Estimates of the Achievable Potential for Electricity Efficiency Improvements in U.S. Residences

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This paper investigates the potential to achieve electricity efficiency improvements in US residences through public policies—specifically, appliance efficiency standards, utility demand-side management programs, and building energy-efficiency standards. This study is unique among achievable potential estimates both in its end-use technology detail and comprehensive treatment of residential energy-efficiency policies at the national level. The resulting methodology is well-documented and addresses shortcomings of standard technical potential analyses, thus yielding valuable information for program designers and policy-makers.

This study builds upon the most extensive database of residential energy efficient technologies yet developed. The savings potential and cost for each efficiency measure in this database are modified to reflect the expected results of new policies implemented between 1990 and 2010. The technical potential modifications are: the market penetration of efficiency measures, the costs of administering policies, and adjustments to the technical potential estimates to reflect empirical energy savings and costs (accounting for factors such as takeback, measure persistence, and inaccurate engineering estimates). Including the effect of all adjustment factors, new policies can achieve 45% of the technical potential electricity savings during the period 1990 to 2010, or 18% of the frozen-efficiency baseline electricity consumption forecast for the year 2010.

Introduction

Many analyses over the past two decades have estimated that current technologies can save substantial amounts of energy at less cost than producing that energy—ranging from 15 to 70% of the consumption that would take place without efficient technologies (Rosenfeld et al. 1993, Komor & Moyad 1992)1 Thus, in theory the cost-effective potential to save energy is substantial. In practice, however, experience shows that market forces and public policies to promote energy efficiency cannot achieve the entire potential. The fundamental question is: given the mixed success of energy-efficiency policies and the real-world constraints on future efficiency improvements, how much of the savings potential can be realized? This paper addresses this question by estimating the achievable potential for electricity efficiency improvements in US residences.

This study builds on a previous estimate of the technical potential for electricity efficiency improvements in the US residential sector (Koomey et al. 1991). That study assembled a database containing cost and performance data for each efficiency measure. The current achievable potential study uses this technology database but modifies the savings potential and cost for each measure to reflect expected policy results. Factors included in these modifications are: 1) the market penetration of efficiency measures, 2) the costs of administering policies, and 3) adjustments to the technical potential savings estimates reflecting the experience of measures implemented in the past. This study considers three classes of policies: 1) appliance efficiency standards, 2) utility demand-side management (DSM) programs, and 3) building energy-efficiency standards. Due to the broad assumptions required, this study is not an attempt to definitively quantify the achievable potential. Rather, it is an exploration of the factors influencing the achievable potential and an estimate of the potential using representative values for those factors.

Background

Supply curves of conserved energy are a method of estimating the *minimum* possible future energy consumption. The supply curves of conserved energy method has two principal features. First, by sequencing the efficiency measures, this method avoids double-counting energy savings for multiple measures applied to the same building or appliance (such as thermal shell upgrades and HVAC equipment replacement). Second, the supply curves method uses the cost of conserved energy (CCE) to order the measures by cost-effectiveness. An advantage of the CCE method is that the price of electricity is exogenous to the calculation, thus allowing simple evaluation of measures under different energy price assumptions. More details on the supply curve methodology are provided by Meier et al. (1983).

US Residential Technical Potential

The achievable potential presented in this paper is based on a previous study that estimated the technical potential for electricity efficiency improvements in the US residential sector by 2010 (Koomey et al. 1991). The savings potential was measured relative to a frozen efficiency baseline, in which natural stock turnover still takes place but efficiencies do not improve beyond the average for new units purchased in 1990. The frozen efficiency baseline consumption in 2010 is estimated to be 1019 TWh. The study concluded that by 2010, annual residential electricity consumption could be reduced by 404 TWh (40% of baseline consumption) by fully implementing all measures that cost less than the 1990 national average residential retail price of electricity (7.8 ¢/kWh). The study used the average investor-owned utility real cost of capital (7% real discount rate) to calculate costs of conserved energy. The results incorporate physical constraints such as stock turnover rates and production phase-in limits for new technologies.

Policy Overview

This study evaluates three types of policies—appliance standards, utility demand-side management programs, and building standards. These are the primary policies that have been enacted, or actively considered, to address failures on the demand-side of the residential energy market. Additional policies, such as information campaigns, are not explicitly treated in this study because their effects are difficult to quantify; instead, they are assumed to be an integral part of the policies analyzed in this study.

