Achieving high performance with theft analytics

Leveraging smart grid deployments to enhance revenue protection

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Introduction

The recent economic meltdown was tough on electric utility revenue protection teams. In Florida, Tampa Electric Company and Progress Energy reported increases of 10 to 15 percent in 2009.[1] American Electric Power, a utility that serves rust-belt states such as Michigan and Indiana, investigated 27 percent more theft cases in January and February of 2009 than it had the previous year.[2]

Outside the United States, energy diversion has been estimated to be about a CA$100 million problem in British Columbia, Canada, as of the end of 2010, according to BC Hydro reports.[3] In South Africa, Eskom called for tougher laws to combat theft in 2010, citing annual losses in the range of R 4.4 billion (US$638 million).[4] The Turkish Electricity Distribution Company reported theft increased from 14.4 percent of generation in 2008 to 17.7 percent in 2009.[5] And as is the case with many developing countries, India's energy diversion figures represent a significant drain on the nation's already stretched energy delivery infrastructure. India's T&D losses equal about a third of power generated in the country, and theft costs the nation's distribution companies an estimated US$16 billion per year.[6]

Fortunately, while energy diversion has been increasing, the evolution of smart grid technologies has brought about better ways to analyze and identify potential diversion. Smart meters and grid devices provide the type of data that can be leveraged by back-office analytics and software techniques to detect theft and support the next steps of revenue protection—prosecution and payment collection. Leveraging smart grid devices for revenue protection enables utilities to achieve powerful payback benefits from their smart grid investments. This paper introduces a capability framework for utilities to consider in the pursuit of achieving high performance. We review smart grid and back-office analytics maturity against the types of diversion that can be identified and benefits captured based on various smart grid deployment levels.

The business problem: theft techniques and impact

In the United States, energy diversion costs ratepayers an estimated $6 billion annually.[7] Nontechnical revenue losses are estimated to account for 2 to 4 percent of revenues in the utility meter-to-cash cycle, and an estimated 80 percent of those losses stem from theft or metering defects.[8] A 2007 World Bank report on South Asia stated that system losses range from 20 to 45 percent.[9]

The most common methods of energy diversion include:

Neighborhood power diversion
Users divert energy from a neighboring apartment or premises.

Meter tampering
Consumers tilt or remove a meter from the socket, insert the meter upside-down in the socket or place magnets on electromechanical meters.

Meter switching
A high-consumption or disconnected consumer illegally switches meters with the unit from a nearby low-consumption, vacated or abandoned premises.

Wire partial bypass of the meter (jumpers) inside the meter enclosure
The user connects a wire (often jumper cables) before and after the meter reading unit to partially bypass the meter, thus causing some of the current to not be registered by the meter. Typically, the bypass supplies power to large and stable loads such as air conditioning or heating.
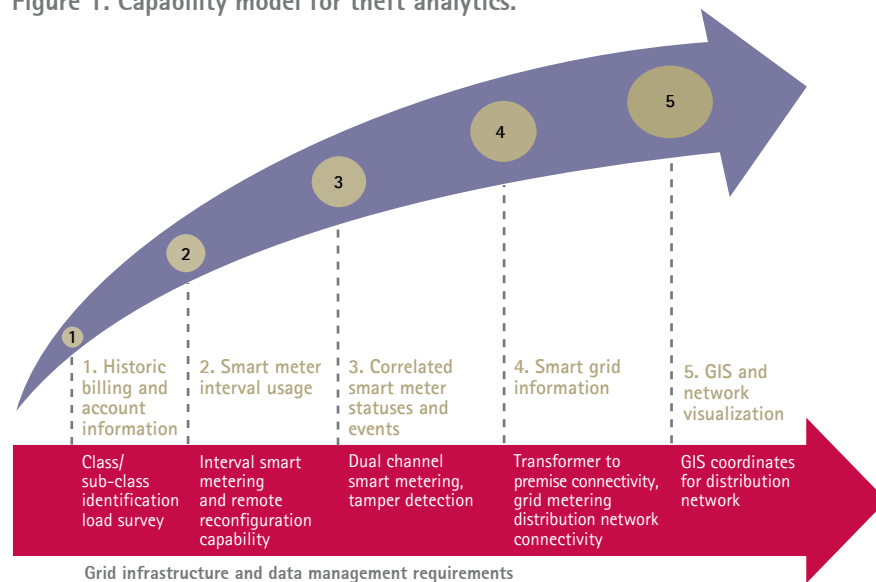
Complete bypass of the meter from the low-voltage grid
A tap may be made on the service drop from inside the customer premises, making observation of the tap process and the actual tap impossible from the outside. Some utilities estimate that secondary voltage taps ahead of the meter accounted for two-thirds of investigated energy thefts.

Direct connection to the primary voltage grid/distribution feeder with a pirate distribution transformer
This method requires lineman skills and is generally dangerous for anyone who is not trained. It is more likely to be done in rural locations than urban or suburban.

A capability model for diversion analysis

Figure 1. Capability model for theft analytics.

1. Historic billing and account information	2. Smart meter interval usage	3. Correlated smart meter statuses and events	4. Smart grid information	5. GIS and network visualization
Class/sub-class identification load survey	Interval smart metering and remote reconfiguration capability	Dual channel smart metering, tamper detection	Transformer to premise connectivity, grid metering distribution network connectivity	GIS coordinates for distribution network

Grid infrastructure and data management requirements

Source: Accenture.

The increased deployment of smart metering and smart grid technologies, along with the ability to leverage powerful back-office analytics of data from such deployments, provides utilities with new opportunities for identifying and analyzing energy diversion in the distribution network.

Figure 1 illustrates Accenture's viewpoint on a capability model for revenue diversion analysis, starting with basic analytics on customer, account and billing data and progressing through analytics based on data from smart grid feeder and transformer meters. Note that the highest level, Level 5, represents an aggregation of capabilities of the prior levels, with an emphasis on utilizing geographic information systems (GIS) and network visualization to apply geospatial analytics to the problem of energy diversion.

