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CONSERVATION VOLTAGE REDUCTION POTENTIAL IN THE PACIFIC NORTHWEST

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ABSTRACT

This paper summarizes a study performed by Pacific Northwest Laboratory (PNL) indicating that the region-wide implementation of conservation voltage reduction (CVR) would provide a significant level of electric energy conservation in the Bonneville Power Administration (BPA) service area. This resource was estimated by developing supply curves showing the magnitude of energy savings as a function of CVR implementation cost. Energy savings were estimated for residential, commercial, agricultural irrigation, and industrial consumer classes. Using the convention of expressing energy conservation in average megawatts (AMW), the CVR conservation resource in the Pacific Northwest was estimated to be between 170 and 268 AMW at a cost of 5 cents/kWh. Estimates were also made for the contribution of major load sectors to the total CVR resource. Approximately 55% of the total was estimated to be available in the residential sector. Contributions by the other sectors considered were as follows: commercial, 29%; industrial, 14%; and agricultural irrigation, 3%. A large portion (142 to 230 AMW) of the conservation resource would be available at less than 1 cent/kWh. A median estimate of the regional CVR resource at 1 cent/kWh (179 AMW) exceeds the conservation potential (150 AMW) expected from possible implementation of major efficiency improvements (reconductoring, transformer replacement, and voltage upgrading) on Pacific Northwest transmission and distribution (T&D) systems. This paper also shows that CVR can be more effective than conventional demand-side management measures in reducing system peak load.

1. INTRODUCTION

End-use service voltages must be regulated by electric utility companies to protect consumer equipment. This regulation is generally provided on the distribution portion of the utility system. Standard voltages used in the

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(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

United States are specified by the American National Standards Institute (ANSI Standard C 84.1-82). The regulation of distribution system voltages to narrower ranges than those permitted by ANSI standards has been subject to study, debate, and practical implementation over the last several years. This practice has become known as CVR and has been applied by many utilities in the United States to reduce both peak load and end-use energy consumption (De Steese et al. 1987).

The BPA and electric utilities in the Pacific Northwest continue to evaluate conservation options and remain ready to acquire economically attractive resources when needed. Such effort contributes to the energy resource acquisition plan developed by the Northwest Power Planning Council (NWPPC 1986, 1989). The studies summarized in this paper were sponsored by the BPA for the following purposes: 1) to determine if CVR could be a significant energy conservation measure in the BPA service area and 2) to evaluate CVR as a peak load management option and 3) to assist BPA in developing a position on CVR implementation. The BPA service area includes approximately 150 utility systems in Oregon, Washington, Idaho, western Montana, and parts of Nevada, Utah and, Wyoming.

2. ENERGY CONSERVATION STUDY

A methodology was developed to estimate CVR supply curves that relate energy savings to implementation costs for a hypothetical, region-wide CVR program in the Pacific Northwest. Details of the analysis and results are published (De Steese et al. 1987). The following sections summarize this effort.

Study Approach

Utility distribution systems in the BPA service area were characterized in terms of feeder length and predominant consumer class served (residential, commercial, industrial, and agricultural) using information supplied by many utilities. Energy savings were estimated by considering CVR applications according to feeder length and consumer class. Implementation costs for CVR were developed for 27 measures. These ranged from the typically low cost measures for applying CVR to short, high-density urban feeders to higher cost modifications that are necessary to implement CVR on long, low-density suburban and rural lines. Supply curves showing the size of CVR resources were

constructed by aggregating energy savings for each consumer class at each level of CVR implementation cost.

Two basic CVR implementation strategies were considered. The first is known as line-drop compensation (LDC) regulation. This strategy involves regulation that keeps the most distant portion of the circuit at some minimum acceptable voltage level such as 114 volts (secondary equivalent), while the rest of the circuit voltage is allowed to vary with load conditions. During periods of peak load, the substation voltage can rise to the maximum allowable service voltage (126 volts), but at all other times would be somewhat less. During off-peak periods the entire circuit would operate near the minimum controlled voltage. Thus, energy consumption of end-use loads is reduced because the average circuit voltage is less than it would with conventional voltage regulation.