The interaction between policies can significantly change the magnitude and cost of energy savings. There are many ways in which these interactions can occur; two specific interactions are considered in this study. First, utility programs often serve as vehicles for accelerating the development and adoption of new technologies, in turn accelerating the time at which those technologies can be incorporated into appliance standards. Second, appliance standards are often used as the basis from which incremental efficiency levels are given rebates in utility programs.

Methodology

In this study, policy impacts are modeled as modifications to the technical potential study discussed previously. The modifications involve four steps applied to each measure in the database. The first step is to determine the type of policy(ies) that will be used to encourage adoption of the efficient technology. Second, by drawing on empirical data about the effectiveness of past and current policies, I estimate an expected market penetration of the measure as a result of policies. Third, I recalculate the cost of the measure to include the assumed costs of implementing the policies. Fourth, I adjust the measure's expected energy savings to account for empirically observed conditions the measure will experience in actual use (such as post-measure changes in equipment usage).

Several formal models have been developed to estimate market penetration, as summarized by Kendall and Cates (1991). Generally, the data requirements for these models are impractical for a national level study such as this. Moreover, the parameters used in these models are often based on analyst's judgment of the adoption rate and ultimate penetration of a technology, and the model serves simply to formalize the judgment process. Therefore, this study dispenses with a formal model of market penetration. Instead, I use representative values for the rate of adoption and ultimate penetration of each policy, based on analogies to past policies where possible. The "first principles" of market penetration are the assumed annual rate of penetration for a specific program, and the starting and ending dates of policies. These inputs, combined with information about the rate of turnover and additions to the stock, permit estimation of the cumulative market penetration by the end of the study period (2010).

Market Penetration Examples

Each efficiency measure is promoted through two main policies: (1) the appropriate type of standard (either building or appliance, depending on the end-use), and (2) a utility program lasting from 1990 until the standard becomes effective. In some cases the utility program is omitted because the standard becomes effective early enough in the study that a utility program would have a negligible impact. For the utility programs I assume an annual penetration rate, defined as the fraction of new purchases or existing stock that is upgraded to more efficient equipment in a given year. A ramp-up period of one to five years, during which the program gradually becomes fully operational, precedes this steady-state penetration rate. Detailed market penetration results for each end-use are documented by Brown (1993).

Building Codes and Utility Programs for Space Conditioning. Table 1 shows the adoption of the ASHRAE 90.2 and advanced ASHRAE standards over the course of the study period, along with utility programs to promote more efficient new construction.

Appliance Standards. The assumed schedule of federal energy-efficiency standards (both current and future) for all appliances is shown in Table 2. The beginning dates of appliance standards are based on information about the DOE appliance standard review cycle from the Lawrence Berkeley Laboratory Energy Conservation Policy Group.[2]

Utility Programs for Non-Space Conditioning End-Uses. In this study, utility programs, due to their

Table 1. Penetration of Policies for Upgrading New Thermal Shells (% of new homes meeting efficiency level)

	Efficiency Level			
Policy:	**ASHRAE 90.2**		**Advanced ASHRAE**	
Year	**Utility Programs**	**Building Standards**	**Utility Programs**	**Building Standards**
1990	5%	0%	5%	0%
1991	15%	0%	15%	0%
1992	25%	0%	25%	0%
1993	35%	0%	35%	0%
1994	45%	0%	45%	0%
1995	0%	40%	50%	0%
1996	0%	48%	50%	0%
1997	0%	56%	50%	0%
1998	0%	64%	50%	0%
1999	0%	72%	50%	0%
2000	0%	80%	50%	0%
2001	0%	80%	50%	0%
2002	0%	80%	50%	0%
2003	0%	80%	50%	7%
2004	0%	80%	50%	21%
2005	0%	80%	0%	35%
2006	0%	80%	0%	42%
2007	0%	80%	0%	49%
2008	0%	80%	0%	56%
2009	0%	80%	0%	63%
2010	0%	80%	0%	70%
2010 Cumulative Penetration:	7%	50%	35%	10%

Notes:

1. Building standards penetration includes the effect of incomplete enforcement (80% enforcement for ASHRAE 90.2; 70% enforcement for advanced building standards).
2. Assumes that utility programs end when ASHRAE 90.2 is adopted. Annual penetration of building standards in 1995 is a result of 50% of housing starts occuring in jurisdictions adopting ASHRAE 90.2, combined with 80% enforcement.

