U.S. DEPARTMENT OF ENERGY | Office of Electricity Delivery and Energy Reliability

11.30.2011

Energy Efficiency in Distribution Systems

Impact Analysis Approach

SMARTGRID.GOV
RECOVERY ACT SMART GRID PROGRAMS

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Six areas are of particular interest for determining smart grid impacts.

Peak Demand and Electricity Consumption

- Advanced Metering Infrastructure
- Pricing Programs and Customer Devices
- Direct Load Control

Operations and Maintenance Savings from Advanced Metering

- Meter Reading
- Service changes
- Outage management

Distribution System Reliability

- Feeder switching
- Monitoring and health sensors

Energy Efficiency in Distribution Systems

- Voltage optimization
- Conservation voltage reduction
- Line losses

Operations and Maintenance Savings from Distribution Automation

- Automated and remote operations
- Operational Efficiency

Transmission System Operations and Reliability

- Application of synchrophasor technology for wide area monitoring, visualization and control

Note that AMI can be used to increase the functionality of distribution applications.

DOE's Smart Grid Benefits Framework relates smart grid assets, functions and benefits.

Smart Grid Assets → **Higher Functionality** → **Benefits for Utilities, Consumers and Society**

Smart Grid Assets

- Smart meters
- Automated switches
- Phasor measurement units

Higher Functionality

- Better load measurement and management
- Faster circuit switching
- Grid disturbance monitoring

Benefits for Utilities, Consumers and Society

- Peak load reduction
- Shorter outages
- Better grid reliability

Our analysis will try to determine how asset combinations can be used to reduce distribution losses and end-use energy consumption.

Analysis Objectives
• Determine the improvement in energy efficiency from the application of technology used to optimize circuit voltage and implement conservation voltage reduction. • Determine what technology configurations are most important for delivering measurable results. • Quantify the value of energy and capacity savings for utilities, electricity savings for customers, and lower emissions.

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Voltage and VAR control technologies monitor power, determine control settings, and then physically adjust voltage and reactive power.

Equipment to change voltage and power factor

- Transformer LTCs
- Distribution capacitor banks
- Distribution voltage regulators

Technology to measure voltage and power factor, control equipment, and coordinate/optimize settings

- Substation voltage and current sensors (including CTs/VTs)
- Distribution voltage and current sensors (typically included in control packages)
- SCADA to communicate readings back to central location
- Smart meters
- AMI communications to communicate readings back to central location
- Control packages for transformer load tap changers (LTCs)
- Control packages for capacitors
- Control packages for voltage regulators
- Distribution management systems and voltage optimization software

