Economics of Distribution Efficiency Projects

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Abstract--**The economic evaluation of distribution-efficiency projects for six circuits was conducted with a goal to find the most cost-effective planning techniques to improve overall energy efficiency. For each circuit, voltage reduction was modeled along with several efficiency-improvement options such as phase balancing. In many cases, options helped reduce losses while flattening voltage profiles. With flatter voltage profiles, voltage reduction becomes more effective. The costs and economic benefits of each option were calculated so that economically optimal efficiency options could be selected.**

Index Terms--**Distribution System, Economics, Efficiency, Planning Techniques**

I. INTRODUCTION

SIX circuits from the EPRI Green Circuits energy efficiency collaborative were selected for the economic analysis [1]. The six circuits represent different topologies, operating conditions, and control strategies as shown in Table 1.

The goal of the economic analysis was to simulate energy efficiency projects while comparing project costs verse energy savings. The projects included circuit enhancements that reduce losses and improve voltage profiles. Improving voltage profiles allows greater reduction of circuit voltage, which improves end-use efficiency and reduces overall consumption. The analysis shows the viability of efficiency projects. The efficiency study and results are presented in this paper.

TABLE 1. CIRCUIT CHARACTERISTICS

Circuit	A	B	C	D	E	F
Primary Voltage	12.5 kV	34.5 kV	25 kV	12.5 kV	25 kV	13.2 kV
Voltage Regulation	Sub-station feeder &three remote	Sub-station feeder	Sub-station feeder	Sub-station feeder	Sub-station feeder	Sub-station bus
Primary Conductor	Over-head	Over-head	Over-head	Under-ground	Over-head	Over-head
Total Primary Circuit Miles	105 mi	73 mi	44 mi	15 mi	30 mi	84 mi
Furthest Distance from Sub	10.5 mi	4.6 mi	9.2 mi	2.0 mi	8.5 mi	8.5 mi
Total Reactive Compensation	3900 kvar	2400 kvar	0 kvar	3600 kvar	2250 kvar	12750 kvar
Peak Demand	13 MW	15 MW	7.1 MW	5.7 MW	5.7 MW	29 MW
Load Factor	0.33	0.38	0.32	0.40	0.39	0.55
Modeled Load Power Factor	0.98	0.93	0.93	0.92	0.85	0.90

II. EFFICIENCY ANALYSIS

The electrical model for each circuit was built in the OpenDSS simulation platform. The OpenDSS tool has the functionality to derive hourly solutions for an annual simulation. The circuit response with controls such as voltage regulators and capacitor banks adjust to the hourly load. Losses, load, and voltage were monitored for all hours of the simulation. The analysis approach follows that described in [1], with the exception that more efficiency options were evaluated in a consistent fashion to allow better economic comparisons.

Model verification and improvement may be needed to implement an efficiency study. In the Green Circuits project [1], most utilities needed to field check phasing of models along with settings of capacitor and voltage regulator controls. Many utilities also needed to upgrade their circuit models.

A. Efficiency Projects Analyzed

Five primary categories of efficiency improvements were analyzed for each circuit. The categories and label abbreviations include:

- VR – Voltage reduction
- PB – Phase balancing and/or simple reconfigurations combined with voltage reduction
- VAR – Var (reactive power) optimization combined with voltage reduction
- REG – Additional voltage regulators combined with voltage reduction
- R – Re-conductoring combined with voltage reduction

The order of improvements listed above is generally a good order in priority for circuit improvements; the benefits tend to accumulate. In the analysis, each option was evaluated separately. Combinations of promising options were also evaluated. Simulations with combinations of options typically had similar results as linearly adding the energy savings from each component.

By combining voltage reduction with other efficiency options, losses were reduced while voltage profiles were flattened. This improved the distribution system efficiency (lower losses) and end-use efficiency (lower end-use consumption).

1) Voltage Reduction - VR

Voltage feedback was used to model voltage reduction. Regulators were controlled to 118.5 V (120 V base) at a three-phase primary remote endpoint. The set point was adjusted for each efficiency option to maintain greater than 118 V on all primary feeder buses during the annual simulation. If the

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circuit voltage prior to voltage reduction was at the limit—thus restricting the application of voltage reduction—minor circuit modifications were made to bring all voltages within limits.