The second strategy considered was compression of the voltage range on a feeder, often called voltage spread reduction (VSR). For circuits with adequate voltage margin, VSR may be implemented by setting regulator voltage-level controls to a narrower range while maintaining the required minimum voltage at the most distant load. For example, by using VSR to limit the voltage on a feeder to the lower half the ±5% band allowed by the ANSI Standard, an average voltage reduction of 2.5% can be implemented on the feeder. When VSR is used in conjunction with LDC regulation, it is often possible to implement voltage reductions in excess of 5% while maintaining an adequate voltage at the most distance load.

Estimation of Energy Savings

Energy savings produced by CVR can vary considerably depending on both system configuration and the individual response of end-use appliances. A bounded range of CVR energy savings was estimated to accommodate the variability of these parameters. The lower bound of this range was synthesized from data on the voltage dependence of end-use energy consumption measured in the laboratory (EPRI 1981, 1982; Chen et al. 1982).

As this approach developed, test computations showed that energy savings synthesized from appliance response data fell consistently below the energy savings at the consumer class-level reported by Kirshner and Giorsetto (1984). Kirshner and Giorsetto analyzed many voltage reduction studies performed by various utilities. The overall conclusion of their statistical analysis was

that for each 1% reduction in average voltage, the corresponding reduction in energy consumption of the residential, commercial, and industrial sectors is 0.765%, 0.991% and 0.409%, respectively. Potential energy savings were scaled from these results and used as an upper bound of the estimated CVR resource in the Pacific Northwest.

Energy Savings for Application of 2.5% CVR

The above techniques were used to provide an overall indication of the CVR resource that might be realized by applying a hypothetical 2.5% voltage reduction on all distribution systems in the BPA service area. Figure 1 displays the class-level resource components as estimated by each approach. The resource potential of such a program was estimate to range from 151 AMW (lower bound) to 233 AMW (upper bound).

The above estimates, made at a fixed 2.5% voltage reduction, provided a useful measure of the relative contributions of consumer sectors to the total regional resource. The residential sector was the primary contributor to the CVR resource and was estimated to be 55% of the total. Contributions by the other sectors considered were commercial (29%), industrial (14%), and agricultural (3%).

Estimation of CVR Implementation Costs

A telephone survey was conducted with more than 30 utilities to gather information on circuit length, regulation strategy, voltage margin, and construction costs. A total of 27 CVR implementation measures were defined and assigned an average cost, based on information supplied by correspondent utilities. To simplify the analytical problem, distribution systems were divided into three feeder length categories: less than 3 miles, 3 to 12 miles, and greater than 12 miles. Estimates were made to associate each of these measures with an appropriate feeder length category, a percentage of feeders in the category that could accommodate each measure, the average voltage reduction potentially achievable and average cost per installation. Results of this portion of the analysis are summarized in Tables 1, 2, and 3.