The five levels of the model correlate the required level of maturity in grid infrastructure, smart metering, modeling of distribution network connectivity and back-office capabilities to levels of maturity in energy diversion identification and analysis. Since the model is structured in the context of grid infrastructure and back-office data management capabilities as a frame of reference, it also provides a framework that can be used to develop a roadmap for a revenue diversion analytics solution aligned with smart meter and smart grid implementation activities.

Turning data into insight

Level 1

Historic customer, billing and account information uses monthly billing or time-of-use values in the utilities' customer information systems (CIS), as well as detailed load-survey information on seasonally adjusted usage ranges for similar customers (customer class and sub-class) to look for usage anomalies that fall outside statistical norms. Even in situations where a utility only reads residential customer meters once a month for billing, this form of analytics can be useful for detecting simple, unsophisticated types of diversion and large-grained usage anomalies, such as those caused by defective, slow or stopped meters, simple forms of meter bypass, neighborhood power diversion and unregistered consumers, which might result from soft shut-off policies.

This form of analytics compares usage to predetermined thresholds and patterns of use by certain customer classes and even by data such as household size or business type. To make the model more robust, utilities can leverage additional information, including load-survey data, weather data and CIS processes for tracking move-out, vacation notifications, foreclosures or other events that affect consumption. Utilities should also impose thresholds for comparison. Examples include looking for consumption that is 20 percent more or less than a customer's seasonally adjusted usage or a vacant-house threshold that exceeds normal leakage, such as more than 10 kilowatt-hours (kWh) per billing cycle. An on-site inspection might be in order when usage falls outside the expected threshold.

A limitation of such modeling is that, in the absence of smart metering, reports of anomalies only occur once for each billing cycle and have to be of an aggregated magnitude that shows up as an anomaly in the average seasonally usage pattern for the billing month.

Depending on the legal framework and consumer privacy laws in effect in the jurisdiction, the analytical framework may also involve proactive identification of likely sources of energy diversion and nonpayment via the analysis of the customer's credit history, criminal history and payment/account history for the customer's network of social connections.

Figure 2. Load profiles: The two-peak residential profile and step waveform of street lighting.

Daily usage profile (residential and street lighting)
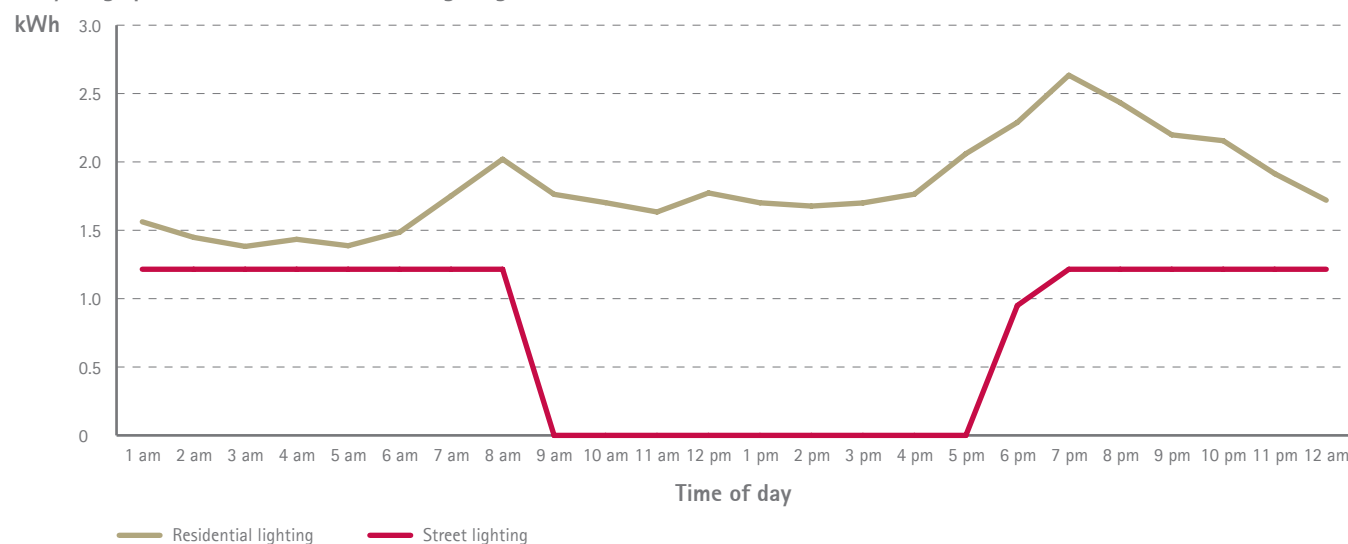
Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?
Page=Supplier_Residential.

Level 2

Smart meter interval usage utilizes similar comparative analytics as level 1, but it examines interval data profiles and daily usage values to identify finer-grained and more sophisticated types of diversion or tampering. The analytical techniques are based on a comparison of a customer's hourly or more granular usage pattern with that of the customer class and sub-class on a time of day, weather and seasonally adjusted basis. Through review and analysis of normal usage patterns and suspect patterns, the approach allows utilities to target specific types of diversion, such as a partial bypass during the weekend or during specific times of the day. In addition, the analytics enable utilities to target suspect patterns, such as consecutive zero reads for additional investigation.

Since it is unlikely any customer would go through two or more intervals without registering any consumption on the meter, consecutive zeros may reflect meter tampering or theft. Utilities also can look for measurement and conversion errors in the metrology or in the back office (such as defective meters and incorrect meter multipliers).

Load-profile analysis also comes into play to identify situations in which the diversion is being used to feed loads that follow a pattern not typically associated with the customer class. One example would be situations in which residential diversion of electricity via a meter bypass is used to provide electricity to illegal marijuana grow houses. As Figure 2 illustrates, residential load typically follows a two-peak pattern, while street lighting follows a step waveform because lights get

switched on and off. These load profiles are valuable for detecting electricity theft in cases involving marijuana grow houses, which are a primary source of revenue diversion for some utilities located throughout the world. Grow houses use high-intensity, warmth-producing lights, and the on-off operation of these lights results in a step waveform load similar to that of street lighting.

