for the end user or automation system to adjust equipment operations. Benefits of this approach include 1) simple one-way communications leading to low system complexity, 2) no issues regarding privacy or autonomy, and 3) an easily implementable approach in regions having an electricity wholesale market due to the availability of a day-ahead or intraday price profile from this market.

Using the price signal, the operation of responsive devices can be optimized economically by a local intelligent controller that is owned by and/or under the control of the consumer. Such a controller would thus be able to increase the consumer's loads during low-priced periods, and generation during high-priced periods, while taking the device states and user preferences into account. The controller has the opportunity to unleash the full response potential. To bill the customer according to the prices signaled, a communicating electricity meter needs to measure usage at a resolution appropriate to track response from the price signal. The recent tecŸology developments in advanced metering are providing solutions to mitigate the privacy risks.

These characteristics have advantages compared to the central optimization case; however, the reaction of a demand-response pool to each price reaction signal is difficult to predict without knowing each device's state and end user's preferences.

Transactive Control and Coordination

The transactive control quadrant offers distinct advantages in integrating flexible devices in the electricity operations. Here, smart homes, buildings, and industrial sites engage in automated market trade with others at the distribution system level and with representation of the bulk system. Communications are based on prices and energy quantities in a two-way negotiation.

Analogous to the price reaction approach, the operation of the flexible devices is optimized economically by a local intelligent controller (or agent) under the control of the end user. This controller receives price information and takes the device state and user preferences into account to operate local demand and supply resources. This is the same as the price reaction approach except that, before the price reaction takes place, the local controller communicates the available flexibility combined with their preferences and conditions to an electronic marketplace through a market transaction (price/quantity bid). Consuming devices communicate their willingness to pay, while producing devices communicate the price for which they are willing to produce.

Since all resources participating in the market communicate their intended reaction to a range of price levels, the pool reaction to a range of price signals is known up front and the market mechanism can determine the price for an appropriate balance of supply and demand. From the end user's or energy consumer's point of view, the local energy management system agent acts on behalf of the user or consumer to bid into the market and reacts to the resulting market price signals. Unlike the centralized optimization approach, no direct outside control is involved here. However, from a system perspective, the participants engage in coordinated control actions. With this approach, demand response moves from influencing, with an uncertain overall response, into market-based control with a collaboratively derived dynamic price as a control signal to trigger a predictable system reaction. This is why this approach is sometimes referred to as market-based control or transactive control multiagent system (see "Distributed Intelligence and Multiagent Systems").

When properly implemented, the market bids sent by the end users' energy management systems can be aggregated together. When this is done for two devices, the resulting bid represents the preferences of the two devices together. The message size of the aggregated bid curve is a simple combination of the individual device bid curves. Using this property, a highly scalable system can be obtained when, in a response cluster, bids are aggregated together. The processing and communication time then scales with the height of the aggregation tree instead of with the number

Distributed Intelligence and Multiagent Systems

The study of market-based approaches as a distributed intelligence mechanism for solving multiobjective optimization problems have their roots in economic theory. With the advent of information and communications technology and the growth of robotics and intelligent systems, their application to solve complex systems of systems problems is expanding. The increasing pervasiveness of computational resources in devices enables local intelligence, and their communications connectivity allows them to interact. This interaction of intelligent devices is foundational to the discipline of multiagent systems and the methods and tools that support them.

For the purposes of this article, devices or systems are intelligent if they are able to perceive their surroundings to gather information about the context of their operation. Like people, they can reason autonomously by processing information in a goal-directed way to forecast, plan, and act. Distributed multiagent systems are characterized by a population of intelligent devices that communicate with each other to exchange information (measured or derived) to better accomplish their independent objectives through cooperation and joint action. Multiagent systems are constrained by their environment, which imposes physical, temporal, and policy (economic or other) conditions on their interaction. In this regard, intelligent agents reside in an ecosystem of products, services, deployment platforms, and other supporting infrastructure. Like societies of people, they interact with more or less independent decision-making authority within cultural and governing policy structures. As their intelligence is captured in cyber-based programs, multiagent systems can reside in the real world or run in a simulated cyberworld. This is particularly important for complex systems design and testing, and simulation.

of devices participating. Further, the approach protects the end user's privacy as the bids communicate only information about energy quantities and prices. When these bids are aggregated on the level of a house, a building, or an industrial site before being communicated externally, the information exchanged is comparable to that of a metering system collecting near-real-time data as described for the price reaction approach above. And unlike the centralized optimization approach, no complicated models of the devices, consumer behavior, or preferences are exchanged or maintained. In summary, TE approaches are able to access the full response potential of flexible devices, provide greater certainty about the momentary system reaction, realize an efficient market with proper incentives, and protect the privacy of the end user whose devices participate in the energy management task.