Capacitor bank

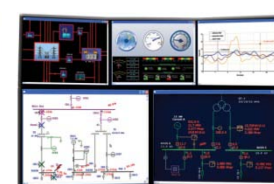
Voltage regulator

Line voltage sensor

Smart meter

Control package

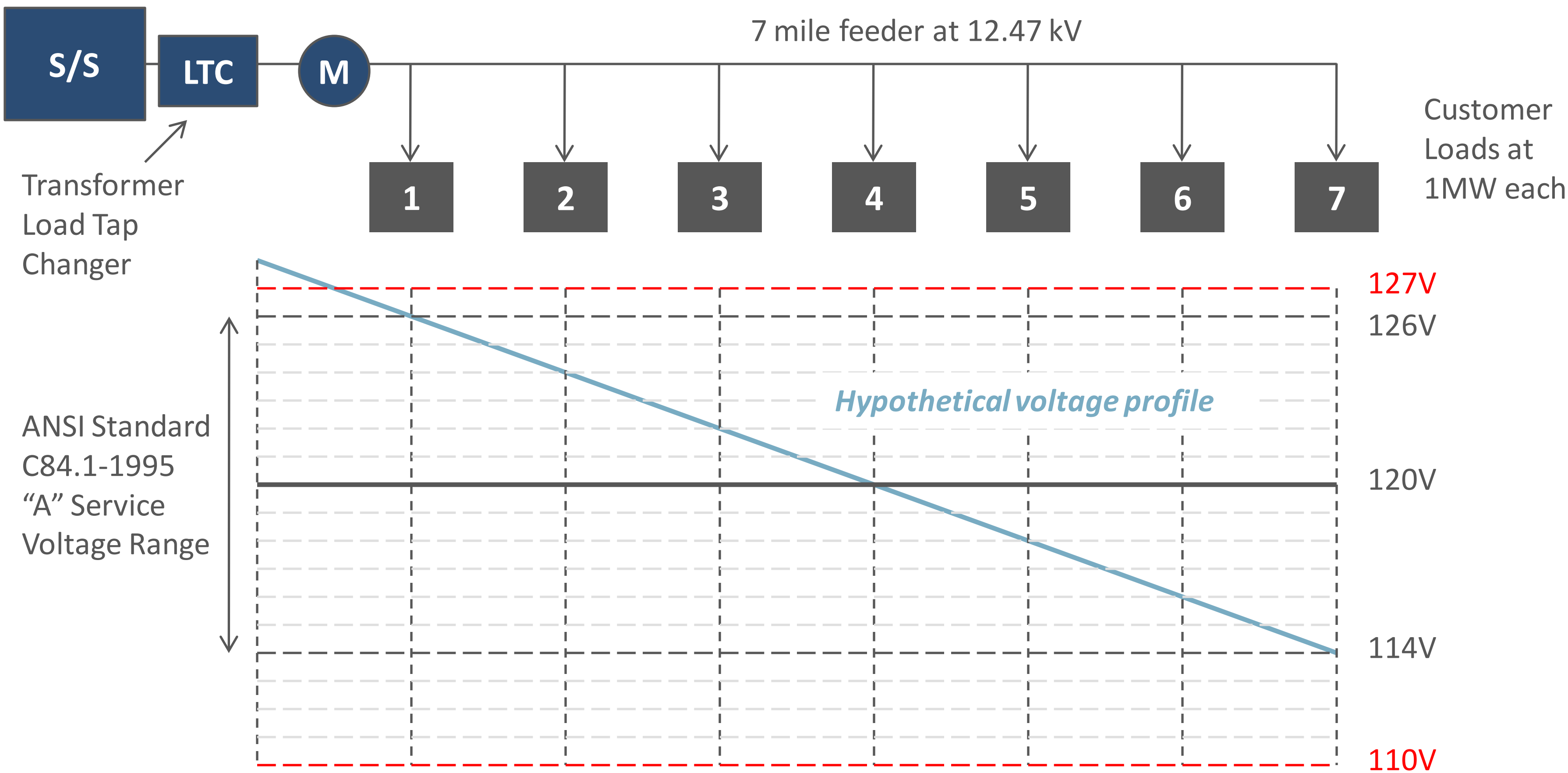
Distribution Management System



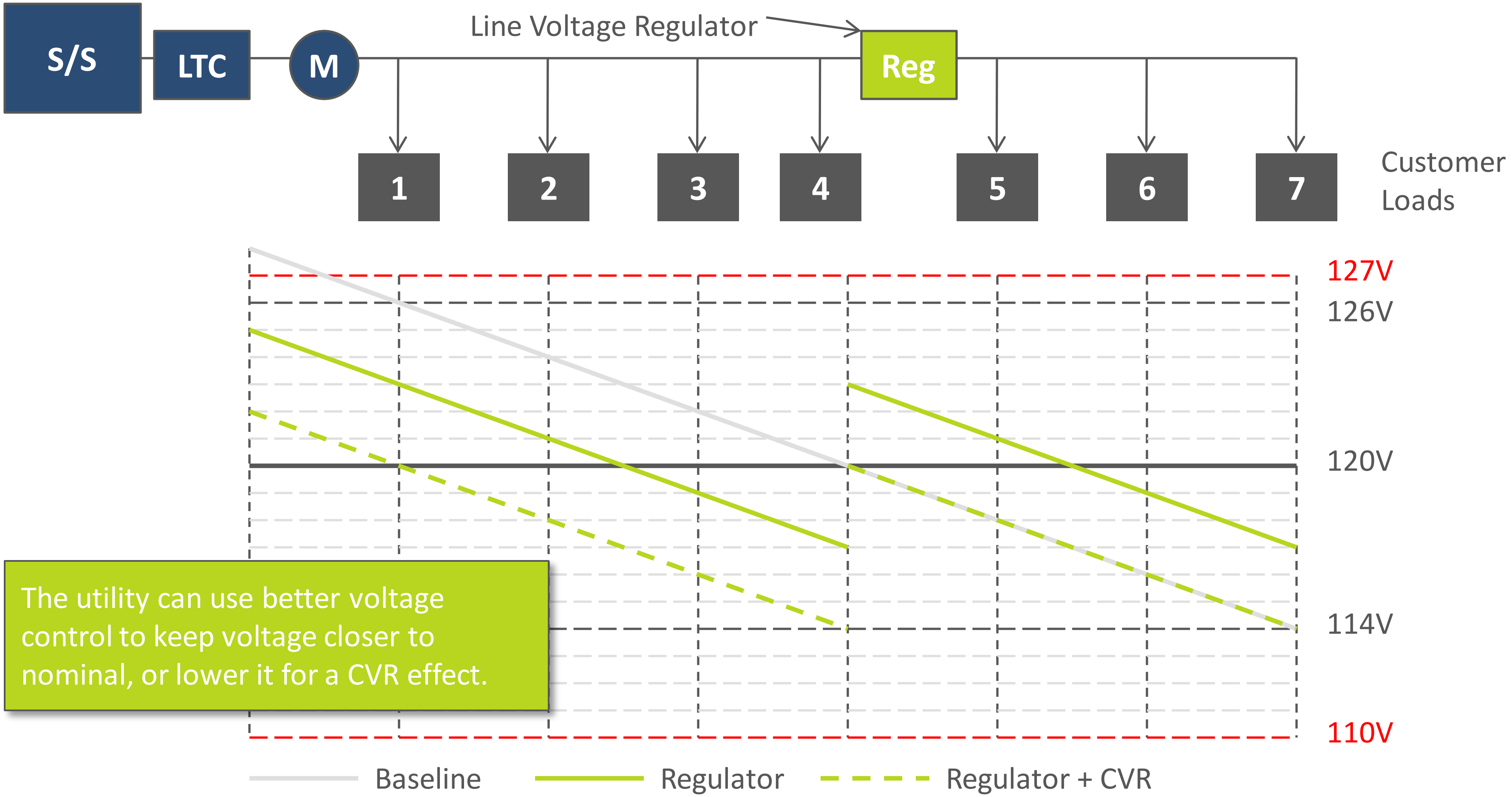
Utilities are pursuing three general objectives as part of their SGIG projects.

Voltage and VAR Control (VVC)	Operating transformer load tap-changers, line voltage regulators and capacitor banks to adjust voltage along a distribution circuit and compensate load power factor.
Voltage Optimization (VO)	Coordinating VVC devices to achieve voltage profiles that meet the utility's operational objectives, including energy delivery efficiency, power quality, and reliability.
Conservation Voltage Reduction (CVR)	Utilizing VVC and VO functionality to lower distribution voltages for energy savings, without causing customer voltages to fall below minimum operating limits.

Line voltage drops from the LTC at the head of the distribution line to customers farther out on the line.

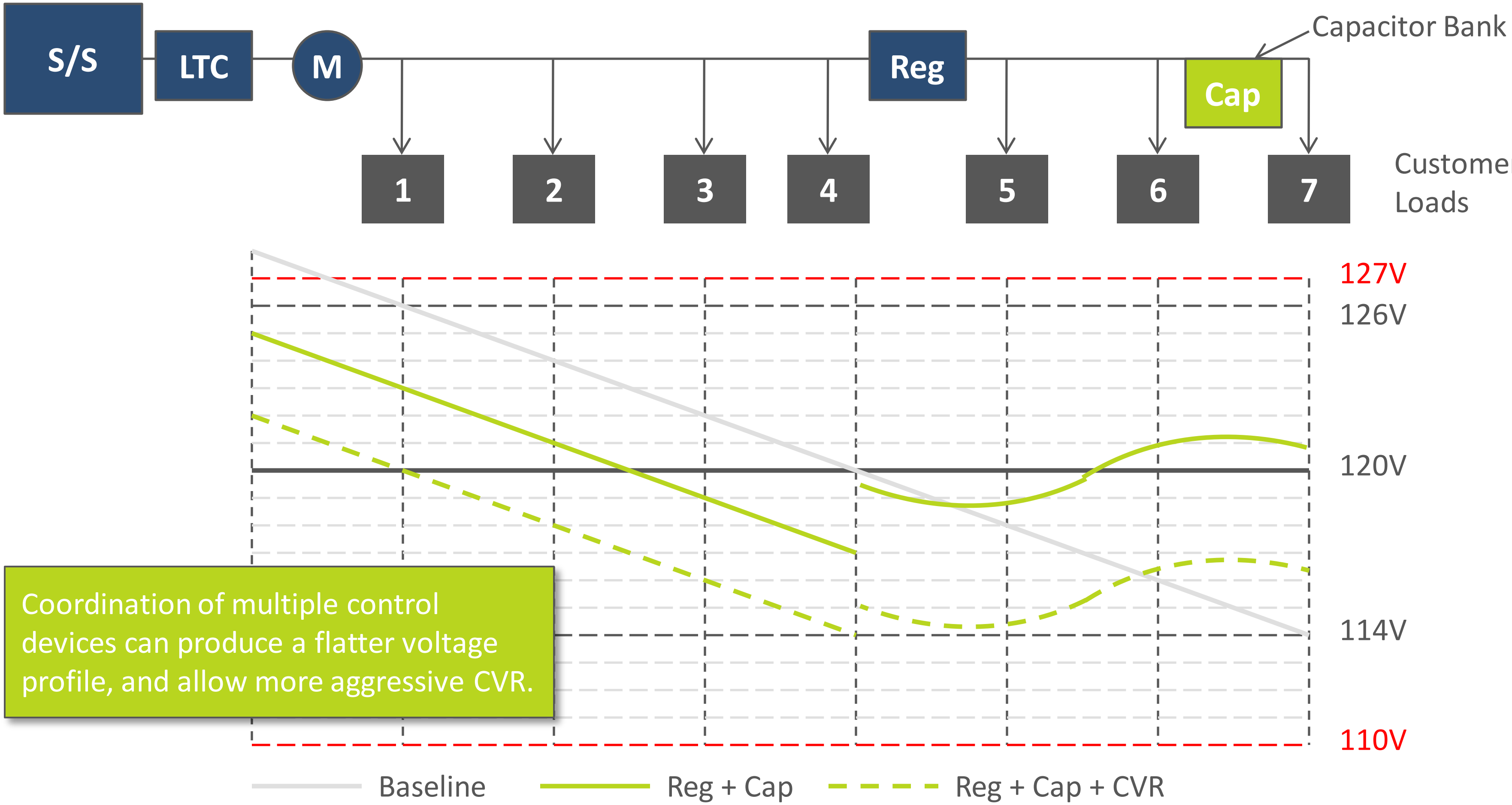


A voltage regulator can boost (raise) or buck (lower) voltage at a point on the distribution line and regulate down-line voltage.



The utility can use better voltage control to keep voltage closer to nominal, or lower it for a CVR effect.

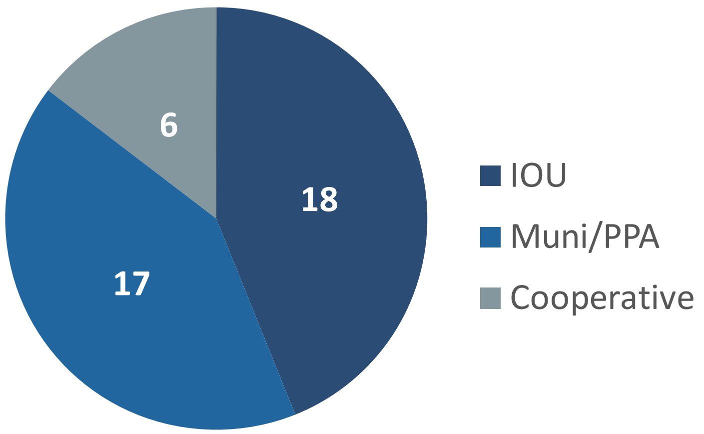
A capacitor bank can help regulation by compensating for the lagging power factor of load and the line itself.