Additionally, even under conditions of a partial bypass in which part of the energy is flowing through the meter for some or all of the time, the interval usage from an average-sized grow house will exceed average residential usage by an order of five to 10 times, and the step pattern associated with the lighting load will be the dominant pattern demonstrated by the metered

Figure 3. Load profile of an illegal marijuana grow house with and without a partial meter bypass.

Comparing grow house usage profile against typical residential and lighting profiles
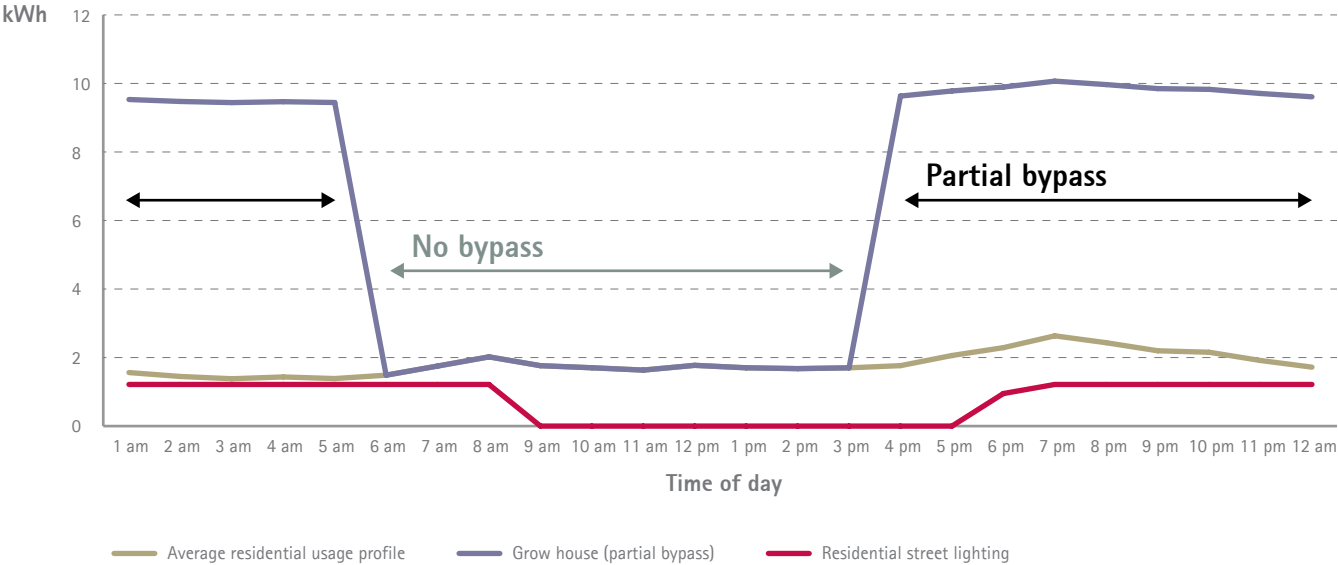
Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?
Page=Supplier_Residential.

load. This pattern is illustrated in Figure 3, which shows both the waveform and the magnitude of hourly usage of a residential grow house with a partial meter bypass compared to a typical residential load patterns.

Note that while this and other examples in this paper use a grow house for illustrating examples of large-scale diversion, one can also take this approach for other forms of diversion.

Level 3

Correlated analysis of smart meter information assumes a utility has smart metering and back-office systems that can support capabilities such as dual-channel interval metering for import and export values, as well as smart meters with statuses and device initiated reporting of possible tamper statuses and events such as tilt detection, momentary outages and reverse

rotation. Given these technologies, utilities can look for individual meter tampering and bypass or unauthorized usage.

The anomalies that represent such pilferage can be identified through analytical capabilities that correlate smart meter information with back-office information such as customer's rate in CIS/billing system, service orders and other data. Some examples of such analytics and diversion detection patterns include:

- Detection of reverse energy accumulation on an account that is not on a net-metering or energy-generation rate.
- A large number of momentary interruptions in a multiday window that exceed a preconfigured threshold or follow specific patterns (such as repeated occurrence during peak days).

- Meter alerts that report events, such as unauthorized configuration, outages upgrades, optical-probe access events or meter tilt alerts without any service orders that these can be correlated to and load itself when there has been a service disconnection at the premises.

By correlating these status and event notifications against other real-time events and enterprise information, such as service calls, blink counts on the feeder or scheduled upgrades, candidates for diversion investigation become much more apparent.

Level 4

Correlated analysis of smart grid information is where utilities truly begin to leverage investments in smart grid deployments and back-office capabilities to realize benefits associated

with improved detection and analysis of their revenue diversion and non-technical loss problem. This approach involves transformer and feeder metering, as well as corresponding back-office analytics. The solution, which is discussed in further detail under "Leveraging smart grid infrastructure today" on page 10, requires that the utility has information pertaining to transformer-to-premises connectivity and maintains up-to-date connectivity models of each premise and distribution transformers to its feeder line and phase based on the as-operated state of the distribution grid, and information from the supervisory control and data acquisition (SCADA) system and distribution management system (DMS).

Level 5

Visualization extensions analyze information along multiple dimensions for greater understanding of areas where diversion is happening and, perhaps, predictive capabilities. Such analytics combine time-based information from smart meters, event alerts and sensors with a geospatial model of structural and connectivity aspects of the distribution system from substations to premises, as well as enterprise data on customers and how each account ties into the distribution network connectivity model. To achieve this, utilities will need to have captured GIS coordinates for meters and other smart grid assets as part of the smart grid rollout, and they will also need to maintain an up-to-date connectivity model that reflects the as-operated state of the distribution grid.

In the back office, utilities need to develop architecture and models that enable real-time and online analytical processing (OLAP) of smart grid facts and measurements, such as meter and sensor readings and status across the dimensions of time, distribution network topology and geospatial hierarchies and coordinates.