TE Systems Implementations

In terms of customer privacy, scalability, and efficiency, TE systems have clear advantages over more common smart grid coordination, such as price reactive systems and centralized optimization. Both in the United States and Europe, TE research has had a strong focus on intelligent agent-based innovation in household equipment and field demonstrations involving grid operators, energy supply companies, power technology companies, and regulators.

TE Systems Implementations in the United States

The U.S. Department of Energy partnered with several organizations in three major demonstration projects using TE mechanisms to coordinate distributed energy resources with system operations.

Olympic Peninsula Demonstration, 2006–2007

This first proof-of-concept TE project was located in an area of the Olympic Peninsula of Washington state, which receives electricity through a radial transmission connection to the Pacific Northwest power grid. The project tested the potential for flexibility offered in coordinating distributed energy resources to postpone or remove the need for a transmission upgrade. The project used a 5-min double-auction market technique to coordinate four large municipal water pumps, two backup diesel generators, and residential demand response from electric water and space heating systems in 112 homes. The project established the viability of TE to achieve multiple objectives: system peak load and distribution constraint management; wholesale price purchases by the utility; and residential, commercial, and municipal energy cost savings.

The market received supply bids from the utility based upon a markup of the wholesale price of energy in the area. The diesel generators' bid was based on the actual fixed and variable costs incurred for operation. The pumps' bid into the market was based on water-reservoir levels that they were designed to regulate. And the residential demand-response equipment allowed the households to specify their automatic price-response preferences. To capture their preferences, a list of comfort settings named to indicate ranges between most comfortable (nonprice responsive) to greatest economy (highly price responsive). The 5-min market determined the clearing price for energy and broadcast that to the market participants. Each participant's bidding equipment would operate based on whether their bid was higher or lower than the market-clearing price.

Figure 2 is the operational dashboard for the demonstration. Besides coordinating the price-responsive resources