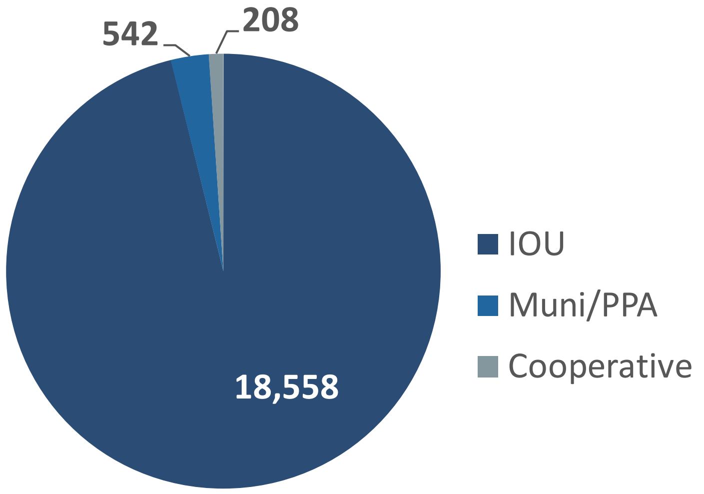
Coordination of multiple control devices can produce a flatter voltage profile, and allow more aggressive CVR.

Over 19,000 capacitor banks are being deployed by 41 projects as part of the SGIG program.

41 SGIG Projects Expected to Deploy Voltage and VAR Control Functionality



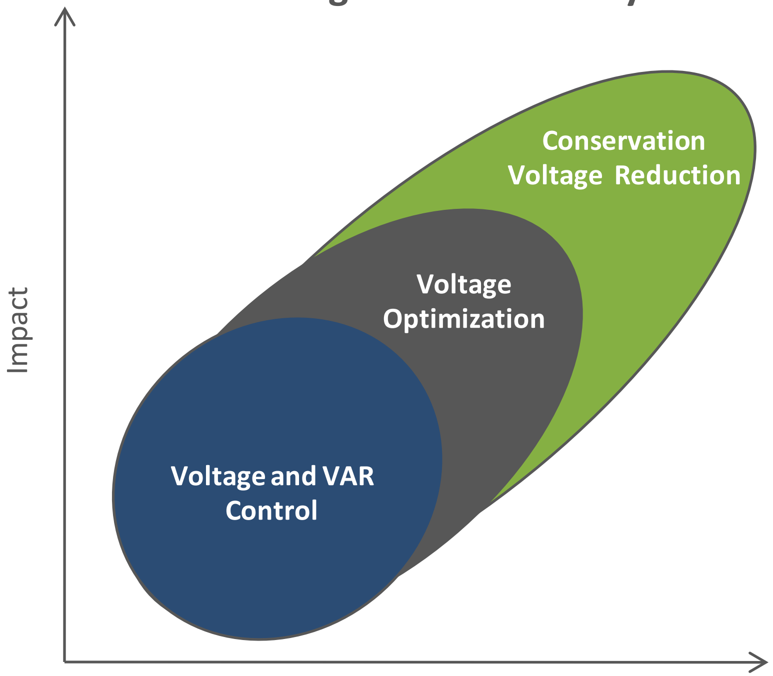
Number of Automated Capacitors Expected to be Deployed by Utility Type



Source: SGIG Build metrics and Navigant analysis

Projects vary with utility objectives, operational experience, and current system configurations and equipment.

We expect that impact will increase with higher functionality

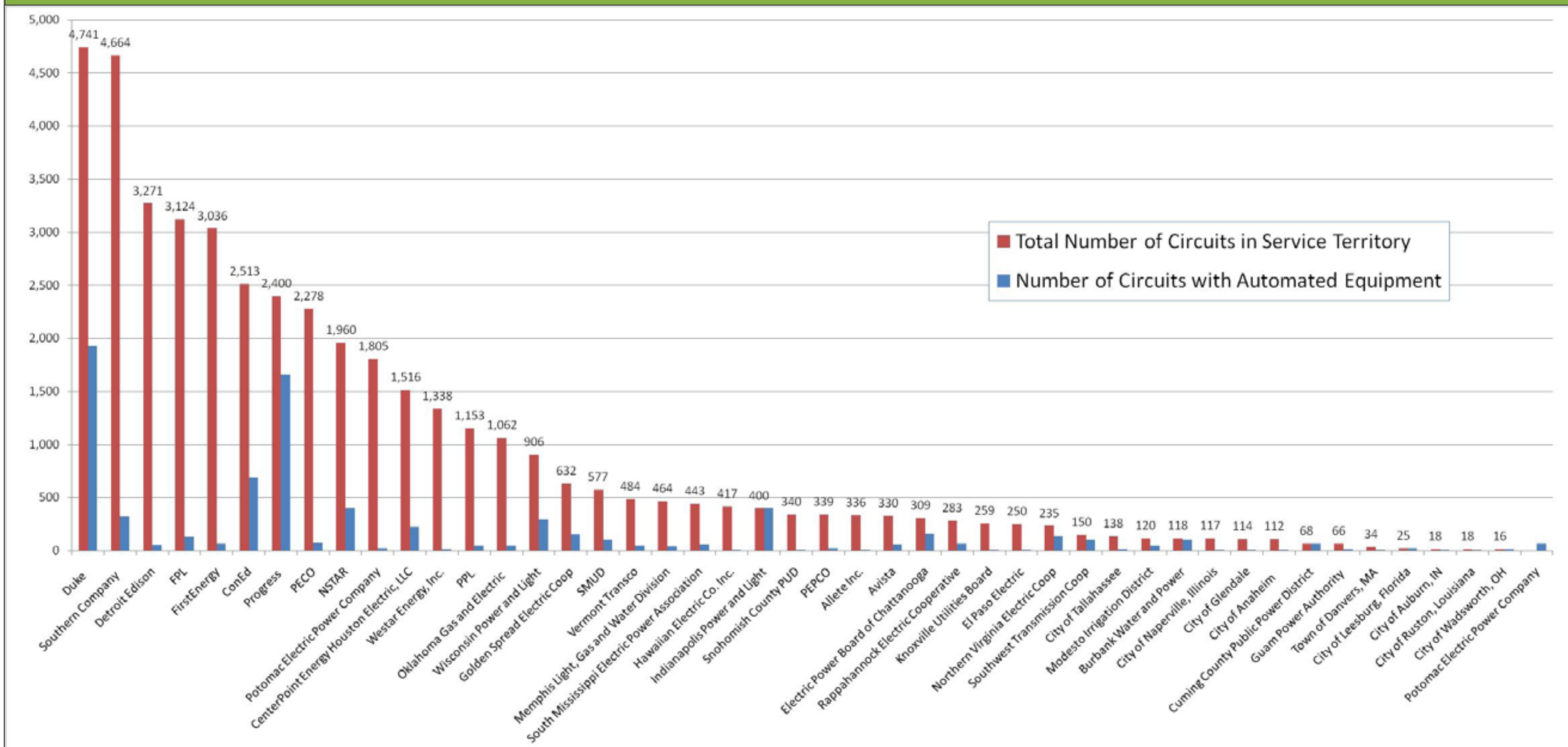


Functionality	SGIG Projects
Voltage and VAR Control	17
Voltage Optimization	11
Voltage Optimization and CVR	13
Total	41

Source: SGIG Proposals, MBRPs Build metrics and Navigant analysis

On average SGIG projects are installing automated equipment on about 25% of the circuits in their service territory.