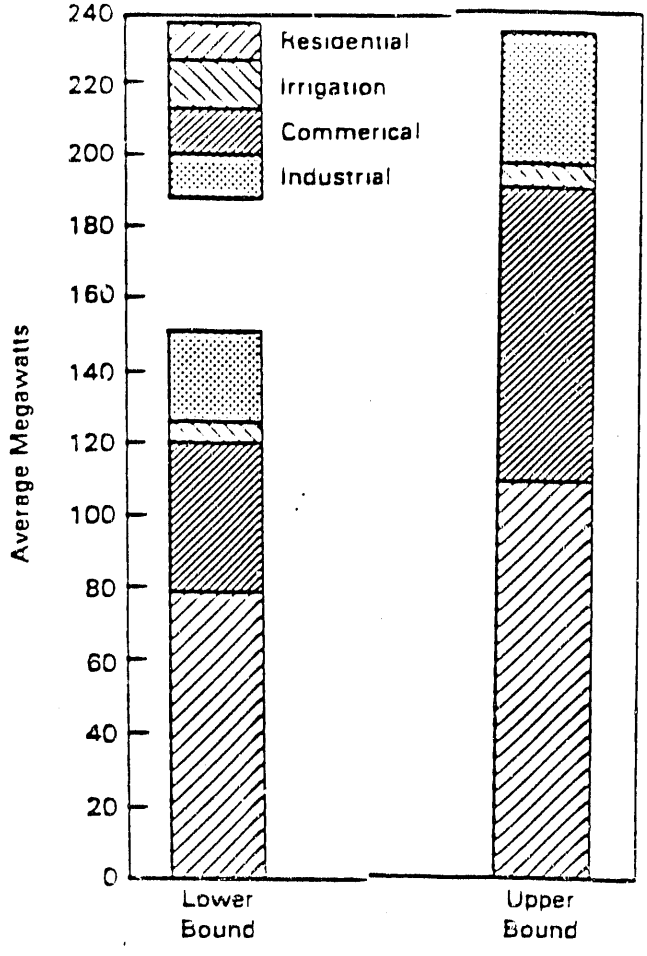

FIGURE 1. Resource Components from a 2.5% Voltage Reduction

CVR Supply Curve Development and Results

The conservation resources estimated by the supply curves were based on the actual voltage reductions achievable with each CVR measure and feeder class. Energy savings were allocated to the circuit categories based on the proportion of the number of circuits in that category to the total number of circuits. Implementation costs for CVR were levelized over a 30-year period. Present values were then calculated and distributed to each year according to a fixed-payment mortgage schedule.

Supply curves were constructed by combining the annual cost with the energy savings realized from the implementation of each CVR measure. The annual costs were divided by annual energy savings to obtain the cost of the hypothetical program (in cents) per unit of energy conservation (kilowatt-hours). These results were then paired and ordered by cost per kWh of energy savings from the lowest to the highest. A sum of energy savings at each cost was accumulated and expressed in average megawatts (AMW - total yearly energy savings in megawatt hours divided by 8760, the number of hours in a year). This cumulative sum was the total conservation potential at a given cost plus the sum of all the savings at lower costs. Supply curves for CVR were obtained, as shown in Figure 2, by plotting cost per kWh versus the cumulative energy savings estimated in the above manner.

The supply curves represent the CVR conservation resources potentially available from all utilities (investor- and publicly-owned) operating in the BPA service area. Each supply curves shows a substantial resource at costs less than 0.1 cent/kWh. The curves then rise sharply in cost for the remainder of the resource.

Up to 1 cent/kWh (142 to 230 AMW), the resource is very competitive with all other conservation approaches. The median CVR resource at this cost (179 AMW) exceeds the 150 AMW of conservation estimated by Tepel et al. (1987), for a hypothetical program of efficiency improvements (reconductoring, transformer replacement, and voltage upgrading) applied to electric power T&D systems in the Pacific Northwest.

TABLE 1. CVR Implementation Costs: Distribution Circuits Less Than Three Miles in Length

	Option	Circuits (%)	Voltage Reduction (%)	Cost/Circuit
1	Reregulation 5% Lower and Line Drop Compensation	12.7	5.7	$150
2	Reregulation 5% Lower	14.0	5.0	$150
3	Line Drop Compensation	31.3	2.4	$150
4	Reregulation 1.2% Lower	17.6	1.2	$150
5	Balance Feeders, LDC, and 5% Reduction	0.8	5.7	$390
6	Balance Feeders and 5% Reduction	0.7	5.0	$390
7	Balance Feeders and LDC	1.9	2.4	$390
8	Balance Feeders and 1.2% Reduction	1.1	1.2	$390
9	Capacitor Addition	9.0	2.5	$24,800
10	Regulator Addition	8.0	3.2	$8010
11	Capacitors and Regulators	2.9	3.2	$32,800

TABLE 2 CVR Implementation Costs: Distribution Circuits From 3 to 12 Miles in Length