Geospatial analytics can show revenue protection teams which areas are most susceptible to diversion at a given time, allowing utility workers to prioritize field investigation efforts based on what the analytic engine shows them. This awareness also has the potential to enhance planning capabilities and safety for investigators by giving them a way to pinpoint suspected theft locations via satellite images, such as those found in Google Maps™.[10]

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Leveraging smart grid infrastructure today

Figure 4. Feeder section analysis.
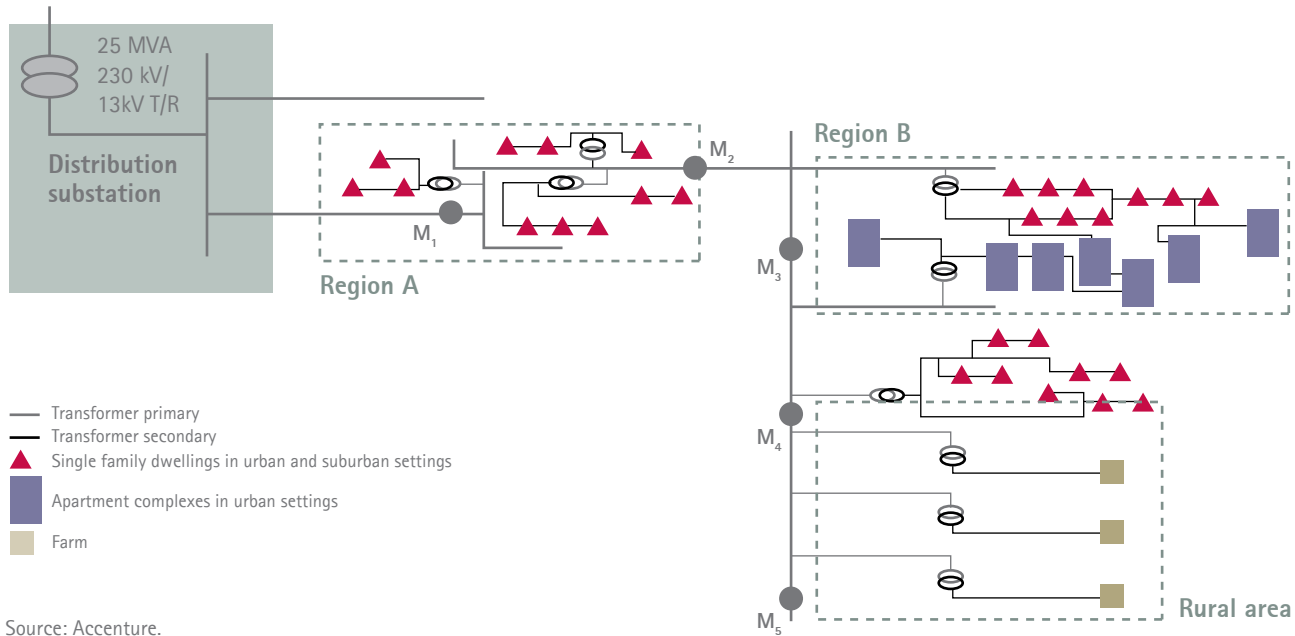
Source: Accenture.

Feeder section analysis

Feeder section analysis is an important analytical approach that can be used in association with smart grid deployments to identify diversion associated with tap-ins on the primary side of the distribution transformer (in urban and suburban settings) or directly in to the distribution feeder (which generally occur in rural settings where long sections of feeders often go uninspected for extended periods). The typical high load values associated with such diversion allows utilities to use "energy-balance" techniques for detection. This method uses single-phase feeder meters placed on the feeder at a utility selected interval, such as every 50 customers per phase. These devices allow monitoring of energy imports and exports within individual feeder sections as illustrated in Figure 4.

Figure 4 shows an example of a feeder from a distribution substation with sections feeding three distinct regions through secondary lines. Distribution transformers are depicted by the over-lapping gray (transformer primary) and black circles (transformer secondary). Feeder meters are generally represented in the figure above with the notation M_i.

The utility can calculate the net energy delivered to that section as the difference in energies from the upstream feeder meter (M_{n-1}) and the one downstream (M_n) over a period of time. Then, the utility can balance that against the sum of energies registered in the meters of customers served from that feeder section. This can be mathematically represented as:

$$s(t) = \int_0^t \left\{ M_{n-1}(t) - M_n(t) - \sum_k m_k(t) - L_n(t) \right\} dt$$

On any feeder section, with no diversion, the difference in energy usage measured between feeder meters on both ends of section over time ("T") should be nearly the same as the sum of metered energy usage (m_k) measured for same period for consumers on that section. Slight differences will be due to line losses and unmetered loads (L_n) connected to secondary distribution, but these are quite small compared to the diversions utility workers generally target.

With no energy diversion, the net energy delivered will match fairly closely the sum of consumption for the meters at customer premises. Normal line losses should be in the 0.5 to 4 percent range.

When large energy diversions are present, the energy delivered to the feeder section will significantly exceed the sum from the premises meters for the time periods when diversion is

Figure 5. Representative results from a utility feeder metering pilot.

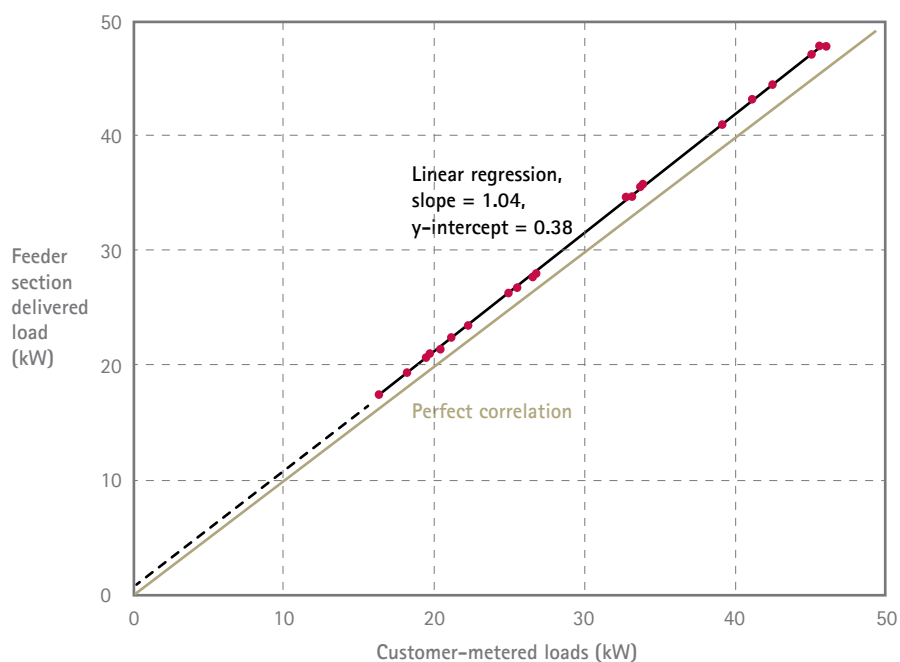| Feeder section number	Number of customers	Net of feeder meters ($M_{n-1} - M_n$) (kWh)	Σ (metered customer usage) (kWh)	Energy balance	
				Missing (kWh)	Missing (%)
1	61	6,787	3,872	2,915	42.9
2	52	5,087	3,727	1,360	26.7
3	43	3,727	3,698	29	0.8
4	18	1,576	1,521	55	3.5
Rest	201	18,095	14,054	4,041	22.3
Total	375	35,272	26,872	8,400	23.8