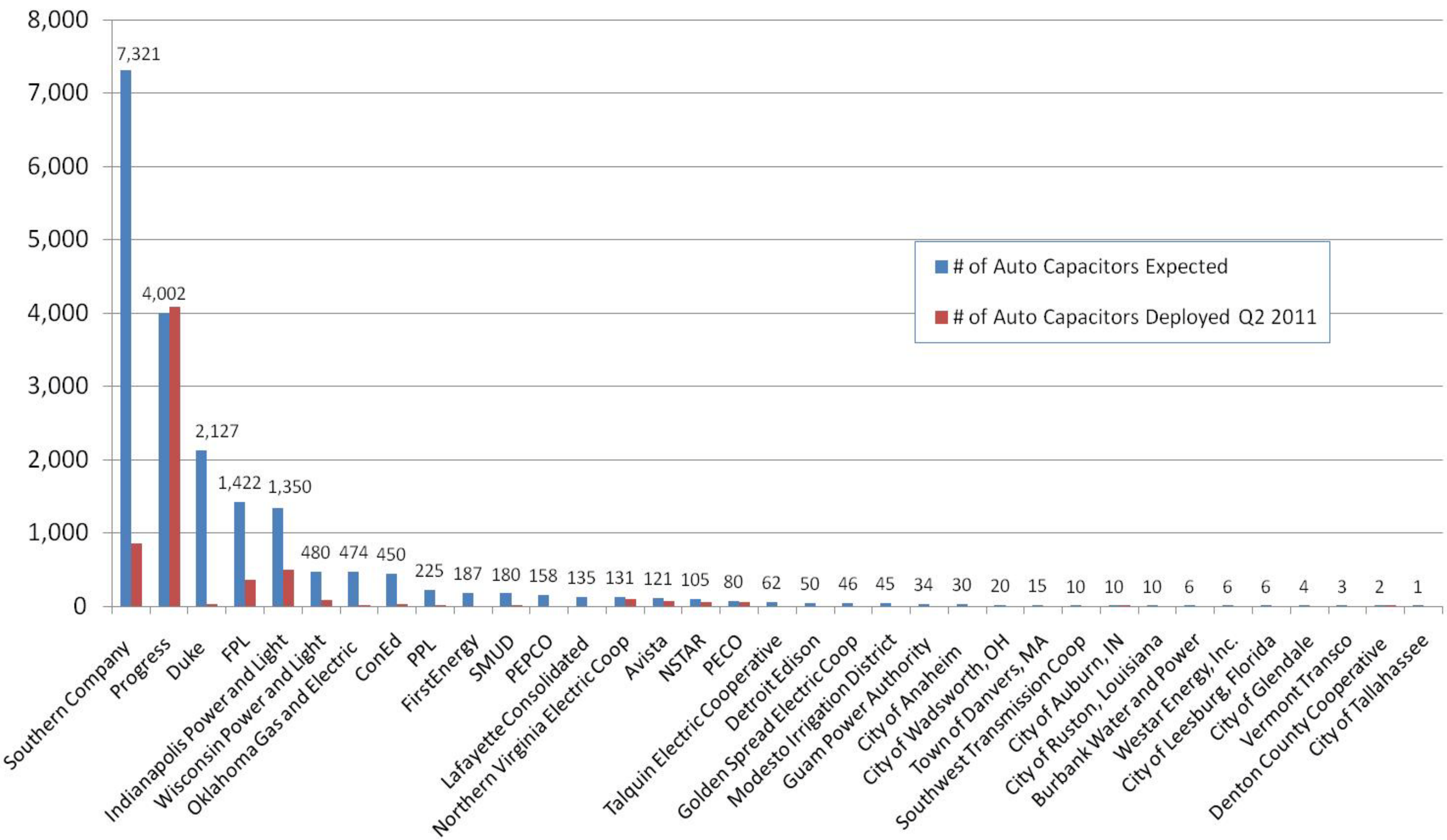
Number of Circuits with Automated Equipment vs. Total Service Territory



Source: SGIG Build metrics and Navigant analysis

* Includes projects that are installing automated feeder switches on some or all of the circuits

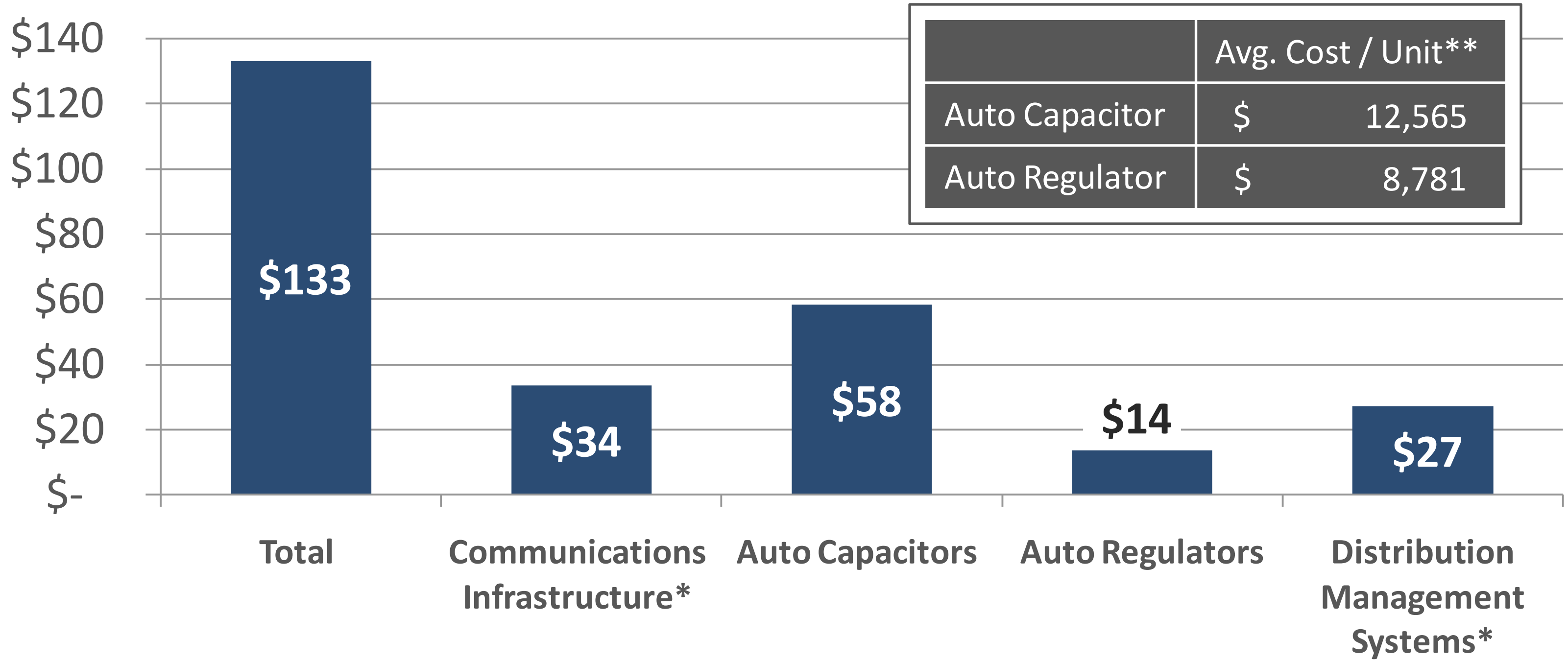
Nearly 19,000 capacitor banks are being deployed as part of the SGIG program. More than 80% are being deployed by four Investor Owned Utilities.



Source: SGIG Build metrics and Navigant analysis

As of Q2 2011, recipients had spent approximately $133 million on VVC assets.

Installed Costs ($ Millions) of Volt/Var and Supporting Equipment as of 2Q 2011



	Avg. Cost / Unit**
Auto Capacitor	$ 12,565
Auto Regulator	$ 8,781

Source: SGIG Build metrics and Navigant analysis

•Fifty percent of total costs allocated to volt/var. Assumed other costs allocated to reliability initiatives

** Avg. Const / Unit estimates include communication infrastructure

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Key metrics will be collected from SGIG and SGD projects for use in analyzing Voltage and VAR Control with smart grid.