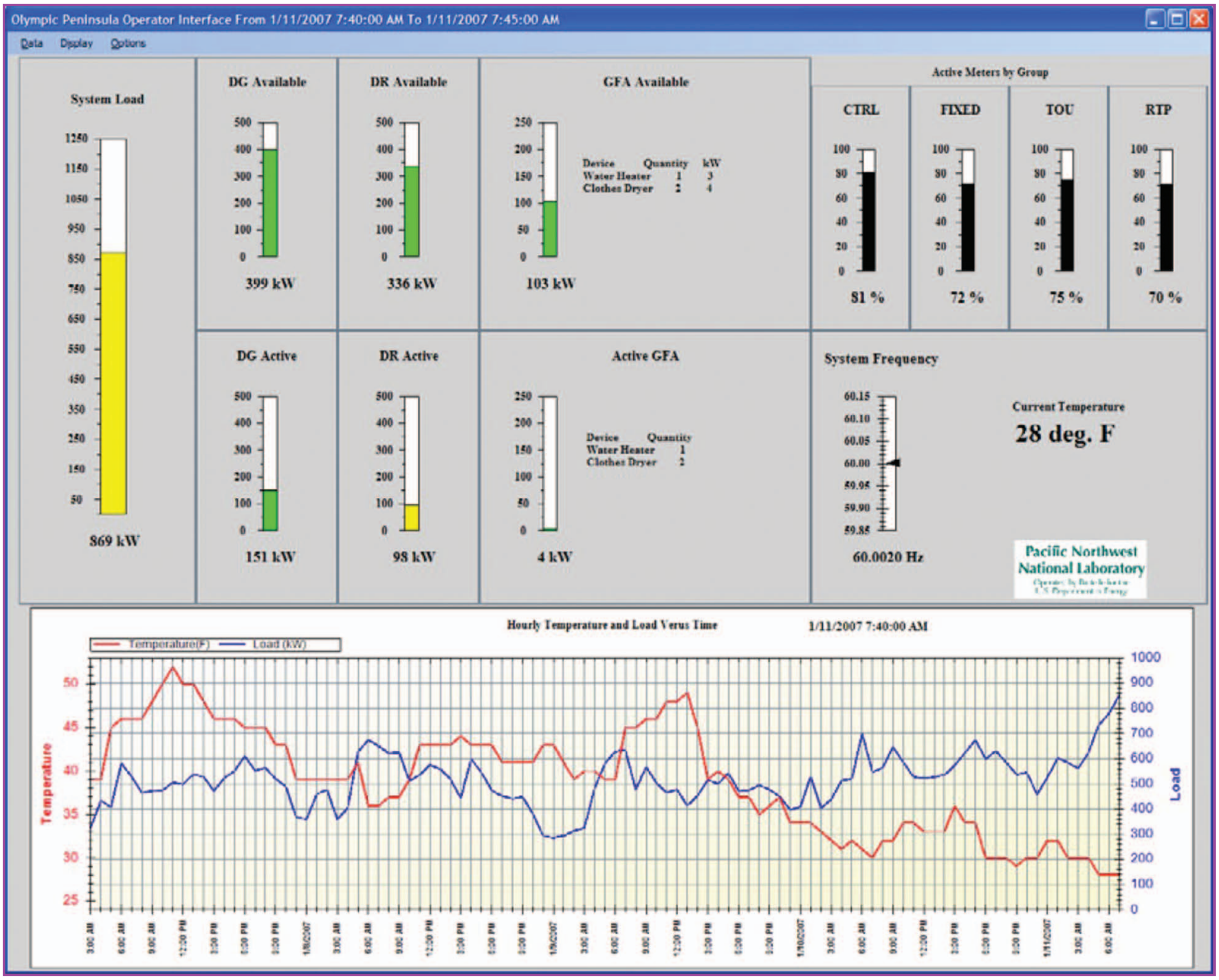

figure 2. The Olympic Peninsula dashboard summary.

to wholesale price fluctuations, the transactive system also managed congestion on a distribution circuit, by managing all of the devices as if they were on one circuit and seasonally adjusting the capacity setting of that circuit to exercise constrained operating conditions. The project controlled the imported capacity of the circuit below the constraint for all but one 5-min interval over the entire project year.

AEP Ohio gridSMART Real-Time Pricing Demonstration, 2010–2014

Building upon the Olympic Peninsula project, the AEP Ohio gridSMART (gridSMART is a registered trademark of AEP Ohio) demonstration project had a real-time pricing (RTP) component, called SMART Choice (SMART Choice is a registered trademark of AEP Ohio), that used a 5-min double-auction market to dispatch participating responsive loads on each of four distribution circuits. The preferences of household occupants were reflected in software agents that developed an overall price flexibility curve for the household and coordinated device control actions [in this case heating, ventilation, and air conditioning (HVAC) units] with the market system. A market clearing engine at the operations center aggregated the bids from all households to form a price-sensitive demand curve for the distribution circuit and calculated a clearing price and a supply bid, which incorporated the regional market operator's (PJM) 5-min wholesale locational marginal price for electricity. The clearing price was broadcast back to the households and captured in the billing system according to a tariff approved by the regulator, the Public Utility Commission of Ohio. An overview of the RTP system design is presented in Figure 3.

The RTP experiments ran over the late spring and summer of 2013 and involved four feeders with approximately 200 households actively participating. Figure 4 shows this transactive system in action on a hot summer day. As expected, the short-term energy use was negatively correlated with the electricity price. In addition, many experiments were held to determine the HVAC resources' response to peak-shaving conditions by temporarily lowering the circuit capacity limits on the circuits. Under this situation, the billing system

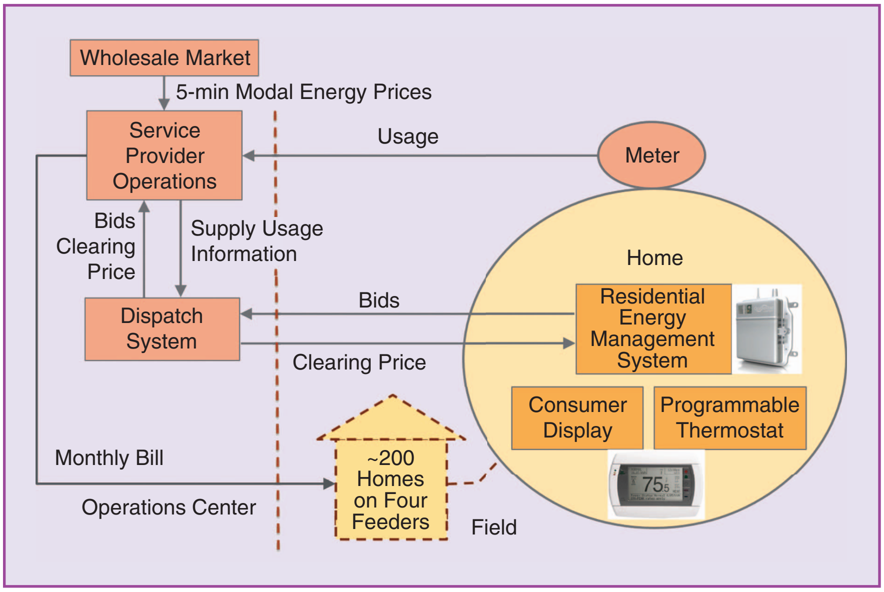

figure 3. A design overview of the AEP Ohio gridSMART RTP system.

clearing price. An analysis of the field results indicated that wholesale purchases and household bills reduced by about 5% each.

