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Michael P. Vandenbergh

Thomas Dietz

Gerald T. Gardner

Jonathan Gilligan

Paul C. Stern

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Thomas Dietz[a], Gerald T. Gardner[b], Jonathan Gilligan[c], Paul C. Stern[d,1], and Michael P. Vandenbergh[e]

[a]Department of Sociology and Environmental Science and Policy Program, Michigan State University, East Lansing, MI 48864; [b]Department of Behavioral Sciences, University of Michigan, Dearborn, MI 48128; [c]Department of Earth and Environmental Sciences, Vanderbilt University, Nashville TN 37235; [d]Division of Behavioral and Social Sciences and Education, National Research Council, Washington, DC 20001; and [e]Climate Change Research Network, Vanderbilt University Law School, Nashville, TN 37203

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Most climate change policy attention has been addressed to long-term options, such as inducing new, low-carbon energy technologies and creating cap-and-trade regimes for emissions. We use a behavioral approach to examine the reasonably achievable potential for near-term reductions by altered adoption and use of available technologies in US homes and nonbusiness travel. We estimate the plasticity of 17 household action types in 5 behaviorally distinct categories by use of data on the most effective documented interventions that do not involve new regulatory measures. These interventions vary by type of action and typically combine several policy tools and strong social marketing. National implementation could save an estimated 123 million metric tons of carbon per year in year 10, which is 20% of household direct emissions or 7.4% of US national emissions, with little or no reduction in household well-being. The potential of household action deserves increased policy attention. Future analyses of this potential should incorporate behavioral as well as economic and engineering elements.

climate mitigation | climate policy | energy efficiency | household behavior | energy consumption

Global greenhouse gas emissions and associated climate change have been increasing at accelerating rates in recent years. For example, atmospheric CO_2 concentration increased by an annual average of 1.5 ppm/yr in 1980–1999, 2.0 ppm/yr in 2000–2007, and 2.2 ppm in 2007 (1). Prompt change in this trajectory is necessary to reach the ambitious stabilization targets now being discussed, but most policy attention has been directed to slow-acting options. New technologies for low-carbon energy supply, energy efficiency, and carbon sequestration must overcome various technical, economic, institutional, and societal obstacles and will take decades to develop and penetrate markets (2, 3). The most prominent policy approaches to the climate commons dilemma—national and international cap-and-trade regimes—face issues of implementation feasibility that could delay achievement of carbon emissions reduction objectives for years (4–6). For the United States, these include setting meaningful caps, promulgating regulations to implement the program, monitoring emissions and emissions offsets, and controlling offshoring and other responses of covered entities that could undercut the objectives of the regime (7, 8).

Cap-and-trade programs and policies to induce technologic innovation may not be sufficient to achieve ambitious near- and long-term emissions reduction targets. Time lags likely from implementation of complex policy (e.g., the 1,400-page Clean Energy and Security Act of 2009) and from getting to emissions caps that are substantially more stringent than business-as-usual levels also may make it difficult for the United States to demonstrate international leadership. Complementary strategies are probably needed and certainly advisable. Among these, opportunities for short-term emissions reductions have been relatively neglected.

We focus on a short-term option with substantial potential for carbon emissions reduction: altering the adoption and use of available technologies in US homes and nonbusiness travel by means of behaviorally oriented policies and interventions. This potential "behavioral wedge" can reduce emissions much more quickly than other kinds of changes and deserves explicit consideration as part of climate policy (9). It can potentially help avoid "overshoot" of greenhouse gas concentration targets; provide a demonstration effect; reduce emissions at low cost; and buy time to develop new technologies, policies, and institutions to reach longer-term greenhouse gas emissions targets and to develop adaptation strategies.

Individual and household behavioral change faces well-known barriers (10), but more is known about how to overcome these barriers than is commonly recognized (11–14). Lack of familiarity with this knowledge among scholars and policy makers is a major obstacle to achieving prompt, large, low-cost emissions reductions. We apply a behavioral approach that complements engineering and economic approaches to estimate the reasonably achievable potential for near-term emissions reduction from behavioral change in households. We focus on US households because they are a major emitter and because there is a significant body of knowledge about the potential to achieve near-term reductions in that sector.

Direct energy use by households accounts for approximately 38% of overall US CO_2 emissions, or 626 million metric tons of carbon (MtC) in 2005 (15, 16). This is approximately 8% of global emissions and larger than the emissions of any entire country except China. National policy initiatives have addressed households only indirectly, mainly through setting motor vehicle, lighting, and appliance efficiency standards. Recent reviews of the available research suggest a large near-term potential for emissions reductions from behavioral changes involving the adoption and altered use of available in-home and personal transportation technologies, without waiting for new technologies or regulations or changing household lifestyle (15, 17). We develop a quantitative estimate of this potential at the national level, aggregated across behaviors.