2) *Phase Balancing - PB*

Phase balancing reduces line losses and evens out voltage drops among phases, which helps flatten voltage profiles. Phases were balanced by moving a single-phase tap to another phase, rotating a three-phase tap, converting a single-phase lateral to two-phase, or splitting a single-phase lateral with the isolated segment reconnected at a new location. Other simple reconfigurations (like changing open tie positions) were also considered.

3) *Reactive Power Optimization - VAR*

Reactive power optimization reduces reactive flows while stabilizing voltage profiles. Options evaluated for reactive power optimization included the removal of capacitor banks, reducing capacitor bank size, and adding switched reactive power control algorithms. For each case study, capacitor banks were also optimally applied from scratch. In the optimal capacitor application, 15-kV class circuits used 300- or 900-kvar banks, while the rating doubled for 25-kV class circuits. New capacitor banks were placed on the circuit based on a light-load case and/or a high-load case. In the light-load case, fixed capacitor banks were placed on the circuit such that the capacitor bank serves 50% reactive load upstream and 50% downstream. In the high-load case, switched capacitor banks were placed on the circuit to provide 50% support upstream and 50% downstream.

4) *Voltage Regulators - REG*

Additional voltage regulators help flatten voltage profiles. Because line regulators control each phase independently, the use of line regulators helps compensate for unequal phase loadings and can be particularly beneficial on circuits that have significant voltage drop on long single-phase laterals. Voltage regulators were not tested as an option on circuits with relatively flat voltage profiles.

5) *Recondictoring - R*

Re-conductoring reduces losses and reduces voltage drop along that section of circuit. For each re-conductoring analysis, it was assumed that the new conductor replaced existing conductor without requiring new right-of-way, but pole replacement may be required if the conductor size significantly increased. The amount of circuit replaced in the re-conductoring options was limited to approximately 1-, 2-, or 3-mile sections so that comparisons can be made across the different circuits.

B. Additional Projects

In addition to the options considered in this paper, efficiency improvements on a specific feeder could include:

- Adding parallel circuit sections
- Upgrading to a higher voltage class
- More significant reconfigurations (adding new feeders and redistributing load to new feeders, for example)

Longer-term efforts to improve efficiency may also involve upgrading monitoring, substation feeder metering, GIS systems, distribution modeling databases, and communication systems. For example, changing planning criteria for allowable secondary voltage drop is another long-term approach to improve voltage profiles and efficiency.

III. ECONOMIC ANALYSIS AND FINANCIAL FACTORS

The system upgrade costs associated with each efficiency project were compared to the energy savings in the economic analysis. For proper comparison over the lifetime of each project, the net present value (NPV) was calculated. The system upgrade costs included the investment costs in addition to those for operation and maintenance.

The two metrics used to determine the economic acceptability of each project included the benefit-cost ratio (BCR) and levelized cost (LC). The benefit-cost was determined with the project cost, value of energy saved, and value of peak demand reduction over the lifetime of each project. The levelized cost was determined with the project cost levelized by the energy saved over the lifetime of each project and does not include potential benefit from total peak demand reduction. An economically viable project has a benefit-cost value greater than one or a levelized cost less than or equal to the maximum marginal cost of purchase power.

A mini survey sent to several Green Circuit participants revealed their average marginal cost of purchase power, as shown in Table 2. The maximum marginal cost of purchase power used in this analysis to determine economically acceptable projects was $0.08/kWh.

TABLE 2. AVERAGE MARGINAL COST FOR SEVERAL GREEN CIRCUIT PARTICIPANTS

Participant	Cents/kWh
A	2.55
B	7.38
C	9.60
D	2.40
E	3.50
F	6.00

The economic analysis used the parameters and values listed in Table 3 to determine present worth of the efficiency option costs and savings. The present worth of the option costs depends on the investment cost, fixed charge rate, annual operation and maintenance expenses, associated inflation rates, capital and planned equipment life, and the present worth rate. The present worth of the efficiency option savings were based on annual energy and peak demand reduction, energy and demand rates, associated inflation rates, planned equipment life, and present worth rate.

The economic analysis did not include impacts on reduced kWh sales associated with voltage reduction. This analysis assumed that billing losses were recovered by adjusted billing strategies or other rate-recovery mechanisms.