The field data was also used to calibrate simulated household demand-response models for investigating higher penetration levels participants. Figure 5 plots the expected response to congestion events on a feeder with 100% RTP household penetration. The dotted line represents a simulation without RTP response and the remaining lines show responses and the rebound for one-, two-, four-, and six-hour congestion events that represent the maximum response using the diversity of thermostat settings seen in the field.

rebates a household for the difference between the congested clearing price and the normal 5-min real-time price and provides an incentive payment to a household if its bid was above the normal clearing price but below the congestion

Pacific Northwest Smart Grid Demonstration, 2010–2015

The Pacific Northwest Smart Grid Demonstration (PNWSGD) included multiple states and cooperation from

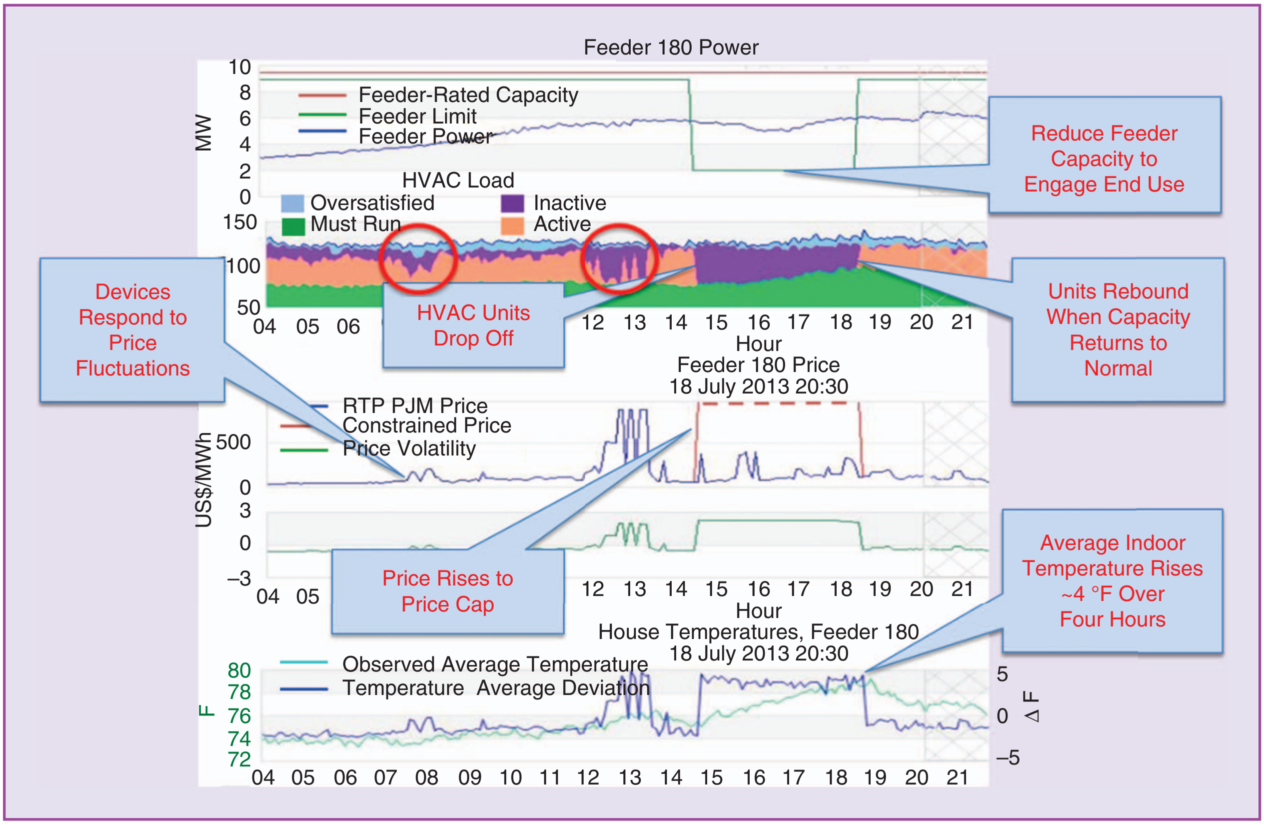

figure 4. The AEP Ohio gridSMART RTP transactive system in action.

multiple electric utilities, including rural electric co-ops and investor-owned, municipal, and other public utilities, as indicated in Figure 6. There were 55 unique instantiations of distinct smart grid systems demonstrated at the project sites. The local objectives for these systems included improved reliability, energy conservation, improved efficiency, and demand responsiveness. The demonstration deployed a transactive system to coordinate the operation of distributed energy resources and addressed regional objectives, including the mitigation of renewable energy intermittency and the flattening of system load. The transactive system coordinated a regional response across 11 utilities and showed that distributed assets can respond dynamically on a wide scale.