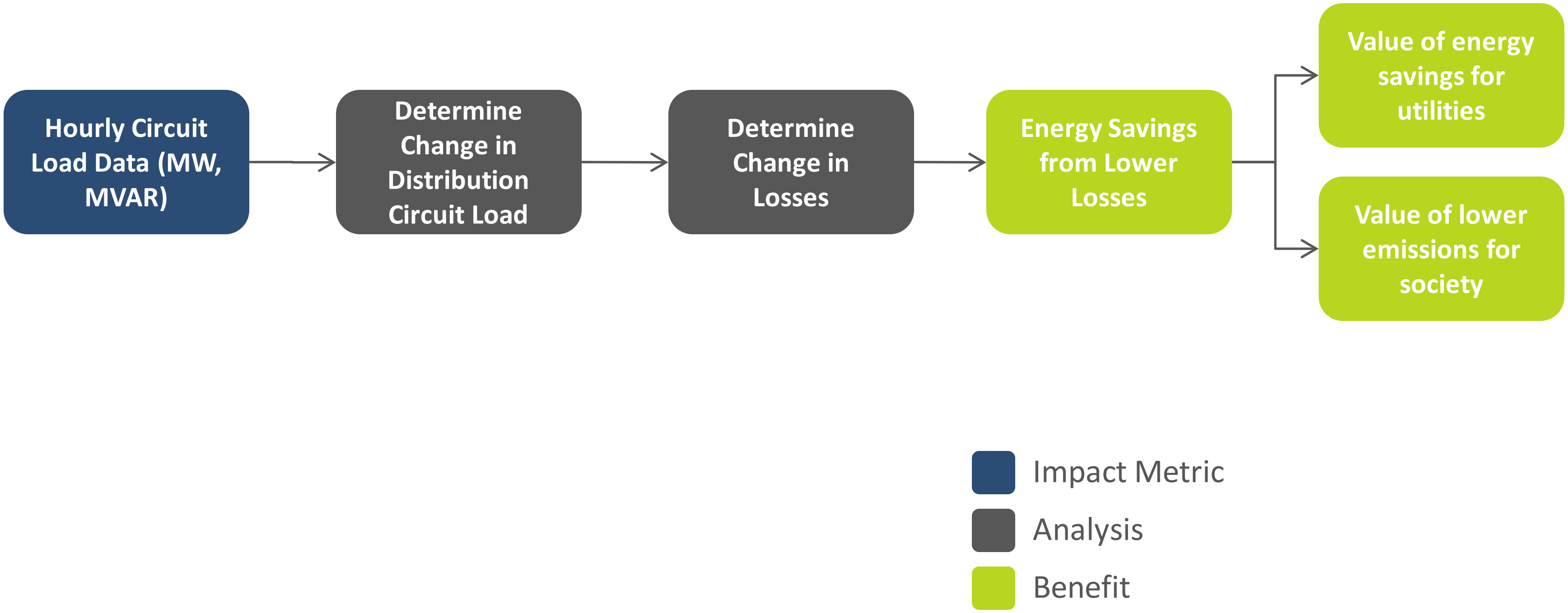
Key Build Metrics (Technologies)

- Automated capacitors
- Automated regulators
- Distribution circuit monitors or SCADA
- Distribution Management Systems (DMS)
- DMS integration with Advanced Metering Infrastructure
- Others
    - CVR algorithms
    - Load balancing
    - Reconductoring

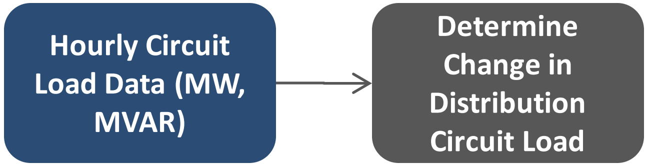
Key Impact Metrics

- Distribution feeder load (hourly and/or average)
- Distribution power factor (hourly and/or average)
- Distribution losses (average/peak, % of load, or MWh for reporting period)
- Emissions reductions from energy savings
- Others
    - Energy savings from CVR

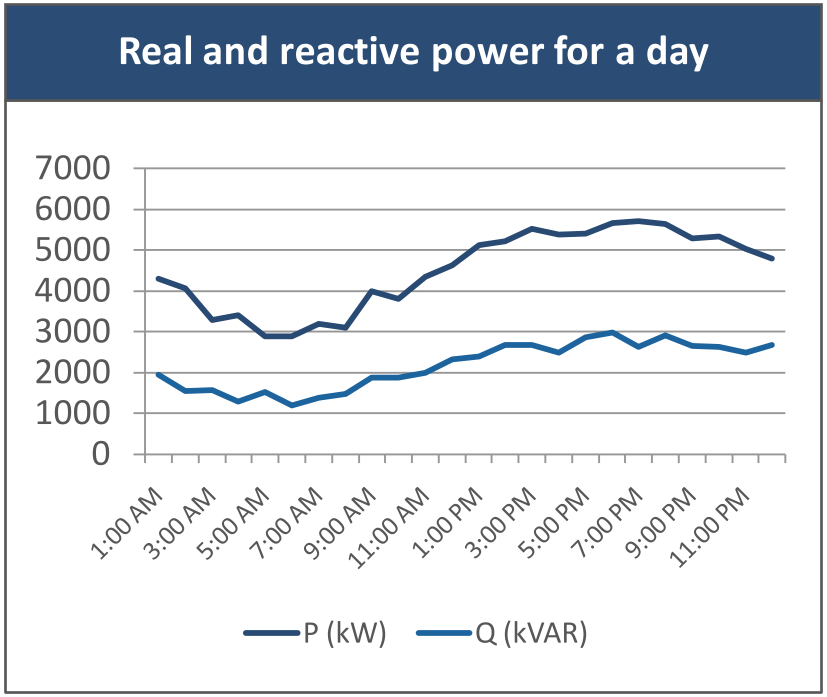
Analyzing the change in hourly circuit load can contribute to determining how much energy is saved by reducing distribution losses.



Many projects are reporting hourly circuit data for real and reactive power, and this data can be used to determine other parameters.



Time	P (kW)	Q (kVAR)
1:00 AM	4298	1949
2:00 AM	4061	1542
3:00 AM	3284	1574
4:00 AM	3408	1277
5:00 AM	2896	1519
6:00 AM	2900	1200
7:00 AM	3185	1388
8:00 AM	3103	1476
9:00 AM	4006	1868
10:00 AM	3817	1884
11:00 AM	4351	1997
12:00 PM	4635	2323
1:00 PM	5129	2390
2:00 PM	5213	2673
3:00 PM	5517	2677
4:00 PM	5378	2478
5:00 PM	5400	2855
6:00 PM	5658	2986
7:00 PM	5720	2638
8:00 PM	5643	2922
9:00 PM	5290	2664
10:00 PM	5346	2628
11:00 PM	5019	2496
12:00 AM	4801	2667

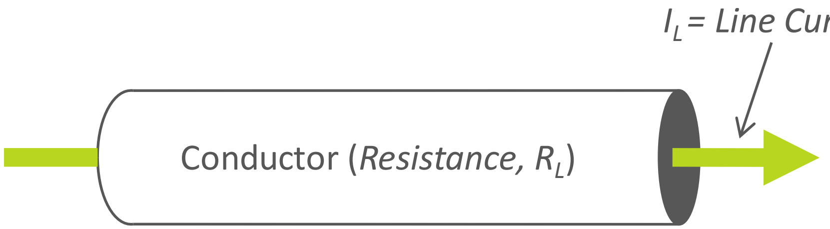


Source: Illustrative results from Navigant analysis

Energy is wasted as electricity flows through distribution lines. This wasted energy is known as "line losses".

Determine Change in Losses → **Energy Savings from Lower Losses**

Modern overhead distribution conductor is typically made of stranded aluminum wire, sometimes with a steel reinforcing core.



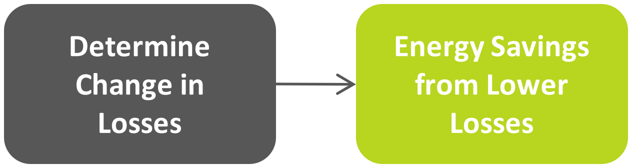
$$P_{line\ losses} = I_L^{\,2} R_L \text{ watts}$$

The resistance (R_L) of the conductor is about 0.3 ohms per mile, and decreases with cross sectional area.