TABLE 3. ECONOMIC PARAMETERS USED TO DETERMINE BCR AND LC

Average Marginal Purchase Energy Rate ($/kWh)	$0.0736
Average Marginal Purchase Demand Rate ($/kW/yr)	$49.00
Capitalized Annual Fixed Charged Rate (pu)	0.160
Annual Inflation Rate for Investment (%/yr)	3.0%
Annual Inflation Rate for O&M (%/yr)	3.0%
Annual Inflation Rate for kWh Energy (%/yr)	4.0%
Annual Inflation Rate for kW Demand (%/yr)	4.0%
Annual Operations, Maintenance, and Insurance Expense (%/yr)	2.0%
Present Worth Rate for Cost of Investment (%/yr)	6.0%
Present Worth Rate for Cost of Energy & Losses (%/yr)	5.0%
Capital Equipment Life Expectancy (yr)	35
Planned life of Energy Savings (yr)	15

The general construction cost estimates used for the economic analysis are shown in Table 4. The voltage reduction cost estimate included a single three-phase voltage regulator, voltage feedback control, and installation. The cost was based on several estimates for individual circuit control. However, bus-level control or alternate control algorithms may add/reduce the cost estimate during actual implementation. Tap adjustment cost estimates were derived from several work order bids and reflect the labor cost for adjusting a single tap. Capacitor costs were derived from vendor cost tables. All reactive power optimization options were based on the assumption that new capacitors would be utilized regardless of existing capacitors on each circuit. The existing capacitors were assumed to have remaining life, and therefore a salvage value was assigned. The cost of new conductor was also derived from vendor price sheets. For significant conductor size upgrades, pole replacement was assumed. Re-conductoring labor costs and pole replacement/labor costs were based on several work order bids.

TABLE 4. CONSTRUCTION COST ESTIMATES

Voltage reduction	
Regulator, control, and installation	$63.6 K
Single-phase tap movement/phasing	
Overhead	$1.4 K
Underground	$2.8 K
OH Capacitors – new, relocated, or modified capacitor	
300 kVAR Fixed	$3,000.00
600 kVAR Fixed	$5,175.75
900 kVAR Fixed	$8,000.00
1200 kVAR Fixed	$7,597.00
300 kVAR Switched	$4,500.00
600 kVAR Switched	$12,573.33
900 kVAR Switched	$12,000.00
1200 kVAR Switched	$23,084.50
Installation	Refer to tap adjustment
Salvage value from remove banks	20% of list price
Reconductoring	
ACSR 336	$8000/mi
ACSR 397	$9600/mi
ACSR 556	$11600/mi
ACSR 795	$16100/mi
Conductor installation	1.8x cost of conductor
New poles with installation at 12kV	3.3x cost of conductor
New poles with installation at 34kV	7.6x cost of conductor
Voltage Regulators and installation	
Single Phase 100 amp	$15,000.00
Three phase 100 amp	$22,000.00
Three phase 219 amps	$42,600.00
Three phase 328 amps	$50,650.00
Three phase 548 amps	$62,000.00

IV. ECONOMIC VIABILITY

The economic viability/acceptability of each efficiency option was strongly correlated to the consumed energy and peak demand on each of the six circuits studied. The benefit-cost ratio and levelized cost for each efficiency option was also significantly influenced by the efficiency gains from voltage reduction. The voltage reduction option was used as the baseline to compare economic acceptability of each efficiency option in Table 5. All options were economically acceptable except those indicated with an asterisk. For the six circuits, levelized costs and benefit-cost ratio had the same order of economically acceptable options. For three circuits, phase balancing or reactive power optimization increased acceptability beyond that from voltage reduction alone. This increase was due to low additional project costs and/or high additional efficiency gains.

Phase balancing tended to be viable for most circuits primarily due to low cost and additional energy savings from further voltage reduction. Reactive power optimization tended to work for similar reasons, but the cost was slightly higher, so its ranking was slightly lower. Re-conductoring and additional voltage regulators tended to be closer to break-even because the capital cost was higher.