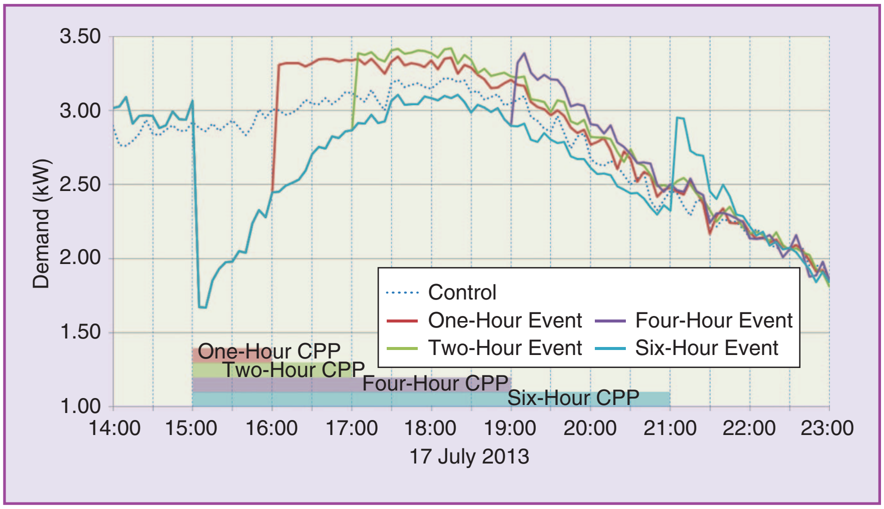

figure 5. A Simulated response to congestion events calibrated from gridSMART field data.

Figure 7 provides a high-level summary of the transactive-node approach developed for this project. Each node represents one or more electrically connected resources.