Table 2. Current and Future Appliance Efficiency Standards

End Use	Efficiency Level	UEC (kWh)	Start Year	2010 Cumulative Penetration
Refrigerator/Freezer				
Current Standard	DOE 3	690	1993	86%
Future Standard	DOE 5	490	1998	61%
Stand-Alone Freezer				
Current Standard	DOE 3		1993	73%
Future Standard	DOE 5		1998	52%
Electric Water Heater	EF≥0.94		1995	71%
Hot Water Consumption				
Showerheads	<2.5 gpm		1994	60%
Faucet Aerators	<2.5 gpm		1994	60%
Clotheswasher				
Current Standard	DOE 3	674	1994	80%
Future Standard	DOE 6	262	1998	58%
Clothesdryer				
Current Standard	DOE 3	966	1994	73%
Future Standard	DOE 5	338	1998	52%
Dishwasher	DOE 3	501	1994	83%
Cooking		694	1995	83%
Furnace Fans		350	1999	68%
Miscellaneous Motors				46%
>1 horsepower	Size-		1998	51%
<1 horsepower	dependent		2002	40%
Televisions		171	1998	80%

Notes:

1. Current-standard efficiency levels and start-years are from Koomey et al. (1991).
2. Future-standard start-years are from LBL Energy Conservation Policy Group (1990).
3. Future-standard efficiency levels are based on advanced measures from Koomey et al. (1991).
4. Standards are for illustration only and do not represent official DOE policy.
5. Refrigerators/Freezers: UECs are based on 18 cu. ft. top-mount auto. defrost model. DOE Level 5 standard includes evacuated panels, twin 5.3 EER compressors, and adaptive defrost (US DOE, Nov 89).
6. Information on showerhead and aerator standards are from Geller & Nadel (1992); gpm=gallons per minute.
7. Clothes washers: DOE Level 6 standard is a horizontal-axis design. UECs based on standard-capacity model (US DOE, Dec 1990).
8. Clothes dryers: DOE Level 5 standard is a heat pump design. UECs based on standard-size electric dryer (US DOE, Dec 1990).
9. Dishwashers: DOE Level 3 standard has booster heater and improved motor (US DOE, Dec 1990).
10. Cooking: Standard assumed to include induction cooktop and convection oven.
11. Furnace Fans: Minimum efficiency is prescribed as part of 1999 heat pump standards.
12. Motors: Energy Policy Act of 1992 prescribes minimum efficiencies for motors >1 hp DOE must decide within 4 years whether to set standards on motors <1 hp (Geller & Nadel 1992).
13. TVs: 2010 penetration assumes constant, linear stock turnover and 15 year life. UEC is for 21" color set.

inherent flexibility, are assumed to target those end-uses and measures not covered by building or appliance standards. Some end-uses, such as lighting, are affected almost exclusively by utility programs. Table 3 shows the utility program market penetration estimates used in this study. The most useful sources of data for estimating market penetration of well-run utility programs are two previous achievable potential studies conducted for Michigan (Krause et al. 1988) and New York (Nadel and Tress 1990).

Table 3. Market Penetration of Utility Programs for Appliances

Measure	Annual Penetration Rate	Program Ramp-up	2010 Cumulative Penetration
Refrigerator & Freezer (Until 1998 std.)	50%	1,5,15,30,50%	16%
Replace Elec. with Gas Water Heater			18%
New Construction	50%	5,15,25,35,45,50%	35%
Replacement	10%		10%
Replace Elec. with Heat Pump Water Heater			31%
New Construction	40%	1,3,5,7,10,15,20,25,30,35,40%	31%
Replacement	40%	1,3,5,7,10,15,20,25,30,35,40%	31%
Upgrade Elec. Water Heater (Until 1995 std.)			6%
New Construction	50%	5,15,25,35,45,50%	7%
Replacement	25%	1,5,15,25%	5%
Reduce Hot Water Consumption			29%
New Construction	50%	5,15,25,35,45,50%	35%
Energy Fitness Retrofit	4%	2, 2.5, 3, 4%	27%
Lighting			36%
New Construction	50%	5,15,25,35,45,50%	35%
Replacement Light Coupons	8%	2,4,6,8%	36%
Energy Fitness Retrofit	4%	2, 2.5, 3, 4%	38%
Clotheswasher			10%
Clothesdryer			10%
Dishwasher			10%
Cooking			10%