	Option	Circuits (%)	Voltage Reduction (%)	Cost/Circuit
12	Reregulation	8.0	2.0	$150
13	Capacitor Addition	13.1	2.0	$27,800
14	Regulator Addition	14.1	2.0	$8010
15	Regulator and Capacitor Addition	11.1	2.0	$47,600
16	Reinsulate	3.2	2.0	$155,000
17	Reconductor	5.0	2.0	$180,000
18	Combination	12.7	2.4	$126,000
19	Reregulation and LDC	4.0	4.4	$150
20	Capacitor Addition	6.4	4.4	$27,800
21	Regulator Addition, Voltage Reduction	6.9	4.4	$8010
22	Regulator and Capacitor Addition	5.4	4.4	$47,800
23	Reinsulation	1.6	4.4	$155,000
24	Reconductor	2.4	4.4	$180,000
25	Combination	6.3	4.6	$126,000

TABLE 3 CVR Implementation Costs: Distribution Circuits Greater Than 12 Miles in Length

	Option	Circuits (%)	Voltage Reduction (%)	Cost/Circuit
26	Reinsulate	43.5	2.5	$486,000
27	Combination	56.5	2.5	$703,000

A CVR resource in the range 170 to 268 AMW was estimated to cost of 5 cents/kWh. This was established by the NWPPC (1986) as the cost-effectiveness threshold for conservation resources based on the 1985 cost of a coal-fired central generating station. Up to this cost level, conservation is considered by the NWPPC to be preferable to providing new capacity with conventional generating resources.

3. PEAK LOAD MANAGEMENT STUDY

In another study performed by PNL for BPA, the System Demand Side Management (SDSM) Assessment, the peak load reduction capability of CVR was compared with that of several demand-side management (DSM) measures. These measures included residential electric thermal storage (ETS), water heater control (WHC), the Model Conservation Standards (MCS) Program and increasing the efficiency of commercial lighting (CL).

Study Approach

The effectiveness of these measures was estimated using a computer program derived from the Conservation-in-Lieu-of-Construction (CILOC) methodology reported by Englin et al. (1987). The approach involved the synthesis of system load shapes for the BPA service area. Each load shape was accumulated by summation of sectoral load components as modified by load growth forecasts and the estimated future penetration and effectiveness of each DSM measure. Load shapes for each case were developed including one for the reference case (no new DSM measures) and one for each DSM scenario. The effectiveness of DSM options was estimated from the reduction in peak load effected by each measure compared to the load shape of the reference case. The computer program used had the ability to synthesize and compare load shapes for system peak conditions occurring anytime within a period of 20 years.