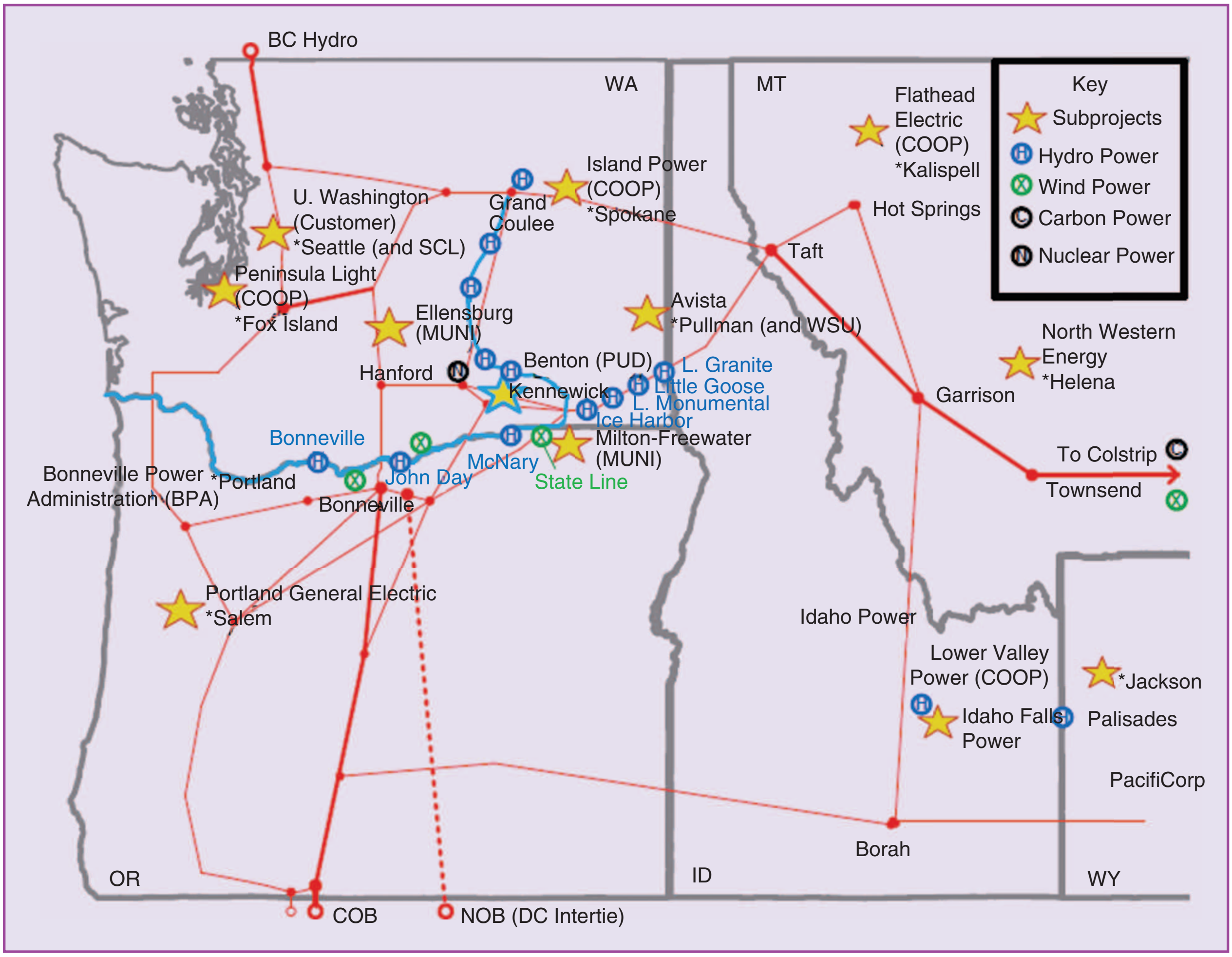

figure 6. The PNWSGD geographical region, including participants and major generation and transmission.

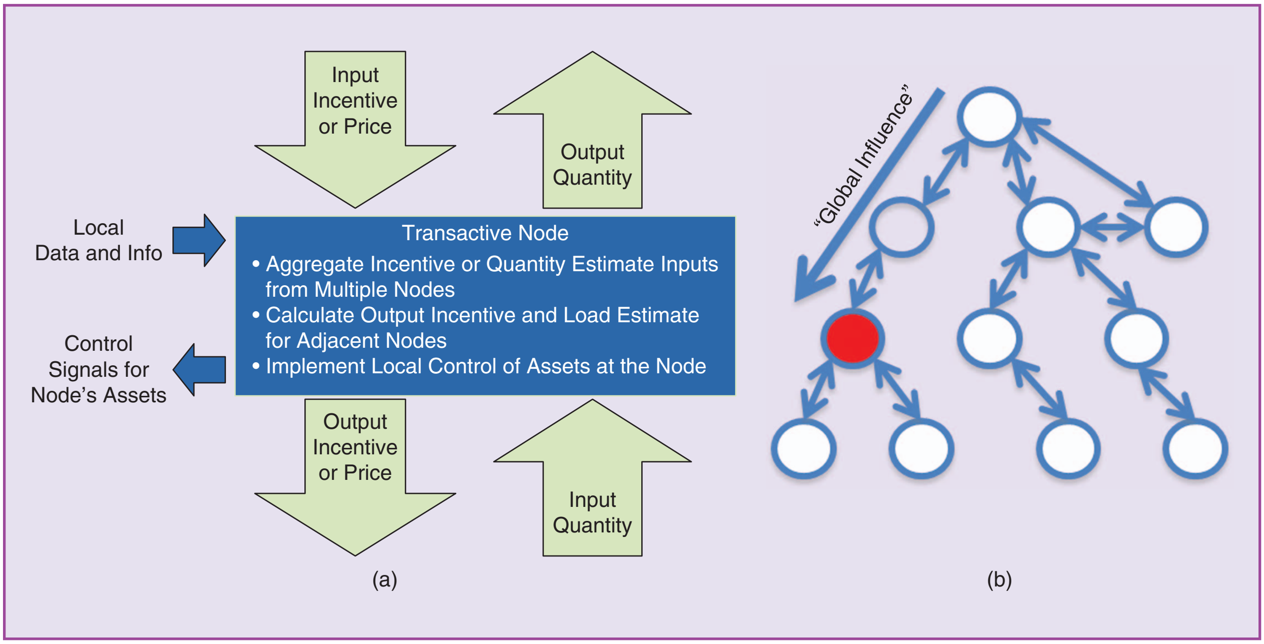

figure 7. The PNWSGD transactive node communicating with electrical neighboring nodes.

Nodes interact with electrically connected neighboring nodes to exchange information about the quantity of energy estimated to be produced or consumed and the cost of that energy. A time series of information is exchanged so that the nodes negotiate operation not only in the next interval but optimize their operation over the time horizon of the time series. Internally, the node manages the resources under its purview to see that their needs and flexibility are properly reflected in the negotiation. The system of nodes iterates exchanging information for each operation's time step until the difference in incentive price and energy exchange between each neighbor converges.