Note: Data is illustrative, examples based on typical diversion-related losses to show expected results.

Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

taking place. Figure 5 illustrates results representative of a diversion-detection pilot conducted by a utility that used feeder metering. While feeder-line sections 3 and 4 show typical losses of 4 percent or lower, feeder sections 1, 2 and several others represented by the word "rest" show losses as high as 42 percent.

An energy balance analysis using linear regression can be used to identify statistically significant differences between energy imports and exports from a feeder section that cannot be explained by losses or metering errors. The scatter plot in Figure 6 illustrates the hourly total customer metered load (Σm_k) on the X axis versus the feeder section delivered load ($M_{n-1} - M_n$) on the Y axis. This plot looks at the correlation between the total customer-metered load and utility-supplied load. In an

Figure 6. Figure feeder section with no theft.

Feeder section delivered load (kW)

Linear regression, slope = 1.04, y-intercept = 0.38

Perfect correlation

Customer-metered loads (kW)

Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

ideal world, the individual hourly data points would show a one-to-one relationship where energy ($M_{n-1} - M_n$) equals energy out ($\sum m_k$). However, in the real world, technical losses and calibration errors should show themselves as a slight change in slope, as represented by the slope of 1.04 in Figure 6 corresponding to technical losses of 4 percent.

Meanwhile, energy theft should show itself as a nonzero y-intercept, meaning that even if the total customer-metered load were to go to zero, energy would still be delivered to the feeder section. Performing simple linear regression on the load scatter plot data will provide the slope (technical line losses and calibration errors) and y-intercept (theft) values directly.

A scatter plot with a nonzero y-intercept, such as in Figure 7, would be indicative of a constant (i.e., 24-hour) electricity theft of 100 kW. The slight dispersion of the data points around the linear regression line indicates that the theft is not perfectly constant throughout the day.

Lastly, a scatter plot that shows two separate trend lines would be indicative of two separate periods during the day during which the theft level changed. In Figure 8, for one period the theft level was 17.5 kW (linear regression No. 1), while for the other period the theft level was 54.7 kW (linear regression No. 2).

Feeder sections with only single-phase customers would require single-phase energy balances. If theft is present, it will be identified on that particular phase, the lowest level of granularity available using feeder metering without transformer metering or any additional pinpoint techniques.

Figure 7. Feeder section with constant theft.
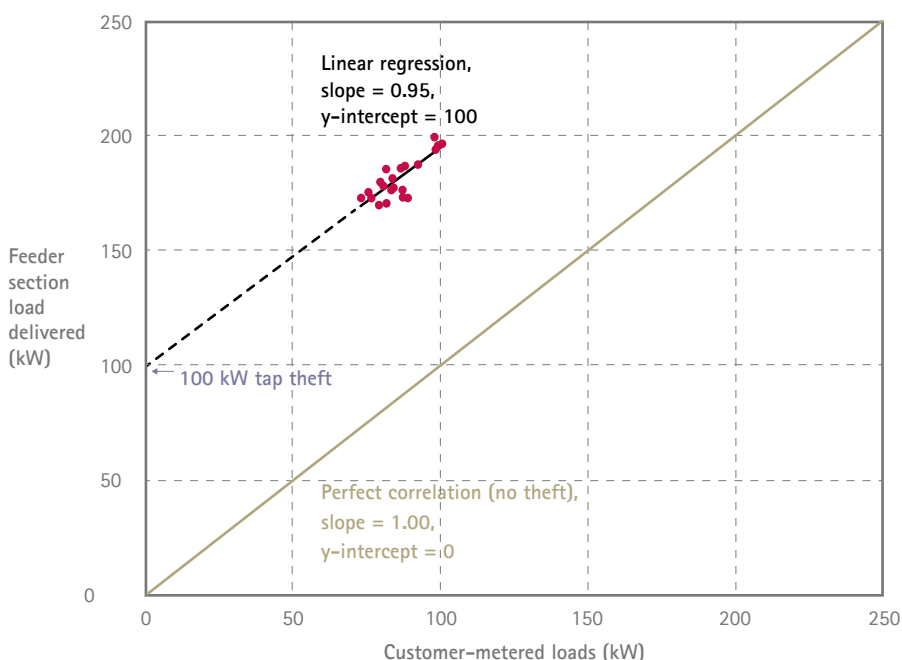
Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