TABLE 5. ECONOMIC VIABILITY OF EFFICIENCY OPTIONS

		Increased Acceptability		**Base Line**				Decreased Acceptability
Benefit Cost Ratio	Ckt A	PB	VAR	VR	R			
	Ckt B			VR	VAR	PB	R	
	Ckt C		PB	VR	VAR	R*		
	Ckt D	VAR	PB	VR	R*			
	Ckt E			VR	PB	VAR	REG	R*
	Ckt F			VR	VAR	PB	REG	R
Levelized Cost	Ckt A	PB	VAR	VR	R			
	Ckt B			VR	VAR	PB	R	
	Ckt C		PB	VR	VAR	R*		
	Ckt D	VAR	PB	VR	R*			
	Ckt E			VR	PB	VAR	REG	R*
	Ckt F			VR	VAR	PB	REG	R

* Economically unacceptable project.

Fig. 1 illustrates the levelized cost for all acceptable projects analyzed for each circuit. Multiple projects were tested under each category. The levelized cost for voltage reduction alone (base voltage feedback) decreased as peak demand/annual energy increased. Phase balancing, reactive power optimization, re-conductoring, and additional voltage regulation then slightly shifted the levelized cost based on additional project cost and energy savings. For the three circuits with highest peak demand and lowest levelized cost for voltage reduction (Circuit A, Circuit B, and Circuit F), re-conductoring was an acceptable option. The significant decrease in levelized cost for the reactive power optimization project on Circuit D was a result of low project cost due to the salvage value from the removal of three 1200-kvar pad-mounted capacitor banks used for transmission system support.

Table 6 and Table 7 show the best benefit-cost ratio and best levelized cost for each category of options for each circuit.

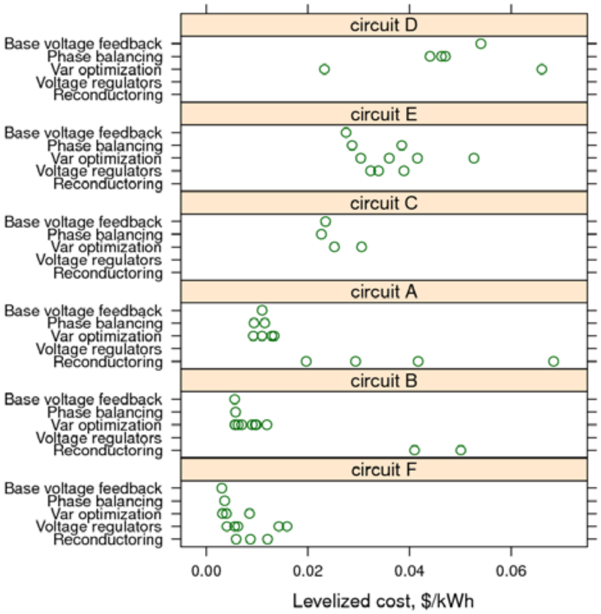

Fig. 1. Acceptable Efficiency Projects With Respect to Levelized Cost

TABLE 6. BENEFIT-COST RATIO FOR THE BEST OPTION IN EACH CATEGORY

	Circuit					
	A	B	C	D	E	F
Base voltage feedback	8.1	17.6	3.5	1.8	3.6	29.9
Phase balancing	9.8	17.0	3.9	2.3	3.4	25.2
Var optimization	9.5	17.2	3.3	4.1	3.1	29.0
Reconductoring	4.7	2.4	0.2	0.4	0.7	15.6
Voltage regulators					3.1	22.4
Combinations	11.3	10.8	3.8	4.7	2.1	5.3

TABLE 7. LEVELIZED COST IN ¢/KWH FOR THE BEST OPTION IN EACH CATEGORY

	Circuit					
	A	B	C	D	E	F
Base voltage feedback	1.1	0.6	2.3	5.4	2.8	0.3
Phase balancing	0.9	0.6	2.3	4.4	2.9	0.4
Var optimization	0.9	0.6	2.5	2.3	3.0	0.3
Reconductoring	2.0	4.1	47.3	24.1	14.0	0.6
Voltage regulators					3.2	0.4
Combinations	0.8	0.9	2.4	2.1	4.6	1.7

Table 8 shows the project categories that are economically acceptable without savings and cost accrued from voltage reduction option VR. Because voltage reduction was applied in all options, projects could not be completely decoupled. These projects would be acceptable as a standalone project after voltage reduction has already been implemented. These projects included reactive power optimization, phase balancing, additional voltage regulation, and the combination (C) of phase balancing and reactive power optimization. Reactive power optimization had the highest additional benefit for circuits under 15 kV due to greater savings from loss reduction. For circuits greater than 15 kV, the benefit was greatest from phase balancing (with the exception of Circuit E).