Notes:
1. Penetration rates are from Nadel and Tress (1990).
2. Penetrations are in addition to those achieved by appliance standards and building codes.
3. Annual Rate is the market share of efficient models in each year.
4. New construction is treated as a "lost opportunity." If efficiency measures are not implemented at time of construction, retrofit does not occur later.
5. Cumulative penetration for Energy Fitness program from Nadel & Tress (47.5%) is reduced by 20% to account for rural customers unreachable by such programs (resulting in 38% nationwide penetration).
6. Penetration of the hot water consumption portion of Energy Fitness program is further reduced by 30% to incorporate the effect of plumbing fixture standards.

Proaram Costs

Program costs are the "overhead" costs to administer programs, set energy-efficiency levels for standards, select technologies eligible for rebates, find participants for DSM programs, and conduct all the other administrative activities that ensure a successful policy. The program costs have been calculated at a detailed level for each measure, using data from Nadel and Tress (1990), Krause et al. (1988), and Berry (1991). These program costs are summarized in Table 4.

Another component of utility program costs are "free riders" - people who would have adopted the technology without the program, but took advantage of the program to subsidize their investment. Free riders increase program costs per TWh of energy savings because the total program cost is allocated over a smaller amount of savings directly attributable to the program. Despite the inherent inaccuracy in free ridership estimates (Vine 1992), these figures are intended to serve as representative values.

Adjustments to Technical Potential

Several factors have been used to adjust the technical potential estimate of energy savings: 1) calibration of engineering estimates to measured data, 2) the takeback effect, and 3) savings persistence. Engineering estimate

Table 4. Summary of Program Costs

Policy	Average Program Cost (¢/kWh)
Appliance Standards	0.25
Utility Programs	0.68
Building Standards	0.33
Overall Average:	0.41

adjustments calibrate estimated energy savings to account for inaccurate assumptions or analysis methods. To date, the empirical results from Nadel and Keating (1991) provide the best summary of these factors. I use these estimates as a rough guideline to the magnitude of adjustment required. The takeback effect is a phenomenon in which increasing the efficiency of energy-using capital equipment saves less energy than expected because consumers simply use the equipment more intensively, thereby "taking back" the energy savings in the form of increased energy services. Savings persistence accounts for the fact that the efficiency of physical devices degrades over time, or in some cases may be rendered inoperable by the building occupants. In this study, each of these the adjustment factors has been estimated separately by end-use because each differs in equipment, operating conditions, and behavioral effects, as shown in Table 5.

Results

After applying the market penetration and adjustment factors discussed previously, the resulting achievable potential supply curve is presented graphically in Figure 1 (labeled "Best Estimate Achievable Potential"). These results show that approximately 185 TWh (0.63 site Quads) of annual electricity savings can be achieved by 2010, which is 45% of the technical potential and 18% of the frozen efficiency baseline consumption forecast for that year. Figure 1 also shows the effect as each factor is

Table 5. Summary of Technical Potential Adjustment Factors (% of original savings estimate not realized)

	Adjustment Factor		
Efficiency Measure	Takeback	Measured-Savings Adjustment	Persistence
Thermal Shell Retrofits	15%	15%	10%
New Thermal Shells	5%	5%	5%
New-Home HVAC Equipment			
Heat Pumps	5%	10%	5%
Air Conditioners	5%	15%	5%
Replacement HVAC Equipment			
Heat Pumps	10%	10%	10%
Air Conditioners	10%	15%	5%
Refrigerators/Freezers	0%	5%	5%
Water Heating			
Efficient New Water Heater	10%	5%	5%
Showerheads and Aerators	15%	5%	10%
Lighting	10%	10%	10%
Clothes Washer	5%	5%	0%
Clothes Dryer	0%	5%	0%
Dishwasher	0%	5%	0%

Notes:
1. Takeback is the reduction in energy savings due to increased usage after measure installation.
2. The measured-savings adjustment accounts for inaccuracies in the original estimates of technical potential energy savings.
3. Persistence accounts for the performance degradation that the energy efficiency measure will suffer over its lifetime, over and above the expected performance degradation of the baseline device.