As line current flows through the conductor, its resistance dissipates power in the form of "line losses".

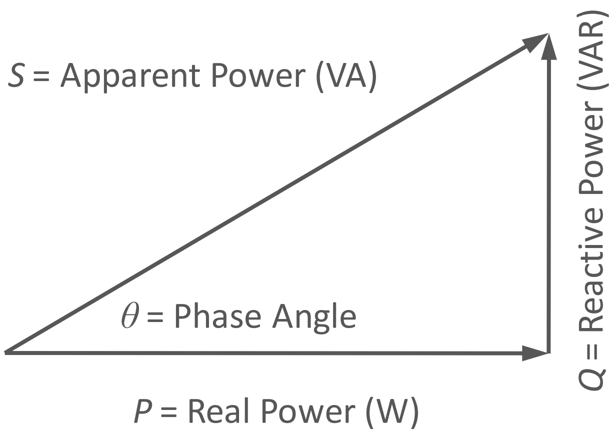
Higher line current means higher line losses, and vice versa

Hourly data for real and reactive power will determine hourly line losses, and the difference between baseline and impact losses yields energy savings.



Some projects will be reporting hourly circuit load data for real (P) and reactive (Q) power. Using this information we will calculate hourly values for apparent power ($S_{3\theta}$) and power factor, and then calculate hourly line current (I_L):

$$I_L = \frac{S_{3\theta}}{\sqrt{3}V_{LL}} \text{ amperes}$$



$$S_{3\theta} = \sqrt{P_{3\theta}^{\ 2} + Q_{3\theta}^{\ 2}} \text{ volt} - \text{amperes}$$

$$\text{power factor} = \cos^{-1}(\theta) = \frac{P_{3\theta}}{S_{3\theta}}$$

With I_L and an assumption of distribution conductor resistance (R_L), we calculate hourly line losses ($P_{line\ losses}$):

$$P_{line\ losses} = I_L^{\ 2} R_L \text{ watts}$$

For each six-month reporting period (4380 hours) the total line losses per circuit or circuit group are:

$$Energy\ Savings = \sum_{n=1}^{4380} P_{baseline} - \sum_{n=1}^{4380} P_{project} \text{ watt-hours}$$

The energy savings from lower distribution losses saves utilities money on wholesale energy, and reduces carbon emissions and their potential cost.

Energy Savings from Lower Losses

→ **Value of energy savings for utilities**

$$Value(\$) = Energy\ Savings(MWh) \times Wholesale\ Energy\ Cost(\$/MWh)$$

→ **Value of lower emissions for society**

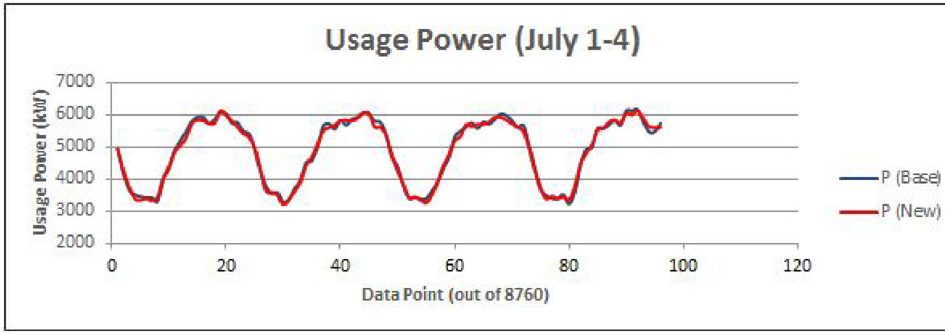
$$CO_2\ Emissions(tons) = Energy\ Savings(MWh) \times CO_2\ Emissions\ Factor\left({tons}/{MWh}\right)$$

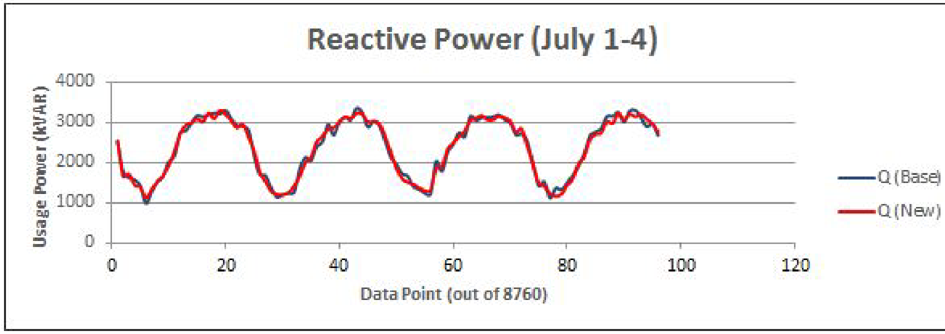
$$Value(\$) = CO_2\ Emissions(tons) \times CO_2\ Cost\left({\$}/{ton}\right)$$

This project is seeking to improve distribution circuit voltage regulation and reduce losses.

Distribution automation project implementing better voltage regulation to improve power quality and reduce losses. This includes the coordinated operation of a voltage regulator with a transformer load-tap changer at a substation.

Reported hourly data for real and reactive power (four days in July)

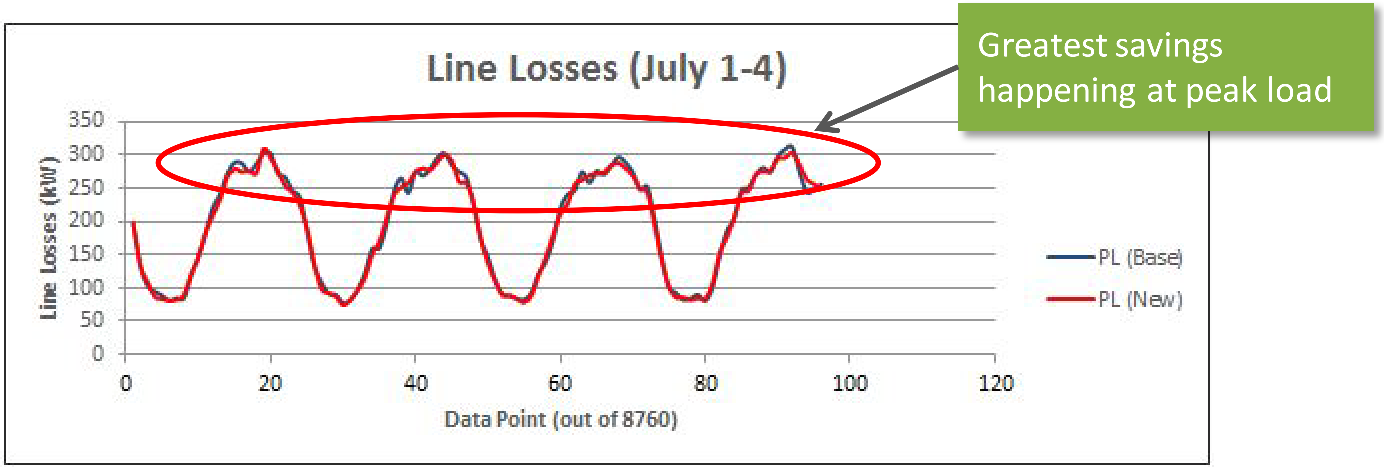




Source: Illustrative results from Navigant analysis

This project was able to reduce line losses by about one percent over a year.