TABLE 8. ACCEPTABLE EFFICIENCY PROJECTS WITHOUT CONSIDERING SAVINGS FROM OPTION VOLTAGE REDUCTION

		Highest		Lowest
Project Viability after Option VR	Ckt A	VAR	C	PB
	Ckt B	PB		
	Ckt C	C	PB	VAR
	Ckt D	C	VAR	PB
	Ckt E	none		
	Ckt F	VAR	REG	

A. *Economic Viability with Voltage Reduction Only at Peak*

Demand and loss reduction occurring during the peak load hour provides savings that potentially lead to economically acceptable projects based on BCR criteria.

The voltage reduction option was acceptable based on peak hour demand reduction for Circuit B and Circuit F. Due to lower peak hour savings on Circuit A, Circuit D, and Circuit E, additional annual energy savings would be necessary for voltage reduction acceptability. The peak demand and losses increased with voltage reduction on Circuit C due to voltage regulation-up at peak hour.

Peak hour savings are influenced by feeder voltages and load. The feeder voltage for Circuit B was relatively high and stiff, thus allowing for significant peak hour voltage and demand reduction. Circuit F had high circuit load and thus allowed for significant demand reduction with a smaller change in regulated voltage.

V. ECONOMIC PARAMETER SENSITIVITY

Levelized cost (LC) by definition has fewer economic variables than benefit-cost ratio because LC is normalized to energy saved rather than value of energy saved. The benefit-cost ratio (BCR) incorporates the energy and demand rates to define the monetary value of reduced energy and peak demand. The sensitivity of these to economic parameters is shown in Table 9. The table expresses the direction of change of benefit-cost ratio and levelized cost when each economic parameter was increased individually. The value 'Constant' is given if the benefit-cost ratio or levelized cost was independent of the parameter.

TABLE 9. EFFECT OF INCREASED PARAMETER VALUE ON BENEFIT-COST RATIO AND LEVELIZED COST

	Benefit-Cost Ratio	***Levelized Cost***
Option Cost	Down	Up
Average Marginal Purchase Energy Rate ($/kWh)	Up	Constant
Average Marginal Purchase Demand Rate ($/kW/yr)	Up	Constant
Capitalized Annual Fixed Charged Rate (pu)	Down	Up
Annual Inflation Rate for O&M (%/yr)	Down	Up
Annual Inflation Rate for kWh Energy (%/yr)	Up	Constant
Annual Inflation Rate for kW Demand (%/yr)	Up	Constant
Annual Operations, Maintenance, and Insurance Expense (%/yr)	Down	Up
Present Worth Rate for Cost of Investment (%/yr)	Up	Down*
Present Worth Rate for Cost of Energy & Losses (%/yr)	Down	Constant
Capital Equipment Life Expectancy (yr)	Constant	Constant
Planned life of Energy Savings (yr)	Up	Down

* Dependent on the annual inflation rate for the investment increasing.

The economic parameters were individually varied for the evaluation of Circuit D voltage reduction option. The parameters were varied by 0.5 and 2 times the default value. The benefit-cost ratios with each modified parameter are shown in Table 10, and the adjusted levelized costs are shown in Table 11. The benefit-cost ratio and levelized cost are also shown for the default (1x) parameters. The option cost, fixed charge rate, energy saved, and marginal cost of energy dictated the acceptability of the efficiency option.