Figure 8. Feeder section with periodic theft.
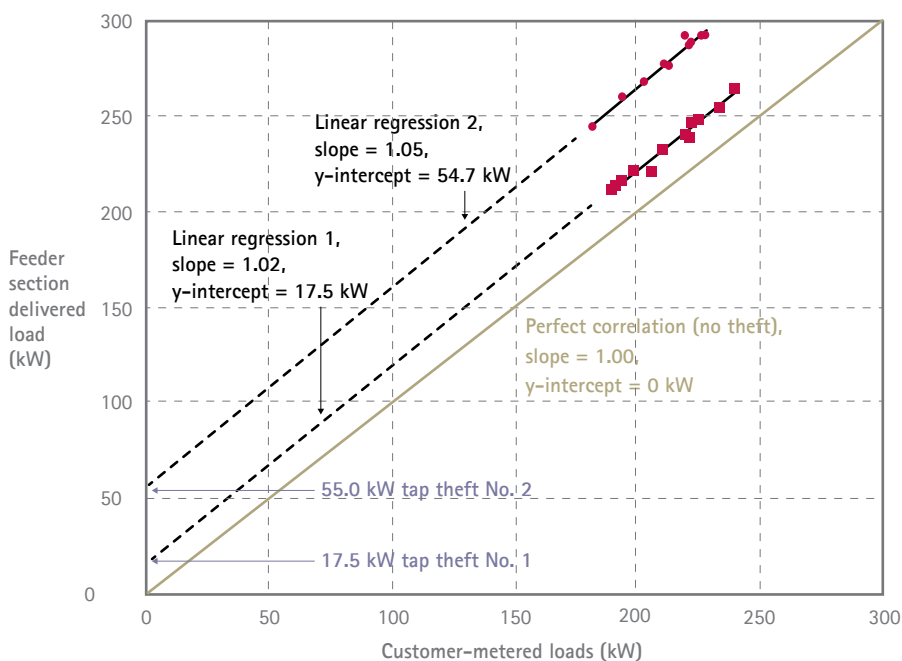
Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

One limitation with utilization of feeder metering for diversion detection is its sensitivity to feeder meter measurement errors at the head of the feeder (i.e., closer to the substation). Assuming a ±0.2 percent class meter, the feeder meters will each register the feeder load at their point of installation with a normally distributed error of less than ±0.2 percent (95 percent confidence level).

In the error analysis, the energy balance error is the sum of the errors from both feeder meters and the 50 customer meters. The customer meter errors are very small and tend to cancel each other out. The feeder meter errors, however, are larger and dominate the overall energy balance error. For the last 50 customers on the feeder, where there is no downstream energy, the energy balance error is less than 240 watts (W), 95 percent of the time. Any energy balance signal greater than 240 W is therefore almost certainly legitimate missing energy and not measurement error. As a result, the average residential diversion with 20 kW of load is easily detected.

However, as one moves closer to the substation and the feeder section's downstream or through load increases, so does the energy balance measurement error. At the substation fence, this measurement error is approximately 9.2 kW (assuming a 25 kilovolt (kV) feeder loading limit of 10 megawatts (MW) or roughly 3,300 kW per phase). At this rate, the average 20 kW diversion is detectable if thieves are tapping into their service drop conductors ahead of the meter and diverting their full load. If, however, the theft is a meter bypass using jumpers in the meter base, the thieves are most likely only diverting or stealing half of their load, or 10 kW. This

is roughly equal to the 95 percent confidence level for energy balance measurement error. Such a measurement therefore has a 95 percent chance of indicating legitimate missing energy or, conversely, a 5 percent or one-in-20 chance of being a measurement error. This measurement technique is at its limit at the substation fence as far as detecting typical theft is concerned.

Three-phase meters are another complicating factor for single-phase energy balances. Since three-phase meters only provide the total three-phase kWh consumption, one has to distribute a three-phase customer's load among the three individual phases. Alternatively, the energy balance could be conducted over a time period when the three-phase load is essentially shut down (possibly overnight). It should also be noted that customers with transformer-rated meters need to have load profile data with similar resolution to that of the residential meters; i.e., 0.01 kWh. Coarser resolution will introduce random noise into the energy balance computation.

For feeder sections with three-phase customers, a three-phase feeder section energy balance involving roughly 150 customers—50 on each of the three phases—would form an optimal unit of analysis. For example, since illegal marijuana grow houses typically exhibit loads in excess of 15 to 20 kW, three-phase nodes and secondary take-outs along the feeder may see load imbalances in excess of 50 percent.

A significant energy imbalance between the three phases could indicate large-scale diversion or, at the very least, the need for feeder balancing/optimization.

Once the known loads and imbalance on each phase have been accounted for (using smart-metered data from customer premises), any additional imbalance is likely to be a result of energy diversion. Figure 9 illustrates energy imbalance analysis for a feeder. The imbalance may be indicative of a potential illegal tap into Phase C.

Identifying theft on feeder sections is helpful, but it does not specifically identify who is stealing electricity, thus creating a need to further pinpoint diversion locations.

Localizing diversion

One of two methods can be used to localize diversions: "low-voltage outlier" and "successive halving." Both techniques allow verification of diversion without requiring access to a customer's property, and significantly reduce the safety risk to investigating crews.

Low–voltage outlier

All customers served from a given distribution transformer should have roughly the same service-entrance voltage. However, if one customer has a very large metered load or diversion, a significant voltage drop of six volts or more may occur on that customer's service leads running from the street to the meter. If there is a low-voltage outlier when comparing customers served from the same transformer, it most likely indicates potential diversion at the customer premise. If that customer does not have a correspondingly large metered load, then that is likely the diversion being sought. This theft localization technique is a potential solution for use in suburban areas where there are many customers served from a single transformer. Significant voltage outliers reported from smart metered endpoints with voltage profiling capability combined with automated analytical processing capabilities in the back office may also

Figure 9. Feeder section energy imbalance analysis.

Phase A
Phase B
Phase C (with grow house)
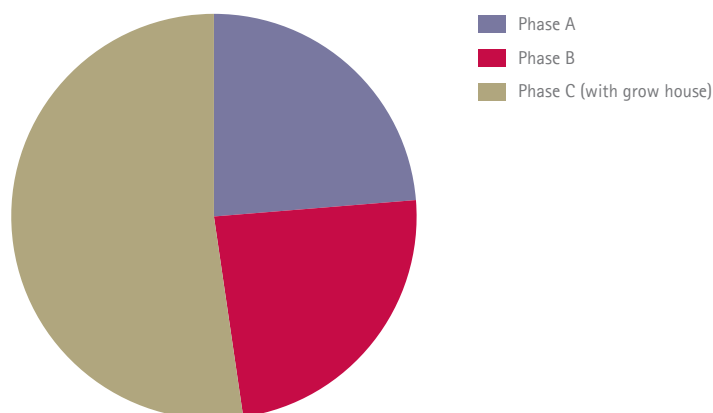
Source: Accenture.

be used as a standalone technique to identify suspected diversion in urban and suburban areas.