	SELECTED DATA (Jan 1 – Dec 31)					FULL YEAR DATA (Same)			
	Baseline	*New*		*Change*		*Baseline*	*New*		*Change*
Usage Energy	35712.1	35524.1	MWh	-0.5%		35712.1	35524.1	MWh	-0.5%
Reactive Power	17111.8	17094.5	MVARh	-0.1%		17111.8	17094.5	MVARh	-0.1%
Apparent Power	39654.8	39462.0	MVAh	-0.5%		39654.8	39462.0	MVAh	-0.5%
Avg Power Factor	0.904	0.903		0.0%		0.904	0.903		0.0%
Avg Current	209.0	208.0	A	-0.5%		209.0	208.0	A	-0.5%
Total Power Losses	1207.66	1195.50	MWh	-1.0%		1207.7	1195.5	MWh	-1.0%



Source: Illustrative results from Navigant analysis

Assuming average wholesale prices and a cost for CO2 emissions, the value of reducing losses by one percent is about $840 per year.

$$Value(\$) = Energy\ Savings(MWh) \times Wholesale\ Energy\ Cost(\$/MWh)$$

At average wholesale market price of $56 per MWh

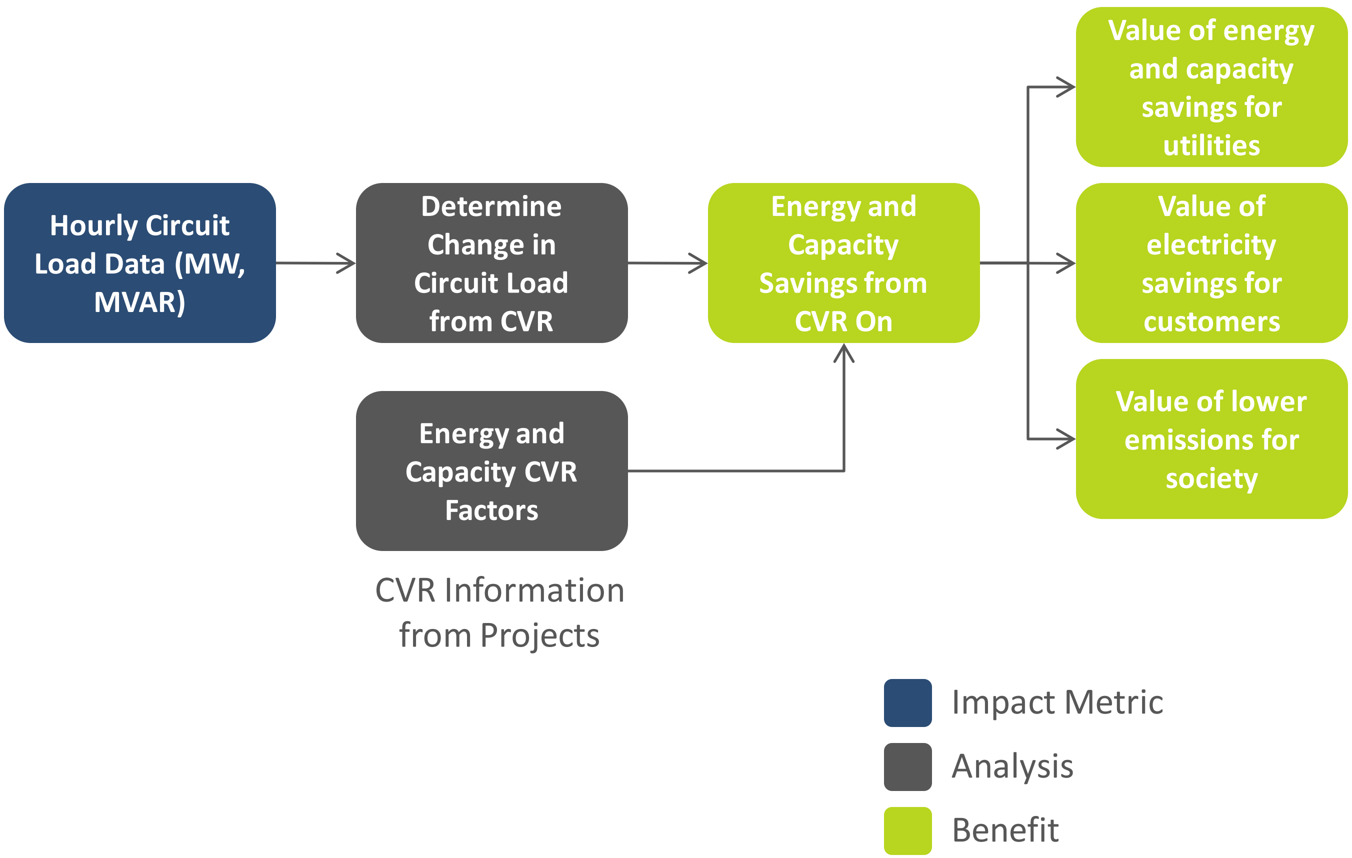
$$Value(\$) = (1207.66 - 1195.50)\,MWh \times 56\,(\$/MWh)$$

$$Value(\$) = \$680 \text{ per circuit, per year}$$

Assuming 1.3 lbs/kWh for electricity generation and a price for CO_2 emissions of $20 per ton

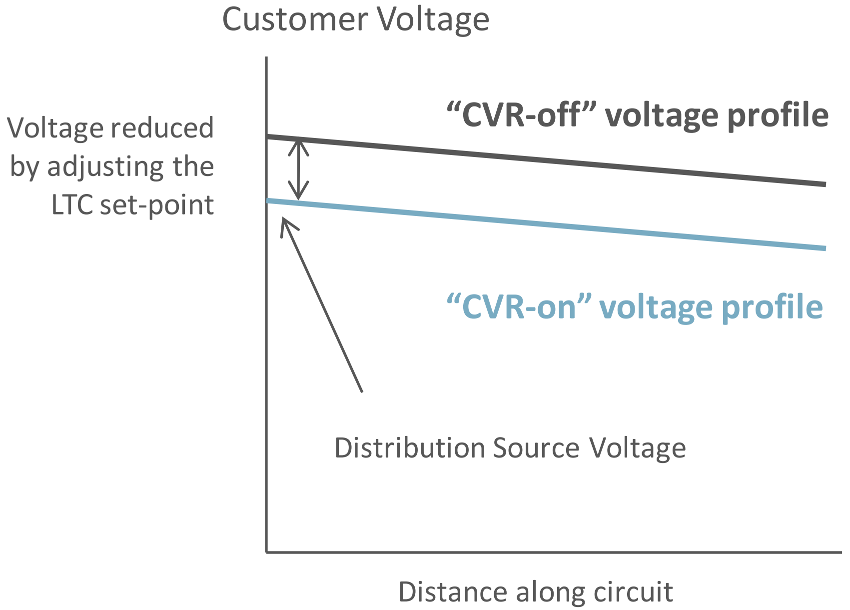
$$Value(\$) = 1.3\,(lbs/kWh) \times 12{,}160(kWh) \times \frac{20(\$/ton)}{2000(lb/ton)} = \$158 \text{ per circuit, per year}$$

We will work closely with projects implementing CVR to determine how its implementation creates energy and capacity savings.



Conservation voltage reduction (CVR) reduces customer voltages along a distribution circuit to reduce electricity demand and energy consumption.

Energy and Capacity CVR Factors

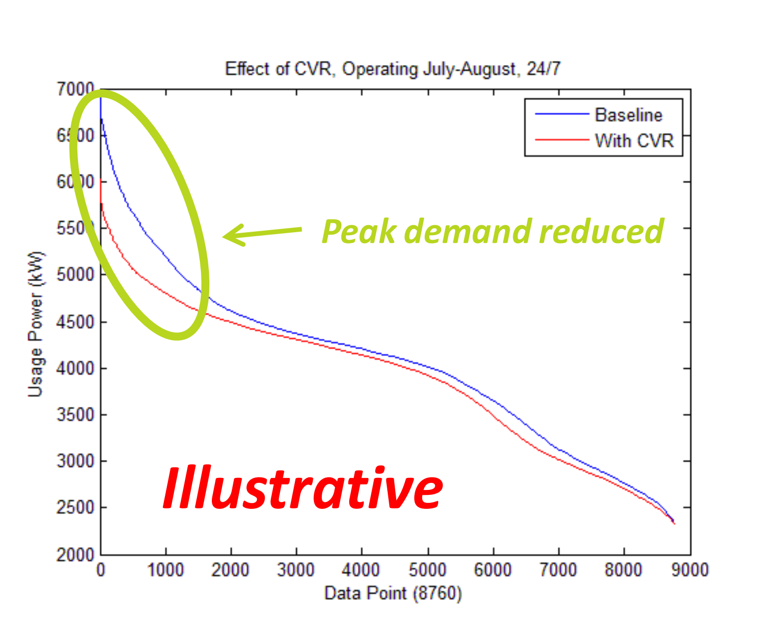


Studies dating back to the 1980s have shown that small reductions in distribution voltage can reduce electricity demand from customer equipment and save energy. This has become known as "conservation voltage reduction (CVR)".