TABLE 10. BENEFIT-COST RATIO RESULTING FROM SCALING INDIVIDUAL PARAMETER DEFAULT VALUES BY 2 AND 0.5 FOR CIRCUIT D OPTION VF

	Benefit-Cost Ratio		
	2x Parameter	1x Parameter	0.5x Parameter
Option Cost ($k)	0.903	1.806	3.613
Energy Saved (MWh)	3.388		1.016
Peak Demand Reduction (kW)	2.031		1.694
Average Marginal Purchase Energy Rate ($/kWh)	3.388		1.016
Average Marginal Purchase Demand Rate ($/kW/yr)	2.031		1.694
Capitalized Annual Fixed Charged Rate (pu)	0.968		3.188
Annual Inflation Rate for O&M (%/yr)	1.747		1.831
Annual Inflation Rate for kWh Energy (%/yr)	2.427		1.587
Annual Inflation Rate for kW Demand (%/yr)	1.895		1.775
Annual Operations, Maintenance, and Insurance Expense (%/yr)	1.594		1.935
Present Worth Rate for Cost of Investment (%/yr)	2.589		1.465
Present Worth Rate for Cost of Energy and Losses (%/yr)	1.265		2.210
Planned life of Energy Savings (yr)	2.323		1.560

TABLE 11. LEVELIZED COST RESULTING FROM SCALING INDIVIDUAL PARAMETER DEFAULT VALUES BY 2 AND 0.5 FOR CIRCUIT D OPTION VF

	Levelized Cost		
	2x Parameter	1x Parameter	0.5x Parameter
Option Cost ($k)	0.108	0.054	0.027
Energy Saved (MWh)	0.027		0.108
Capitalized Annual Fixed Charged Rate (pu)	0.101		0.031
Annual Inflation Rate for Investment (%/yr)	*		*
Annual Inflation Rate for O&M (%/yr)	0.056		0.053
Annual Operations, Maintenance, and Insurance Expense (%/yr)	0.061		0.050
Present Worth Rate for Cost of Investment (%/yr)	*		*
Planned life of Energy Savings (yr)	0.048		0.058

The benefit-cost ratio was inversely proportional to project cost and fixed charge rate; linearly proportional to energy/demand saved, energy/demand rates, and planned life; and nonlinearly proportional to the additional economic parameters. The levelized cost was linearly proportional to project cost, fixed charge rate, and maintenance cost; inversely proportional to energy saved; and nonlinearly proportional to the additional economic parameters.

There was a linear relationship between benefit-cost ratio for voltage reduction and peak demand, as shown in Fig. 2, for the six circuits, and there was an inverse relationship between levelized cost for voltage reduction and peak demand, as shown in and Fig. 3. The relationship was approximately linear (as shown by the linear curve fit with a slope of 1.2) for benefit-cost ratio because the potential benefit from energy reduction was in the numerator. The relationship was approximately inverse for levelized cost (as shown by the power curve fit with exponent -1.5) because the potential benefit from energy reduction was in the denominator.

These relationships occurred because the potential benefit from voltage reduction depended on the load demand. The same percent reduction in voltage will have higher potential benefit from higher initial demand. The benefit-cost ratio and levelized cost were not perfectly linear or inverse due to the magnitude of voltage reduction achieved on each circuit.

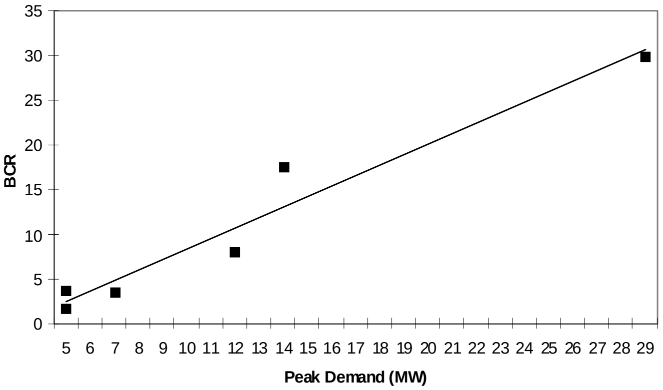

Fig. 2. Benefit-Cost Ratio Relationship with Peak Demand (Linear)

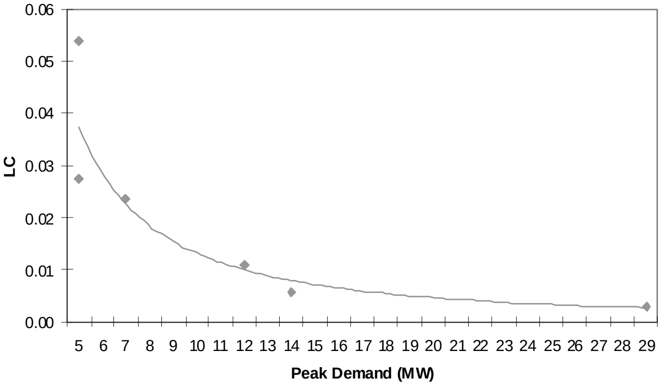

Fig. 3. Levelized Cost Relationship with Peak Demand (Inverse)