The transactive system revealed a continuum of incentives to the utilities and asset systems and engaged assets dynamically according the each asset's capabilities and the flexibility of the asset's owner. In addition, the project used a simulation model of the regional system to assess the impact of a scaled-up deployment of the transactive system. This simulation showed that the region's peak load might be reduced by about 8% if 30% of the region's loads were responding to the transactive system.

TE Systems Implementations in Europe

The major European TE-based coordination mechanism, PowerMatcher, has been installed in approximately 1,000 households and industrial sites to integrate numerous small electricity-consuming and -producing devices in the operation of the electricity infrastructure. Since its incarnation in 2004, the PowerMatcher has been implemented in five major software versions. In a spiral approach, each version was implemented almost from scratch and tested in simulations and field experiments. The first three versions were research implementations written in the C# programming language. The second Java version, PowerMatcher 2.0, is industrial-strength software and is open source available through the Flexiblepower Alliance Network (FAN).

PowerMatcher puts the end customer in a central position in the smart grid. It is the end customer who owns the domestic appliance, electrical car, and/or industrial installation that is potentially able to offer the operational flexibility needed for a smart and sustainable electricity grid. PowerMatcher empowers the end customer to sell this flexibility to the parties interested. This selling is completely automatic using a piece of intelligent software installed at the premises of, and running under the authority of, this end customer. This so-called intelligent agent trades on behalf of the end customer. For this trading activity on behalf of the device owner, the uniformed data messages exchanged are stripped of specific local information. Only aggregated information regarding power levels and prices is exchanged, protecting the privacy of the customer.

With the European electricity sector highly unbundled into a market subsystem trading the electricity commodity and a network subsystem dealing with operation of the physical transmission and distribution networks, the two main application fields of the PowerMatcher tecŸology are found in market operations and in active distribution network management. As the operations of these two subsystems are highly separated in Europe, PowerMatcher approaches these as two separate control objectives. The intelligence at the level of the customer premises, regardless of whether it is a household, business, or industry, delivers the available flexibility as a service to both sides. This leads to the multigoal optimization model depicted in Figure 8.

> TE systems have clear advantages over more common smart grid coordination, such as price reactive systems and centralized optimization.

PowerMatcher Field Experiences

An overview of accomplishments in field trials can be found in Table 1.

Couperus Smart Grid, 2011–2015

The Couperus building in the large The Hague suburb of Ypenburg, The Netherlands, includes an apartment tower of more than 70 m (Figure 9). Each of the approximately 300 apartments in the tower has an individual heat pump feeding low-temperature floor heating and a heat storage tank containing hot tap water. The Couperus smart grid project tested the ability of these heat pumps to 1) integrate wind energy through imbalance reduction and 2) capacity management (peak shaving) on the local low-to-medium voltage substation. In the first case, the heat pumps reacted, through the use of PowerMatcher's electronic market, to the unexpected over- or underproduction of a nearby wind farm. The so-called imbalance of the wind farm, i.e., the difference between its day-ahead forecast and the actual production, was used as a real-time control objective. In the European electricity wholesale markets, these imbalances generally lead to less revenue for the wind farm owner. Thus, reducing imbalance creates value for renewable generators. Simultaneously, the heat pump flexibility was used for congestion management in the local distribution grid.

Each heat pump is represented by an intelligent control agent that delivers the pump's operational flexibility to the electronic market under the condition that it controls the apartment's inner temperature within a temperature band of 0.8 °C around the user set point. In this way, the comfort of the residents is always the first priority: if a resident wants a

figure 8. Orthogonal multiobjective optimization using transactional control and coordination. The intelligent system at the customer's premises delivers the available flexibility in two directions.

table 1. A summary of field validation results for the PowerMatcher.			
Project/Demo	**Description**	**Results**	**Year**
Crisp field experiment	Flexibility sourced from industrial and household sites reacting to fluctuations in wind energy generation.	Electricity market related gain: wind imbalance reduction of 40%.	2005–2006
Microcogeneration field experiment	Flexibility from microcogeneration units at households used to perform peak-load reduction in a distribution grid.	Distribution grid peak-load-reduction of 30% (during summer) to 50% (during winter).	2006–2007
PowerMatching City	Demonstration of simultaneous optimization for energy trade and active distribution management. It included a value assessment of end user flexibility.	Based on the demo's outcomes, the value of end user flexibility in The Netherlands may reach an estimated €3.5 billion (US$2.8 billion). The Netherlands has a population of 17 million people.	2009–2015
Smart-charging electrical vehicles (EVs)	A series of tests with smart-charging EVs coordinated using PowerMatcher, backed by large-scale simulation study (Grid4Vehicles project).	Active network management: distribution grid peak-load-reductions of 30–35%.	First EV test: about 2007; Grid4Vehicles simulation: 2010
SmartHouse/ SmartGrid scalability field experiment	Scalability stress test of large-scale information communications technology (ICT) architecture connected to a cluster of real households.	Scalability beyond 1 million customers is feasible.	2010
EcoGrid EU demonstration	Large-scale demonstration of a novel real-time market involving 5-min electricity prices communicated to about 1,800 households, of which a subset ran PowerMatcher's ICT architecture.	Large-scale roll-out experience for price-based and transactive smart grid technologies. Unleashed flexibility from a large number of heat pumps, making 20% of their power consumption shiftable in time.	2011–2015
Couperus	Approximately 300 apartments with heat pumps (HPs) involved in simultaneous optimization for energy trade and active distribution management.	Electricity market related gain: wind imbalance reduction of 80%. Active network management: proof of principle of locational-price based congestion management. Operation of HPs shiftable up to eight hours.	2011–2015