Recent utility pilot programs have demonstrated that lowering distribution voltage by 1% can reduce demand and energy consumption by 1% or more.

By analyzing hourly load data and talking with utilities, we will try to correlate CVR factors with VVC technology configurations.

CVR reduces demand during peak load periods



Source: Illustrative results from Navigant analysis

Some projects who are pursuing CVR will be reporting hourly circuit load data. By analyzing this data we hope to determine how much demand and energy savings each project achieves with its technology configuration.

CVR Factor (*CVRf*)

$$CVRf = \frac{\Delta P}{\Delta V}\ \text{watts}/\text{volt}$$

We will work with project teams in the focus group to understand how much distribution voltage was reduced to achieve the reduction in load.

The energy savings from CVR saves utilities and their customers money on energy and capacity, and reduces carbon emissions.

Energy and Capacity Savings from CVR On

Value of energy and capacity savings for utilities

$$Value(\$) = Energy\ Savings(MWh) \times Wholesale\ Energy\ Cost(\$/MWh)$$

$$Value(\$) = Capacity\ Savings(MW) \times Wholesale\ Capacity\ Cost(\$/MW)$$

Value of electricity savings for customers

$$Value(\$) = Electricity\ Savings(kWh) \times Average\ Electricity\ Cost(\$/kWh)$$

Value of lower emissions for society

$$CO_2\ Emissions(tons) = Energy\ Savings(MWh) \times CO_2\ Emissions\ Factor\left(\tfrac{tons}{MWh}\right)$$

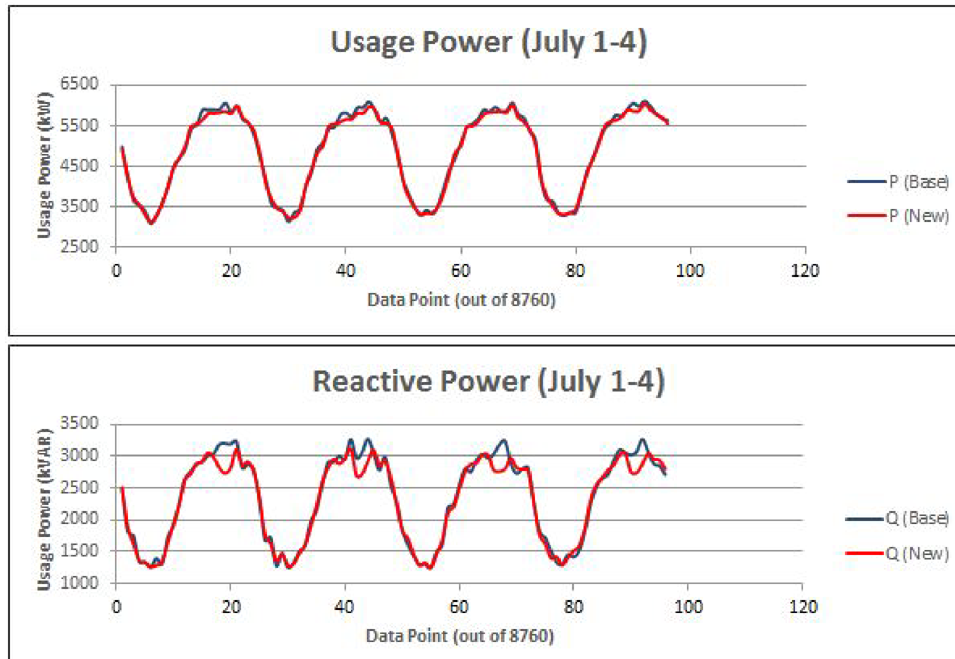
$$Value(\$) = CO_2\ Emissions(tons) \times CO_2\ Cost\left(\tfrac{\$}{ton}\right)$$

This project is seeking to reduce system peak demand with conservation voltage reduction during the summer.

Distribution automation project implementing conservation voltage reduction including the coordinated control of a capacitor bank with a transformer load-tap changer at a substation.

The CVR action was taken as a way to reduce system peak demand during high load periods in July and August.

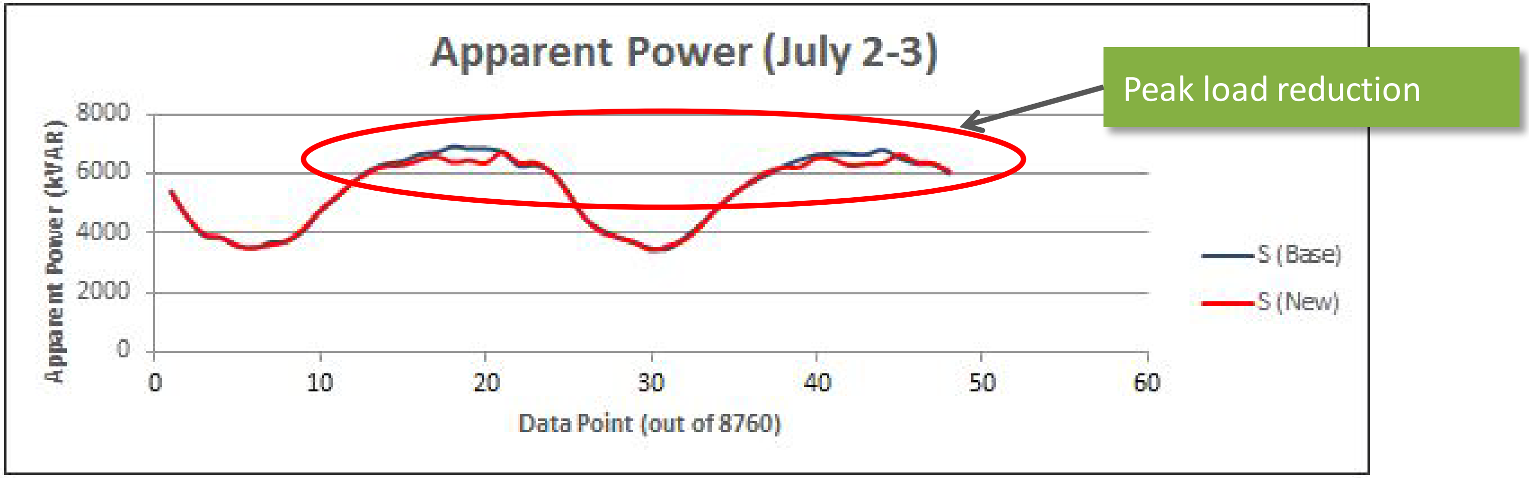
Reported hourly data for real and reactive power (four peak demand days in July)



Source: Illustrative results from Navigant analysis

This project achieved about a 2% reduction in demand by performing CVR during a peak period in July.

	SELECTED DATA (July 1-4, 3PM-9PM)			
	Baseline	*New*		*Change*
Usage Energy	5.841	5.770	MW	-1.2%
Reactive Power	3.092	2.891	MVAR	-6.5%
Apparent Power	6.610	6.456	MVA	-2.3%
Avg Power Factor	0.887	0.896		1.0%
Avg Current	304.6	295.4	A	-3.0%
Total Power Losses	280.2	267.1	kW	-4.7%



Source: Illustrative results from Navigant analysis

Assuming peak wholesale prices the capacity value of CVR is worth over $15,000 per year, per circuit.

$$Value(\$) = Capacity\ \ Savings\,(MW)\times Wholesale\ \ Capacity\ \ Cost\,(\$/MW)$$

At peak wholesale prices

$$Value(\$) = (6.610 - 6.456)\ MW \times 100\ (\$/kW - yr) = \$15{,}400\ \ per\ year,\ per\ circuit$$

Assuming a large utility implements CVR on 25% of its 2000 circuits

$$Value(\$) = 15{,}400\ (\$/circuit) \times 500\ \ circuits = about\ \ \$8\ million\ \ per\ \ year$$