Successive halving

In rural areas, there is typically only one or two customers per transformer, and the secondary voltage distribution systems are much longer. The "voltage outlier" technique will probably not work in this environment. Rural localization of diversions would therefore use a process of successive halving, which means making a spot measurement in the middle of the feeder section, determining which half section the diversion is on and then dividing that half section in half again to repeat the process.

The field investigator would use a portable feeder meter to successively halve the feeder section and access the same analytics system via mobile computer that investigators use in the office. For field investigations, the application would temporarily set the section meters to report five-minute interval data and issue on-demand reads to retrieve and analyze data in near real time. The investigator would "insert" the temporary feeder meter into a GIS model to split the feeder section in two and then run the diversion detection application on each half section. Such efforts would likely take just under two hours to evaluate some 100 customers.

Transformer meters

Some utilities deploy meters on the primary side of distribution service transformers. Such devices are key smart grid technology components that assist utilities with the planning, monitoring and management of distribution transformer assets as well as in understanding the "as-operated" connectivity model for the distribution grid. Transformer meters can also be an important component of a utility's overall revenue assurance and diversion detection strategy, particularly to detect illegal taps on the secondary side or meter bypass situations, which are some of the more common and simpler diversion methods used in urban and suburban settings.

The approach is based on conducting an energy balance analysis between the primary and secondary side of the distribution transformer and can be mathematically represented as:

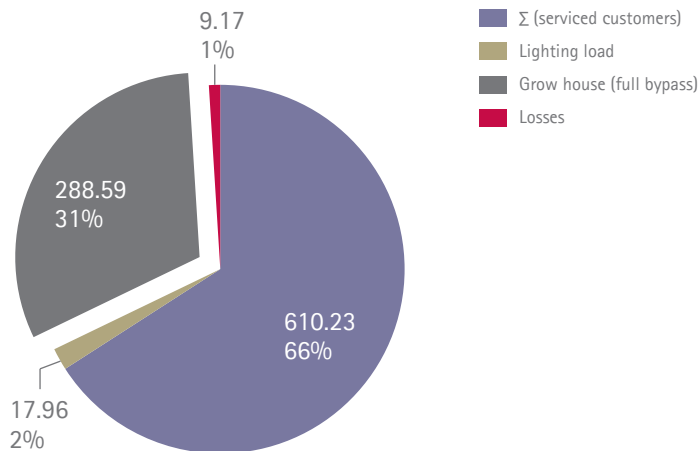$$s(t) = \int_0 \left\{ m_{tp}(t) - \sum_k m_k(t) - \sum_l um(t) - I_x(t) \right\} dt$$

Over a rolling time interval "t," mtp represents the energy usage recorded on the primary by the transformer meter, "m_k" represents the usage recorded by smart meters on consumer premises serviced through the distribution transformer, "um" represents the usage for each unmetered load serviced through the transformer and "I_x" represents transformer losses. Under normal circumstances, transformer losses and unmetered street lighting combined typically account for less than 3 percent of energy consumption at the typical North American distribution/service transformer with four to six residences (or less than 1 kW of average demand). Thus, a differential between the primary and secondary side that is greater than 3 percent of the energy usage recorded on the primary side would be a candidate for investigation.

Figure 10. Transformer metering analysis.
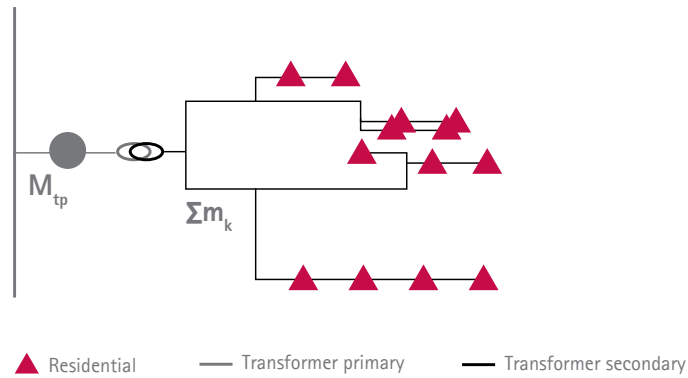
▲ Residential　　—— Transformer primary　　—— Transformer secondary

Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

Figure 11. Transformer usage for one day (kWh), full grow house bypass.

9.17
1%

288.59
31%

610.23
66%

17.96
2%

■ Σ (serviced customers)
■ Lighting load
■ Grow house (full bypass)
■ Losses

Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

In the specific context of secondary diversion using our example of illegal marijuana grow houses, the average daily demand of 15 to 20 kW from a typical grow house will manifest itself as a statistically significant difference that well exceeds the 3 percent factor for losses and can easily approach 15 to 40 percent unaccounted energy between the primary and secondary side. Figure 11 illustrates a typical case in an urban setting with a transformer servicing 14 residences and street lighting with a grow house load that fully bypasses the metered service on the customer's premise.