Results

We find that the national reasonably achievable emissions reduction (RAER) can be approximately 20% in the household sector within 10 years if the most effective nonregulatory interventions are used. This amounts to 123 MtC/yr, or 7.4% of total national emissions—an amount slightly larger than the total national emissions of France (18). It is greater than reducing to zero all emissions in the United States from the petroleum

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[1]To whom correspondence should be addressed. E-mail: pstern@nas.edu.

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Table 1. Achievable carbon emissions from household actions

Behavior change	Category*	Potential emissions reduction (MtC)[†]	Behavioral plasticity (%)[‡]	RAER (MtC)[§]	RAER (%I/H)[§]
Weatherization	W	25.2	90	21.2	3.39
HVAC equipment	W	12.2	80	10.7	1.72
Low-flow showerheads	E	1.4	80	1.1	0.18
Efficient water heater	E	6.7	80	5.4	0.86
Appliances	E	14.7	80	11.7	1.87
Low rolling resistance tires	E	7.4	80	6.5	1.05
Fuel-efficient vehicle	E	56.3	50	31.4	5.02
Change HVAC air filters	M	8.7	30	3.7	0.59
Tune up AC	M	3.0	30	1.4	0.22
Routine auto maintenance	M	8.6	30	4.1	0.66
Laundry temperature	A	0.5	35	0.2	0.04
Water heater temperature	A	2.9	35	1.0	0.17
Standby electricity	D	9.2	35	3.2	0.52
Thermostat setbacks	D	10.1	35	4.5	0.71
Line drying	D	6.0	35	2.2	0.35
Driving behavior	D	24.1	25	7.7	1.23
Carpooling and trip-chaining	D	36.1	15	6.4	1.02
Totals		233		123	20

*See text for definitions of categories W, E, M, A, and D.

[†]Effect of change from the current level of penetration to 100% penetration, corrected for double-counting. Measured in millions of metric tons of carbon (MtC).

[‡]Percentage of the relevant population that has not yet adopted an action that will adopt it by year 10 with the most effective interventions.

[§]Reduction in national CO_2 emissions at year 10 due to the behavioral change from plasticity, expressed in MtC/yr saved and as a percentage of total US individual/household sector emissions (%I/H). Both estimates are corrected for double counting.

refining (69 MtC), iron and steel (38 MtC), and aluminum (13 MtC) industries, each of which is among the largest emitters in the industrial sector (19). The cost of achieving such a reduction through behavioral change may be far lower than the cost of many alternatives (15, 17).

We analyzed 17 types of household action that can appreciably reduce energy consumption using readily available technology, with low or zero cost or attractive returns on investment, and without appreciable changes in lifestyle. We first estimated the potential emissions reduction (PER) from each action, that is, the reduction that would be achieved nationally from 100% adoption of the action (15, 17). We then estimated plasticity (20)—the proportion of current nonadopters that could be induced to take action—from data on the most effective proven interventions. This introduces a behavioral realism to our estimates that is not included in analyses grounded solely in engineering or economics.

We based our plasticity estimates on empirical studies of responses to interventions at the individual and household levels aimed at changing energy consumption and related environmentally significant behaviors (12, 14, 21, 22) and on studies of interventions to induce adoption of health-promoting behaviors that resemble energy-saving behaviors (23–25). These studies make it possible to consider how plasticity is affected by types of intervention (e.g., media campaigns, information, and financial incentives) separately and in combinations and also by the type of behavior (12–14). Our approach contrasts with methods that rely on generic indicators of plasticity, such as price elasticity of demand. It facilitates consideration of the effects of both economic and non-economic stimuli in the same analysis. This is important because evidence from past energy efficiency interventions indicates that responsiveness to price can vary by a factor of 10, depending on nonfinancial aspects of policy implementation (21).

Our plasticity estimates reflect what has been achieved by the most effective documented interventions that do not involve new regulation of technology or behavior. These interventions have been demonstrated in field experiments or in organized programs implemented at the community, city, regional, or state level—many of them in response to the energy crises of the 1970s. Our estimates of emissions reductions are based on scaling the interventions up to national application.