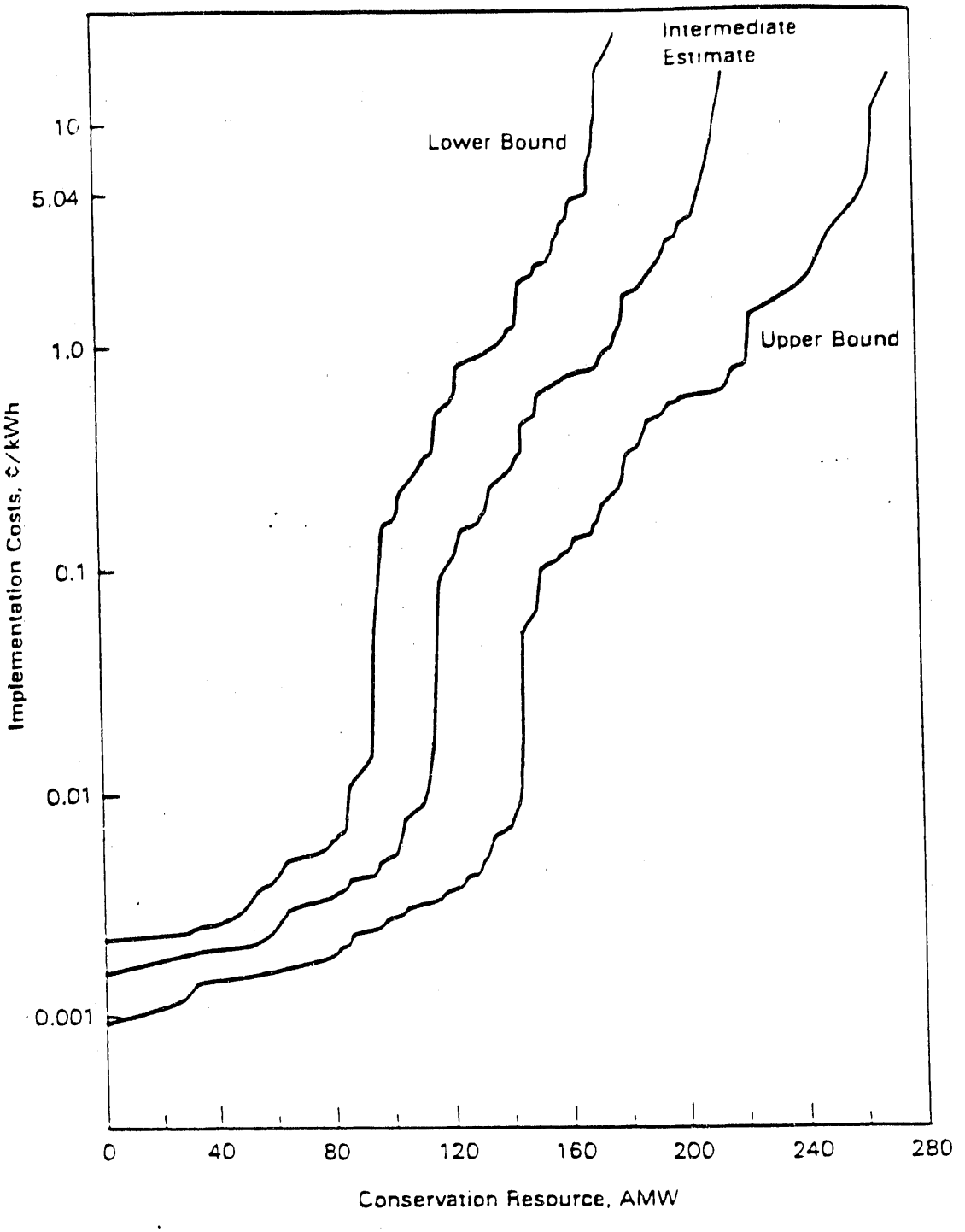

FIGURE 2. CVR Supply Curve for Pacific Northwest Region

Estimate of Average Voltage Reduction

The previous CVR conservation study provided a basis for estimating the average voltage reduction achievable with a regional CVR program. By scaling from the resources estimated for the fixed 2.5% CVR case to the resources indicated by the supply curves, it was concluded that an average region-wide voltage reduction of 2.85% corresponds to the economic (5 cents/kWh) CVR resource. In the SDSM analysis, the assumption was made that CVR measures costing more than 5 cents/kWh would not be included in a CVR program for peak reduction.

Estimation of CVR Effects on End-Use Demand

While the literature describes CVR effects on individual appliances in extensive detail, there are only a few data available that relate CVR value to the load shapes considered in the SDSM analysis. Many references to CVR experience show conflicting results and reach different conclusions about the effectiveness of CVR. The SDSM analysis follows the work of Kirshner and Giorsetto (1984). While, several reports suggest that CVR is more effective in reducing peak load than in producing energy savings, Kirshner and Giorsetto's statistical work indicates that both effects, on average, are similar. The percentage load reductions used in the SDSM study were based on CVR energy conservation effects.

Table 4 shows the effect of CVR on the demand of several end-use loads. The demand reduction for each load type is estimated by multiplying the unit demand response of each load to voltage reduction (% demand reduction/% average voltage reduction) by 2.85, the average voltage reduction estimated, as described above.

The values of the CVR demand reduction shown in Table 4 were input to the computer program to modify the reference load shapes by the indicated fixed percentage throughout the day. However, thermostatically-controlled resistive loads that deliver a constant amount of energy to a process needed special consideration.