temperature of 19°, then his/her heat pump's agent will keep the temperature between 18.6 and 19.4 °C. A temperature variation in such a narrow bandwidth is not noticed by the resident, while it allows the agent to postpone activation of a heat pump by six to eight hours.

figure 9. The Couperus building in The Hague, The Netherlands, was used as a TE test site. (Photo courtesy of Van Dongen-Koschuch Architects and Planners.)

During the demonstration, the wind imbalance was reduced by more than 80%. At the same time the system showed it was capable of performing locational-price based congestion management in the local distribution grid.

Lessons Learned

The analysis results from these demonstrations indicate that independent decision making based on a frequently updated market-based signal can regulate the overall feeder load for economic and reliability benefits. Automation with simple user interfaces and program design is important to make this work. The technology must also be inexpensive and simple to install and maintain. The costs of deploying specialized communications and automation that can host the intelligent agents will likely lead to deployment approaches that incorporate these technologies for additional purposes (such as general building automation, premises security, or health-monitoring systems).

> Independent decision making based on a frequently updated market-based signal can regulate the overall feeder load for economic and reliability benefits.

In all of the demonstrations, it would have been interesting to collect and analyze further data. For example, to analyze household learning patterns and thermostat interactions, a demonstration program needs to operate over a long period (perhaps two years). This would also allow for analysis of seasonal variations. In addition, a greater population of responsive resources on the same feeder could provide direct measurement of the ability of a portfolio of resources to regulate feeder power levels for peak shaving and other benefits. Lastly, additional sensing of equipment operation could corroborate the derived information deduced by statistical analysis of metered data and better inform simulation models.

The demonstrations only begin to address some of the many questions about such a transactive system. Due to the complex nature of interactions between consumers, smart equipment, and the electricity system, as well as the changing demands due to weather and time of day, week, and year, characterizing the amount of flexibility in the distribution system and the elasticity of demand-side resources to price is very difficult. The field data begins to provide insights, but predictive modeling and bell-weather metrics remain immature. More work is needed to develop a theoretical basis for analyzing these complex systems and testing designs for performance and stability prior to deployments.

Conclusions and Future Directions

The potential benefits from harnessing the flexibility in the operation of distributed energy resources to help meet an evolving set of requirements for safe, efficient, reliable, and resilient energy systems grows daily. TE concepts embrace the complex system of systems nature of electric power systems to present practical, scalable ways to integrate the assets of many self-directed participants working toward a mixed set of individual and shared objectives. Characteristics of any reasonable solution need to address the following important concerns:

- ✔ mitigate privacy, free will, and cybersecurity issues
- ✔ define a simple cyberinteraction paradigm, applicable at all levels of the system and supported by standards
- ✔ offer viable transition paths that coexist with traditional approaches
- ✔ provide smooth, stable, predictable operation and graceful degraded performance when stressed.

A transition to TE at the distribution level of the system challenges the status quo. Successful outcomes require acceptance by business and policy decision makers as a cost-effective, valid, equitable, and advantageous revenue/investment recovery mechanism. In addition, a vibrant vendor community (or tecŸology ecosystem) must emerge to supply a healthy variety of transactional products and services, such as operating platforms that support the integration of a heterogeneous mix of equipment, as well as the associated system and device-level automation needed to negotiate, operate to expectations, and reconcile agreed-upon transactions.

Work is underway to socialize TE concepts through the GWAC in North America and FAN in Europe, while FAN is also advancing TE framework standards and the Smart Grid Interoperability Panel is facilitating the extension of existing standards and development of new interface standards.

For Further Reading

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Biographies

Koen Kok is with The Netherlands Organization for Applied Scientific Research and the Technical University of Denmark, Roskilde.

Steve Widergren is with Pacific Northwest National Laboratory, Richland, Washington.