The most effective interventions typically (*i*) combine several policy tools (e.g., information, persuasive appeals, and incentives) to address multiple barriers to behavior change; (*ii*) use strong social marketing, often featuring a combination of mass media appeals and participatory, community-based approaches that rely on social networks and can alter community social norms; and (*iii*) address multiple targets (e.g., individuals, communities, and businesses) (12, 14, 23, 26).* Single policy tools have been notably ineffective in reducing household energy consumption. Mass media appeals and informational programs can change attitudes and increase knowledge, but they normally fail to change behavior because they do not make the desired actions any easier or more financially attractive. Financial incentives alone typically fall far short of producing cost-minimizing behavior—a phenomenon commonly known as the energy efficiency gap (27). However, interventions that combine appeals, information, financial incentives, informal social influences, and efforts to reduce the transaction costs of taking the desired actions have demonstrated synergistic effects beyond the additive effects of single policy tools (12, 13, 28). The most effective package of interventions and the strongest demonstrated effects vary with the category of action targeted.

We combined PER and plasticity to estimate RAER for each action. PER and RAER estimates for actions were corrected for double-counting (e.g., lower thermostat settings yield smaller emissions reductions when combined with more efficient furnaces).[†] Details of all our calculations are provided in the *SI Text*. Table 1 shows the actions and the associated estimates of 10-year emissions reductions.

*Multiple targets can create community-level effects that enhance behavioral change above what can be achieved with a single target. We do not include ''spillover'' savings from businesses and other organizations in our calculations, so we are underestimating the overall impact of the approach we propose.

[†]Our estimates are not corrected for potential ''takeback'' (i.e., a portion of achievable reductions from improved technical efficiency that consumers forgo to gain other benefits, such as increased thermal comfort).

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The 17 types of actions include both adoption of more efficient equipment and changes in use of equipment on hand. We divide the actions into 5 categories on the basis of behaviorally relevant attributes: W (home *weatherization* and upgrades of heating and cooling equipment); E (more efficient vehicles and nonheating and cooling home *equipment*); M (equipment *maintenance*); A (equipment *adjustments*), and D (*daily* use behaviors). This behavioral classification elaborates on previous ones that do not distinguish W from E or A from D (29–31). W and E both involve adoption of equipment, but the equipment differs in the salience of product attributes other than energy savings and cost. A and D both involve changes in equipment usage but differ in the ease of maintaining emission reductions: adjustments made once maintain their effects automatically, but D behaviors must be repeated over and over to achieve their potential.

W actions [weatherizing with attic insulation, by sealing drafts, and installing high-efficiency windows, and replacing inefficient home heating, ventilating, and central air conditioning (HVAC) equipment] are one-time investments in energy-efficient building shells and equipment that have few salient product attributes other than energy savings and financial costs and benefits. Plasticity is estimated from the most effective documented weatherization programs, which have combined financial incentives (grants or rebates covering most of the retrofit cost), convenience features (e.g., one-stop shopping), quality assurance (e.g., certification for contractors, inspection of work), and strong social marketing. The highest recorded plasticity is 85% over 27 months (28); rates of 15–20% per year have been recorded several times (21). Assuming the most effective interventions are deployed, we estimate plasticity of 80% in 5 years and 90% in 10 years, except for furnaces and central AC equipment, for which we assume replacement only at the end of the useful life of existing equipment, resulting in 80% plasticity in 10 years. RAER for W is thus estimated at 5.1% of total household use, or 32 MtC. Strong financial incentives are necessary but insufficient to achieve this plasticity; in the past, plasticity with identical strong incentives has varied by a factor of >10, depending on other aspects of their implementation (21). By supplementing financial incentives with program elements such as energy audits, convenience, and quality assurance, the most effective programs significantly reduce nonfinancial costs of action as well as financial ones (14, 21).

E actions (e.g., adopting more energy-efficient appliances, equipment, and motor vehicles) involve purchases to upgrade the energy efficiency of household equipment, but in most cases product attributes other than cost and energy savings matter to consumers.[‡] We assume replacement at the end of useful life with products of the same type (e.g., size, performance, convenience, and appearance features) that are more efficient. As with heating, ventilating, and AC (HVAC) equipment, we estimate 10-year plasticity at 80% for most equipment classes. We estimate only 50% plasticity for motor vehicle efficiency. The new vehicle fleet may not change fast enough to allow higher plasticity unless consumers forgo other product attributes (e.g., size and acceleration). The most effective interventions probably combine improved rating/labeling systems, other information for households and retailers, financial incentives for households and/or vendors, and strong social marketing (14, 26). RAER for this class of actions is 9.0% of total household emissions, or 56 MtC.