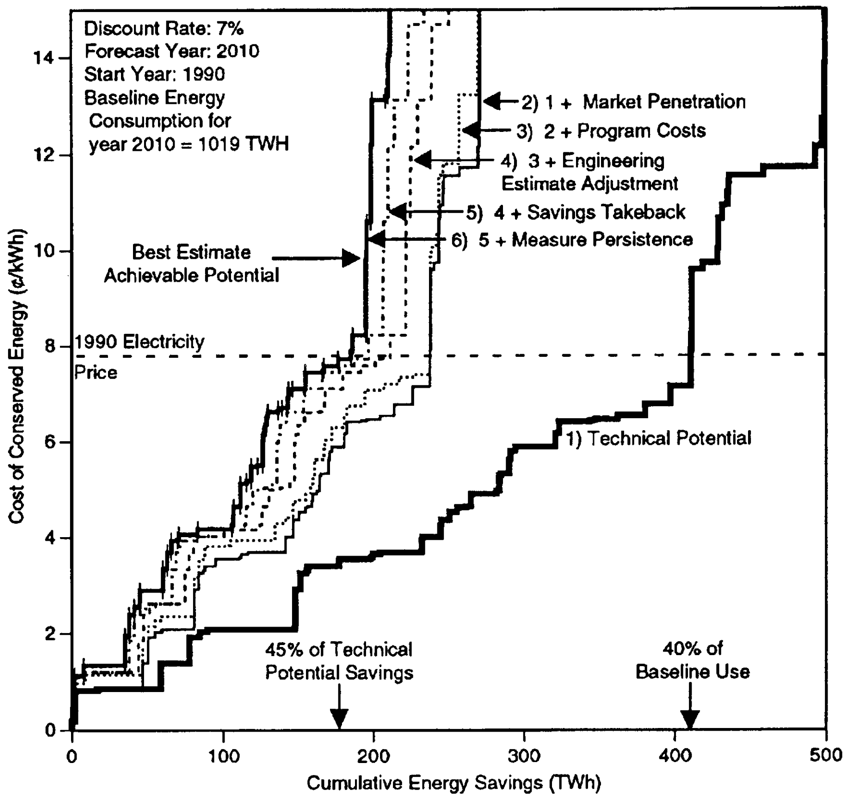

Figure 1. Impact of Technical Potential Adjustment Factors. The series of supply curves illustrates how achievable potential changes with the sequential addition of technical potential ajustment factors.

sequentially added to the calculation. The order in which factors are applied (progressing from the right to the left in the diagram) are: 1) technical potential, 2) market penetration, 3) program costs, 4) engineering estimate adjustment, 5) savings takeback, and 6) measure persistence. Two observations can be made from these curves. First, approximately two-thirds of the difference between the technical and achievable potential is due to market penetration alone. Second, program costs (the smallest dotted line) have essentially no effect on achievable potential, and are a smaller effect than the technical potential adjustment factors.

The achievable potential also shows interesting trends when aggregated by end-use. Table 6 summarizes the achievable potential energy savings by end-use and also the fraction of savings due to each type of policy. The breakdown of savings for the various policies is: 60% of the achievable potential is due to appliance standards, 33% due to utility programs, and 7% due to building standards. Building standards account for only a small fraction of the savings because new construction is only a small fraction of the total building stock and ASH RAE 90.2 is only a small improvement over current construction practices (which are accounted for in the baseline).

Conclusion

Two *caveats* apply to the results presented here, First, the achievable potential is not the *likely* level of energy-efficiency improvements, but rather the savings we can achieve through a concerted effort to institute energy-efficiency policies. Second, the savings potential presented here includes representative values for the technical potential adjustment factors, based on empirical data where possible. A more accurate assessment of achievable potential will require more comprehensive empirical data on the effects and costs of policies. In particular, the costs of standards and the market penetration of utility programs are two areas in which generalized empirical results are needed.