VI. APPLICATION OF RESULTS

There are several ways to apply results from an efficiency/economic analysis to optimize efficiency. Options include:

- *Highest benefit-cost ratio* – Pick the option or combination of options with the highest overall benefit-cost ratio. Combination options that target unique efficiency areas approximately add linearly with respect to total cost and energy savings.
- *Incremental benefit-cost ratio greater than one* – Pick an option whose incremental benefit-cost ratio is greater than one. This maximizes return on incremental investment for project components and must include voltage reduction.
- *Largest efficiency benefit* – Pick the option or combination of options that saves the most energy. Even though this may have a lower benefit-cost ratio, it squeezes the most efficiency out of the system. This is most applicable for a distribution company that can effectively sell its kilowatt-hour savings to an efficiency group. By extracting the most from this distribution resource, more is invested in the distribution system.

The most appropriate strategy will depend on the utility's goals, regulations, incentive programs, billing, and more. Table 12 shows optimal options for each circuit based on two criteria: one with the lowest levelized cost (and highest benefit-cost ratio) and one with the most energy savings with a benefit-cost ratio greater than two. Note that optimal options varied widely depending on circuit and economic criteria.

TABLE 12. OPTIMAL OPTIONS FOR EACH CIRCUIT BASED ON ECONOMIC CRITERIA

Circuit	Economic criteria	Option	Levelized cost ¢/kWh	Benefit-cost ratio	Energy savings
A	Lowest levelized cost	Phase balancing + var optimization	0.8	11.3	3.5%
	Maximum efficiency	Phase balancing + var optimization + reconductoring	3.5	2.9	3.9%
B	Lowest levelized cost	Voltage reduction	0.6	17.6	3.5%
	Maximum efficiency	Phase balancing	0.6	17.0	3.6%
C	Lowest levelized cost	Phase balancing	2.3	3.9	2.2%
	Maximum efficiency	Phase balancing + var optimization	2.4	3.8	2.3%
D	Lowest levelized cost	Phase balancing + var optimization	2.1	4.7	1.3%
	Maximum efficiency	Phase balancing + var optimization	2.1	4.7	1.3%
E	Lowest levelized cost	Voltage reduction	2.8	3.6	1.8%
	Maximum efficiency	Voltage regulators	3.9	2.5	1.9%
F	Lowest levelized cost	Voltage reduction	0.3	29.9	2.4%
	Maximum efficiency	Voltage regulators	0.6	16.2	2.6%

VII. CONCLUSION

Distribution efficiency projects were found economically viable for all six test circuits with the assumption utilities recover lost billing from voltage reduction by rate adjustments or other regulatory recovery mechanisms. Each circuit had potential projects with benefit-cost ratios exceeding 3.4 and levelized life-cycle costs less than $0.03/kWh. The majority of the energy savings comes from voltage reduction.

Circuits with the heaviest loading had the highest benefit-cost ratios. These circuits also included those with higher load densities, bus voltage regulation, and belonging to the 25- and 35-kV class. Longer rural, more voltage-limited circuits had lower benefit-cost ratios.

The highest-ranking efficiency options for a specific circuit depended on circuit characteristics, load placement, circuit issues (like excessive unbalance), economic ranking criteria, and economic assumptions. In some cases, the most economically viable option was only voltage reduction. Often, additional improvements were economically viable.

Because each circuit was different, improvement options should be targeted to that circuits needs. Maximum benefit occurs if voltages are flat and controlled at key load centers. This can affect where to place capacitors or regulators. It is often beneficial to try efficiency options in the following order: phase balancing by rephasing taps, simple reconfigurations to balance phases or loading among sections, capacitor control or placement changes, adding regulators, and then targeted reconductoring.

VIII. ACKNOWLEDGEMENTS

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IX. REFERENCES

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X. BIOGRAPHIES

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