M actions (e.g., changing air filters in HVAC systems, vehicle maintenance) are infrequent, low-cost, or no-cost actions that can be maintained by habit. *A actions* (reducing laundry temperatures, resetting temperatures on water heaters) are infrequent, no-cost actions that, once taken, are maintained automatically. *D actions* (e.g., eliminating standby electricity, thermostat setbacks, line drying, more efficient driving, carpooling, and trip chaining) are frequently repeated actions maintained by habit or repeated conscious choice.

The most effective interventions for M, A, and D actions generally involve combinations of mass-media messages, household- and behavior-specific information, and communication through individuals' social networks and communities, with specifics depending on the target behavior (14, 22, 26). Plasticity is probably behavior-specific in ways not fully understood at present. Few studies exist of interventions targeting single behaviors of these types. However, studies of daily or continuous energy-use feedback, a form of household-specific information, typically show reductions in total in-home energy consumption by 5–12%, probably by inducing change in multiple A and D behaviors (32). Multipronged interventions have produced reductions of 15% or more of home energy use by changing these behaviors (e.g., 33, 34). We conservatively estimate that feedback supplemented by other communication can achieve the plasticities shown in Table 1 for A and D behaviors, which reduce total energy use in homes and in driving by approximately 4%. Very little is known about the plasticity of the M behaviors. Analogies from health behavior campaigns suggest plasticity of 8% to 9% from mass media campaigns (24, 25) and more if communication uses individuals' social networks and communities (23). We believe 30% plasticity is achievable for these maintenance actions because they involve less-difficult changes than most health behaviors. RAER for M, A, and D, respectively is 1.5%, 0.2%, and 3.8%, or 34 MtC/yr in total for these actions.

Discussion

Our estimates of RAER are based on the best available behavioral evidence and provide a reasonable initial guide to what can be achieved by active promotion of household behaviors to reduce greenhouse gas emissions. More precise estimates can be developed with better data. However, decades of research on proenvironmental and health behaviors demonstrate that behavioral interventions can have substantial impacts and show how to design them for maximal effect.

Two kinds of knowledge seem most critical for developing firmer estimates of RAER and achieving more of the potential. One concerns the current penetration of energy-efficient equipment and practices. We could find no data to estimate the penetration of trip chaining, low rolling resistance (LRR) replacement tires, and reduction of standby electricity and very limited data on other actions, including important ones such as water heater temperatures. Better data would yield better estimates.

The other type of knowledge, perhaps even more important, is knowledge related to plasticity, in particular about how the features of interventions, including incentives, education, information, social marketing, quality assurance, and convenience improvements, work separately and together to affect adoption of specific emissions-reducing activities. Energy conservation policies often go without evaluation or are evaluated in ways that are not useful for understanding plasticity or learning how to make interventions more effective. On a related note, there is insufficient information on the costs and institutional requirements (e.g., staffing, program management) of highly effective, large-scale behavioral change initiatives. The experience of successful programs over the last several decades suggests that these are not insurmountable barriers, but additional data would be valuable.

The American Recovery and Reinvestment Act of 2009, commonly known as the stimulus package, and the Consumer Assistance to Recycle and Save (CARS) Act of 2009, better

[‡]More efficient lighting is omitted from our analysis because the 2007 Energy Independence and Security Act mandates phaseout of incandescent lighting and forces a shift to compact fluorescents, yielding PER of 30.2 MtC or 4.8% of household sector emissions in year 10. Further savings can be obtained by voluntary shifts to solid-state (light-emitting diode) lighting, but this technology is new to consumers and we have no basis for estimating plasticity.

known as the "cash for clunkers" program, represent a missed opportunity in this regard. The stimulus package provided $5 billion for low-income home weatherization, $4.3 billion for a 30% tax credit for certain home energy-efficiency investments, and $300 million in rebates for the purchase of Energy Star appliances, as well as additional funds that state and local governments could use for various purposes, including residential energy efficiency (35). The CARS program provided $3 billion for incentives for owners to trade in qualifying older vehicles for more fuel-efficient new ones, with the old ones being scrapped. It is too soon to estimate the effects in terms of emissions reduction, but 2 observations are worth making. First, the programs are quite different in behavioral terms. Although there are questions about the cost effectiveness of CARS, it was a great behavioral success, probably due in part to outstanding marketing, paid for by the industry, and convenience (it featured one-stop shopping, removed all paperwork burdens from the consumer, and provided an instant rebate). This contrasts, for instance, with the tax credit program, which also provides a large financial incentive but has not been as well marketed, does not make shopping easy, and requires paperwork and up to a 1-year delay in collecting the credits. More could have been done to apply the lessons of past behavioral research. Second, they do not include an evaluation component that would allow for learning from these major policy experiments. Of course, these programs were intended primarily to provide quick stimulus to the economy, so these deficiencies are not surprising, but the opportunities for more effective, behaviorally based programs and for learning by doing should not be missed in future policies.