This paper has developed estimates of the achievable potential for electricity efficiency improvements in the US residential sector as a result of three policies: appliance standards, utility DSM programs, and building standards. This study adjusted the technical potential in three ways: 1) added market penetrations; 2) added program administration costs; and 3) adjusted the technical potential energy savings to account for deviations between engineering estimates and observed energy savings. The results show

Table 6. Summary of Achievable Electricity-Efficiency Potential in 2010, Using All Adjustment Factors (for measures costing less than 7.8 ¢/kWh)

	Technical Potential		Achievable Potential			% of Achievable Savings Due to:		
End-use	End-use Energy Savings (TWh)	Avg. CCE (¢kWh)	End-use Energy Savings (TWh)	End-use Tech. Pot. Achieved (%)	Avg. CCE (¢/kWh)	Appliance Standards	Utility Programs	Building Standards
Shell Measures	44.49	3.9	12.76	29%	5.3	0%	66%	34%
Existing House Retrofits	26.45	3.7	5.16	20%	5.7	0%	79%	21%
New Construction	18.04	4.1	7.60	42%	5.0	0%	57%	43%
HVAC Equipment Measures	61.03	2.3	24.61	40%	3.3	68%	26%	6%
Exist. Multifamily Equip.	0.77	2.7	0.48	62%	3.1	89%	11%	0%
Exist. SF & MH Equip.	33.85	2.5	12.74	38%	4.3	85%	15%	0%
New Multifamily Equip.	0.31	4.5	0.14	45%	4.8	73%	27%	0%
New SF & MH Equip.	26.09	1.9	11.25	43%	2.2	47%	40%	13%
Appliances	249.78	3.7	127.20	50.92%	4.1	72%	28%	0%
Refrigerators/Freezers	51.32	4.9	39.59	77%	5.4	90%	10%	0%
Water Heating	89.13	3.0	46.66	52%	2.8	70%	30%	0%
Lighting	57.96	2.1	15.30	26%	2.9	0%	100%	0%
Clothes Washers	5.51	3.6	3.21	58%	3.1	91%	9%	0%
Clothes Dryers	19.99	6.0	12.79	64%	6.5	85%	15%	0%
Dishwashers	3.40	2.9	2.76	81%	3.4	96%	4%	0%
Cooking	13.37	7.2	0.00	0%	8.2	0%	0%	0%
Miscellaneous	9.12	3.5	6.89	76%	3.8	90%	10%	0%
Fuel Switching Measures	55.30	6.0	20.32	36.75%	7.5	0%	47%	53%
Water Heating	16.66	4.9	2.41	14%	6.7	0%	100%	0%
Clothes Dryers	20.29	6.4	9.64	48%	7.6	0%	40%	60%
Cooking	18.35	6.6	8.28	45%	7.7	0%	40%	60%
NAECA Standard Measures with CCEs over elec. price (4)	N/A	N/A	0.29		10.5			
Total (excluding previous line)	410.60	3.8	184.89	45%	4.4	58%	33%	9%

Notes:
1. Frozen efficiency baseline elec. consumption in 2010 is 1019 TWh. The above technical potential is 40% of this baseline.
2. Clothes washer and dishwasher savings include reduced hot water consumption measures for those enduses.
3. Achievable potential includes all adjustment factors: program penetration and costs, engineering estimate adjustment, savings takeback, measure persistence, and DSM program free riders.
4. Three CAC measures, which are part of the existing NAECA standards, have CCEs greater than the price of electricity.
5. Fuel switching potential includes only those housing units that have gas service but use electric equipment.
6. For the clothes washer enduse, the achievable potential CCE is less than the technical potential CCE because fewer of the high-cost measures are implemented in the achievable potential (the CCE is an average over all measures within the enduse).

that by 2010 these policies can achieve approximately *40%* of the technical potential, or 185 TWh of electricity savings out of a frozen efficiency baseline consumption of 1019 TWh (18% savings). This savings potential includes all measures costing less than the 1990 national average retail electricity price (7.8¢/kWh). Approximately 60% of these savings were due to appliance standards, 33% due to DSM programs, and 7% due to building standards.

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Endnotes

1. The results are heavily dependent on assumptions such as the baseline consumption from which savings are measured. The majority of these estimates lie in the range of 30% to 50% savings.

2. Note that the standard levels for advanced options are based on judgement and do not represent DOE policy on actual future standards.

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