With CVR, the demand of such loads is reduced, but they stay on longer in each control cycle. The CVR effect on the space heating load shape, therefore, should be distinguished according to severity of the weather. On an average

TABLE 4. Percentage Effect on Hourly Load Shapes for 2.85% Average CVR Application

End-Use Load	CVR Hourly Demand Reduction (%)
Space Heating	0.0 (a) 5.6 (b)
Cooking	5.6
Incandescent Lights	5.6
Fluorescent Lights	4.3
High-Pressure Lamps	5.6
Motor-Operated Equipment	2.8
Average Residential Sector Energy	2.2
Average Commercial Sector Energy	2.8
Average Industrial Sector Energy	1.2

(a) In periods of nonextreme weather with thermostat control cycle < 1 hour
(b) In periods of extremely cold weather with thermostat cycles > 1 hour

day, when space heating might cycle on and off at a frequency less than 1 hour, the effect of CVR on an hourly-aggregated load shape is negligible. This is because the hourly load shape essentially shows a demand based on average energy consumed each hour. Even if the heating cycle is a few percent longer due to CVR, the hourly demand will not change so long as cycling occurs at less than an hourly frequency. However, in extremely cold weather conditions, space heating systems can operate continuously in a effort to keep up with energy lost to the ambient. In this case, CVR would be effective in reducing the demand of these systems.

Comparison of CVR with Other Demand Side Management Measures

System load shapes were calculated for CVR and each of the demand side measures, mentioned above, using the SDSM computer program. The analysis accounted for reasonable penetration schedules for each of the measures. The computer program was set up to compute Pacific Northwest system load shapes for the peak month (December) in each year for 20 years. Table 5 shows the

TABLE 5 December System Peak Load Reduction (MW)

Year	ETS	WHC	CL	MCS	CVR
1990	12	93	11	16	128
1992	50	153	23	65	175
1994	103	151	35	111	226
1996	158	151	43	158	232
1998	183	151	44	206	239
2000	219	151	45	256	245
2002	232	151	46	307	252
2004	245	152	47	359	259
2006	259	157	48	410	266
2008	272	162	50	460	274
2010	285	167	51	512	282

the simulated December peak load reduction achieved by each measure during the period 1990 to 2010 (odd-numbered years are omitted for convenience).

These results show that for the first 10 years, CVR is the most effective option in the Pacific Northwest for reducing system peak, until it is exceeded by the Model Conservation Standards Program in the Year 2000.

A similar analysis was conducted to evaluate the effectiveness of each measure in reducing the sustained system peak. This is the average system megawatt load during the period 7 a.m. to 10 p.m. In the Pacific Northwest, the management of the sustained peak would improve the ability of the region's predominantly hydropower system to supply peak loads, taking its overnight recharge capability into account. CVR was shown in this analysis to outperform the other load management measures by effecting the largest reduction in sustained peak for a period of 11 years. Again, CVR was shown to be eventually exceeded by the MCS Program as it reached full maturity.

4. CONCLUSIONS

If applied to distribution systems throughout the Pacific Northwest, CVR offers energy conservation potentially as large as 270 AMW at costs up to 5 cents/kWh. A large portion of this CVR resource would be available at a cost of 1 cent/kWh (142 to 230 AMW). A substantial portion of the CVR conservation potential in the Pacific Northwest and, specifically the energy savings at

the lowest cost, occur on residential feeders less than 3 miles in length. These lines are typically found in more densely populated urban areas. Longer (i.e., 3 to 12 mile) lines, typical of suburban areas, could be included in a CVR program at costs less than the NWPPC threshold. However, long rural feeders might be too expensive to include in such a program. Most utilities have a mixture of the different types of feeders; therefore, the value of CVR to a particular utility would need to be considered on an individual basis. A hypothetical CVR Program implemented to effect energy conservation was also shown to provide a peak load management option more effective than some conventional measures. Results of these studies suggest that the systematic implementation of CVR in the Pacific Northwest would be beneficial. By extrapolation, this conclusion also applies to other regions of the nation.

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