Our analysis suggests that most of the 10-year RAER (>13% of total household emissions or 5.2% of total US emissions) can be achieved in 5 years because most actions will ramp up quickly in the early years of an effective program. An average of 60% of the 10-year plasticity could probably be achieved by year 5 in all categories except weatherization, for which, as noted, we anticipate 80% plasticity by year 5. The significance of these reductions can be illustrated in relation to the metaphor of climate "stabilization wedges." Pacala and Socolow (9) argued that adoption of any 7 of 15 existing technologies could be ramped up sufficiently over 50 years to stabilize CO_2 emissions at approximately 7 billion tons of carbon (GtC)/yr to allow time for the development of new technologies that could reduce emissions further. Each wedge would provide a cumulative total of 25 GtC in reductions over the 50-year period compared with "business as usual." If the United States, which emits roughly 20% of global greenhouse gas, were to take a corresponding share of the burden of emissions reduction, it would contribute 7 US wedges of 200 MtC/yr each after 50 years, or 40 MtC each after 10 years. The changes in household behavior outlined above result in a 123 MtC total year-10 RAER or roughly 3 such wedges—44% of the US contribution at year 10.

Extending beyond the United States, similar percentage reductions are likely possible in Canada and Australia, which have carbon profiles roughly comparable to that of the US, and percentage savings of perhaps half the US level may be achievable in the European Union countries and Japan, where the household sector is less energy intensive. Analyses similar to this one would be needed to estimate the potential in other countries. Because the behavioral wedge can ramp up in 10 years, and significant portions of it even more quickly, it provides both a short-term bridge to gain time for slower-acting climate mitigation measures and an important component of a long-term comprehensive domestic and global climate strategy.

Our estimate for US households is conservative. Further 10-year emissions reductions will be achieved by adoption of technologies now almost ready for mass market penetration (e.g., heat pump water heating and space conditioning, electric vehicles, light-emitting diode lighting). Reductions are also likely from household actions that are already being taken but that may not meet our cost criterion, such as purchases of solar technology, green electricity services, carbon offsets, and consumer products with low life-cycle emissions. Still other reductions are possible from behavioral changes that moderately alter lifestyle, such as travel mode changes, telecommuting, and downsizing larger homes and cars. The potential reductions from shifts in consumer purchase patterns, downsizing, and some of these other actions are calculable, but available data are inadequate for making the estimations. For example, carbon calculators, which typically include estimates of emissions associated with purchases of food and other consumer goods, yield inconsistent results and so far do not provide enough information for validation (36).

Lifestyle changes may become necessary in the out-years under constrained energy supply or economic growth scenarios, and they may become more attractive as a result of changes in social attitudes or national or community priorities, some of which might evolve from grassroots efforts to achieve the emissions reductions analyzed here. Additionally, policies that add a financial incentive for carbon emissions reduction are likely to increase behavioral plasticity and may also induce downsizing of household equipment. A US demonstration of leadership on achieving the behavioral wedge might help induce other countries to do the same (37). The potential of behavioral change deserves increased policy attention. Future analyses of the potential of efficiency in meeting emissions goals should incorporate behavioral as well as economic and engineering elements.

Materials and Methods

We analyzed 33 specific actions that constituted the 17 action types (e.g., "driving behavior" combines slower acceleration, 55 mph speed for highway driving, and reduced idling in nontraffic situations). We defined each action precisely enough to allow us to estimate its current penetration, or the proportion of the relevant population that has adopted an action (e.g., the proportion of motor vehicles being driven at 55 mph on the highway). We estimated penetration from the strongest empirical evidence we could find. The precise definitions of the actions and the bases for estimating emissions reductions and current penetration for each are presented in *SI Text*. PER was calculated by multiplying the PER from an action by the size of the population that has not yet adopted it, aggregating across fuels weighted by carbon emission factors for each, and correcting for double-counting of actions that have overlapping effects (e.g., slower driving has a smaller effect in a more energy-efficient vehicle). The methods are described further in *SI Text*. Plasticity was estimated from data on the most effective documented nonregulatory interventions as described above. We estimated RAER by combining plasticity and PER after recalculating the double-counting corrections for the incomplete penetrations of overlapping actions. *SI Text* presents and illustrates the calculation method.

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