Figure 12. Transformer primary usage profiles.
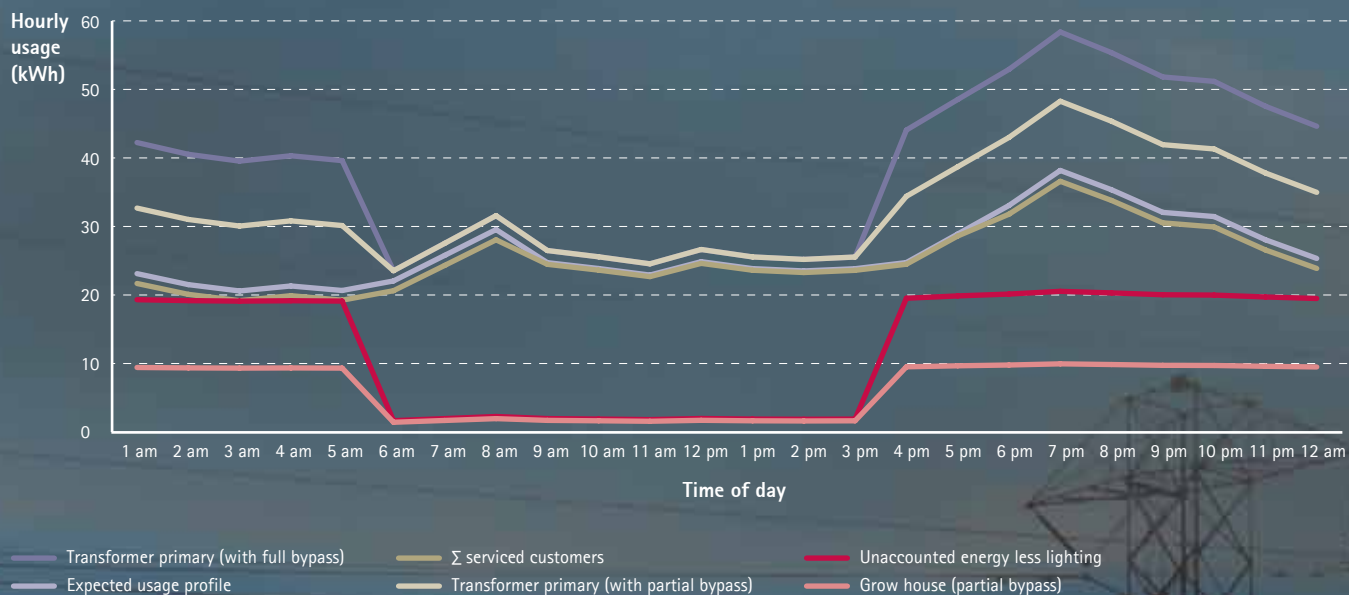
Hourly usage (kWh) / Time of day

Legend:
- Transformer primary (with full bypass)
- Expected usage profile
- Σ serviced customers
- Transformer primary (with partial bypass)
- Unaccounted energy less lighting
- Grow house (partial bypass)

Sources: Accenture analysis, representative data from NorthWestern Energy, Residential Customer Profile, www.northwesternenergy.com/display.aspx?Page=Supplier_Residential.

Additionally, as indicated by Figure 12, review of the transformer meter's interval usage profile could also give clues to possible diversion. That is because the profile will exhibit the familiar step-shaped waveform typical of on-off consumption used with lighting load and grow houses, as previously noted.

Beyond diversion detection: the relative costs and benefits of transformer and feeder meters

Transformer and feeder meters have broader smart grid benefits that go well beyond their impacts for diversion detection.

Using transformer meters reduces field investigation time, as customers and localized areas with high diversion are pinpointed by the data. However, when used in conjunction with feeder metering, they would also enable utilities to validate the "as-built" or known state of the network (recorded in GIS and SCADA systems), identify connectivity modeling errors, maintain up-to-date "as-operated" network models and perform more efficient distributional load flow analysis for DMS applications. Some of the additional distribution automation and smart grid functionality associated with feeder metering include:

Distribution optimization

On a real-time basis, feeder meters can provide feeder demand profiles, thus enabling feeder load balancing, line loss estimation and, to a limited extent, estimation of the thermal state of the feeder lines. Feeder meters can also provide capacity utilization data on a near real-time basis and, on a non-real-time basis, feeder-meter data may be mined for use in capacity planning, feeder and phase rebalancing or utilization studies.

Transformer meters may also be used to accomplish the above, although the utility must roll up current and power values from the end of the feeder back to the substation, and this will fail to find any diversion that may be done directly from the medium voltage (MV) feeder. Since diversions from the MV feeders are likely to be a rural rather than urban or suburban problem, rollup of the transformer meters will give good estimates of feeder loading in urban areas. Unmetered loads are served from secondary voltage distribution, so that the transformer meters also will register this usage.

Volt/var optimization

For volt/var optimization, three primary measurements are needed—voltage, real power and reactive power. Voltage magnitude varies over the length of a feeder due to a variety of factors, including the distribution of loads, the types of loads and the states of any distribution capacitor banks. Since voltage must be kept inside a narrow band at each customer, a view of the voltage profile measured at the feeder meter for the entire feeder circuit can be used to optimize settings for load tap changers, capacitor banks and voltage regulators.

Fault detection, classification and localization

Feeder meters provide a capability to record voltage sags. With this capability, utility workers can perform a partial sag analysis for fault analytics. If using the feeder meters in single-phase form in groups of three, a utility cannot obtain relative phase angles for the phase voltages, which means certain fault classes cannot be distinguished from one another. However, the meters still provide significant fault analytics capability based on voltage sags.

Going back to the theft detection benefits of feeder meters, these devices will detect primary feeder diversions in suburban areas, which would not be seen if only transformer meters were used. And, using feeder meters alone provides a significant reduction in capital cost over a combination transformer- and feeder-meter solution. In examining both options for a utility in the Pacific Northwest, Accenture estimated that using feeder meters exclusively and placing the devices at 50-customer intervals, the utility could save roughly $47 million over the cost of a transformer- and feeder-meter mix. The trade-off is that feeder meters and associated analytical techniques, when used in isolation, provide less diversion-location granularity and are more susceptible to measurement errors at the head of the feeder, which increases the field investigation time to find the actual diversions.

In the end, each utility will need to calculate its own return on investment for smart grid investments, such as feeder or transformer meters or a mix thereof to augment advanced metering infrastructure (AMI) data for advanced theft analytics. Looking back at the five-level continuum of analytic capabilities detailed in this paper, utilities can extract the most benefit from the diversion solution at level 4 and level 5, which go beyond AMI data

to include grid device information in the analytics mix. These solutions truly harness the power of grid equipment to make theft analytics smart. Such solutions require investment in distribution network model management, smart grid infrastructure and data management that many utilities have not yet made but are very relevant for a distribution smart grid. Adding theft analytics benefits to the business case would only help utilities further cost justify these expenditures.

To find out more about theft analytics or how Accenture could help your utility achieve high performance in your smart grid endeavors, please contact:

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