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Decarbonizing residential building energy: A cost-effective approach

David Timmons [a,*], Charalampos Konstantinidis [a], Andrew M. Shapiro [b], Alex Wilson [c]

[a] Economics Department, University of Massachusetts Boston, 100 Morrissey Blvd, Boston, MA 02125-3393, USA
[b] Energy Balance, Inc., 160 White Rock Dr. #1, Montpelier, VT 05602, USA
[c] Resilient Design Institute, 251 Leonard Road, Dummerston, VT 05301, USA

HIGHLIGHTS

- Least-cost decarbonization balances costs of renewable energy and conservation.
- Solar photovoltaic energy may provide an upper bound on energy and conservation cost.
- We apply these principles in a case study and discuss non-marginal cost issues.
- Specific types of policy are needed to minimize decarbonization costs.

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ABSTRACT

Given the problem of climate change, the world economy must eventually switch to carbon neutral energy. In this study we present a cost-effectiveness approach: given a goal of decarbonization, the objective is to accomplish this at minimum cost. For residential building energy, we show that total cost is minimized by equating marginal cost of building energy conserved with marginal cost of obtaining carbon-free energy, where we express costs of both in dollars per kWh. We describe how the cost of solar photovoltaic energy provides an upper bound on the marginal cost of carbon-free energy and thus an upper bound on marginal cost of conserved energy—one should not necessarily spend more on energy conservation than the cost of photovoltaic energy (though there are several caveats). A case study from Vermont, USA illustrates these principles and implementation issues with marginal analysis of energy conservation. From a policy perspective, the principles presented suggest that either carbon taxes or carbon limits could be used to decarbonize building energy at minimum cost, but that approaches using renewable-energy subsidies or prescriptive building codes result in greater decarbonization costs to society. This suggests that new policy approaches be adopted.

1. Introduction

Climate change is the most serious environmental problem confronting the world today. Since fossil fuel use is one of the primary drivers of climate change, addressing climate change will require changing energy production and use across all sectors of the world economy. In this study we focus on carbon emissions from residential building energy use, representing 20% of U.S. greenhouse gas emissions from fossil fuels in 2012 (U.S. Department of State, 2014).

Large-scale decarbonization can be accomplished by both generating carbon-free energy and conserving energy. From a social planner perspective, decarbonization should be accomplished at the minimum cost. As we demonstrate in this article, cost effectiveness provides a guide to determining the optimum mix of energy conservation and renewable energy generation. Furthermore, given that climate change is a global collective-action problem (Ostrom, 2010), achieving decarbonization targets can only be achieved through coordinated action by a large number of actors, including firms and households. With over 115 million households in the United States alone (U.S. Census Bureau, 2014), coordinated action clearly requires appropriate policy instruments, which should induce behavior by individual actors that minimizes decarbonization cost for society as a whole.

Many studies consider the economics of building energy conservation. The U.S. Environmental Protection agency (EPA, 2009) reviews over a dozen studies of energy efficiency potential in the United States, concluding that conservation could reduce U.S. energy usage by about 20% for annualized costs of $0.012 to

* Corresponding author.
E-mail address: david.timmons@umb.edu (D. Timmons).

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$0.052 per kWh. While this is substantially less than the current cost of energy in many locations, the report notes a number of problems that prevent the realization of such reductions, including principle-agent problems, transaction-cost problems, and capital constraints. Most studies are not aimed at complete decarbonization of building energy use, and compare cost of conserved energy to the cost of a fossil-fuel alternative rather than a renewable alternative.

McKinsey and Company (Creyts et al., 2007) develop a carbon abatement supply curve for the United States, finding that CO_2 emissions could be reduced up to 28% from 2005 levels for costs of less than $50 per ton. Building and appliance conservation options account for 19% of total reductions. Many of the options have negative costs, meaning that annualized conservation costs would be less than the cost of energy.

The American Solar Energy Society (Kutscher, 2007) assesses how efficiency improvements could be used in reducing CO_2 emissions by 60–80% before 2050. In contrast to other studies, efficiency contributes 57% of the emissions reductions, with costs ranging from $0 to $0.04/kWh for electricity and $0 to $0.02/kWh for oil and gas. About 40% of the improvements are attributable to buildings. Clearly, there is no precise upper bound on efficiency—the feasible level of efficiency improvement depends on the desired level of CO_2 reduction and on the cost of using energy instead of conserving it. Different studies thus come to very different conclusions about how much energy can be conserved.

A number of studies consider the economics of very-low energy buildings (Galvin, 2010; Harvey, 2013; Parker, 2009). For example, dwellings built to Passive House standards may reduce energy consumption by 90% compared to typical construction (Schnieders and Hermelink, 2006). Yet some studies find the best financial returns from less extensive energy conservation—costs of conservation can outweigh conservation benefits when benefits are based on current prices of fossil fuels. For example, Audenaert et al. (2008) model the same house design built to standard, low-energy, and Passive-House standards, finding the best financial return for the low-energy house, even though a Passive House would use less energy. Galvin (2010) reached similar conclusions about strict energy codes for residential housing in Germany, finding that less-strict codes were economically preferable.

Some studies have calculated the cost of conserved energy (CCE) in value per unit of energy (Galvin, 2010; Harvey, 2013; Parker, 2009; Petersen and Svendsen, 2012). For example, Schnieders and Hermelink (2006) estimate the cost of conserved energy in a Passive House is €0.062/kWh. Calculating cost of conserved energy allows one to compare the marginal costs of conservation options to each other and to the marginal cost of energy (Jakob, 2006). We use the costs of conserved and renewable energy to reflect the relative difficulty of using these means to achieve building energy decarbonization. As described in Section 2.2, the equimarginal principle from economics suggests that minimizing total cost requires all marginal costs to be equal (Field and Field, 2012).

In this paper we apply microeconomic principles to the question of renewable energy supply in a society that has largely eliminated fossil-fuel combustion. Though the Intergovernmental Panel on Climate Change (IPCC) suggests that such a society must emerge by the middle to late 21st century (IPCC, 2014), there is little research on the economics of an energy supply drawn predominantly from renewable sources. We contribute to the decarbonization literature by addressing the problem of cost-effectively decarbonizing when faced with different carbon-reduction options (i.e. energy conservation and carbon-free energy generation), an issue largely overlooked by previous studies. In the following sections we first formally apply the equimarginal principle to building energy decarbonization, showing that marginal cost of conserved energy (MCCE) must equal marginal cost of renewable energy (MCRE) at the minimum total cost. We also provide a method to obtain an explicit estimate of the maximum MCRE, based on the cost of solar photovoltaic (PV) energy. At the optimum, MCRE must equal MCCE, which guides cost-minimizing building energy conservation decisions. We illustrate these microeconomic principles for cost effectiveness in a housing case study in Vermont, USA, describing specific methods for implementing the principles. We conclude with discussion of policy implications, showing that specific policy approaches are needed to minimize cost of decarbonized building energy, and that policies in common use today result in unnecessary costs.

1.1. Cost-effectiveness analysis

Several issues complicate benefit-cost analysis related to climate change. Uncertainty regarding extreme climate outcomes (associated with fat-tailed probability distributions) along with unbounded disutility from extreme outcomes and potentially catastrophic damages suggest that benefits from reducing greenhouse gas emissions may be severely understated (Ackerman and Stanton, 2013; Weitzman, 2009). At the household level, estimated benefits often reflect only fuel savings by individuals, which may not reflect larger social gains from reducing carbon emissions and other pollution. Financial benefit estimates are sensitive to current and projected fuel prices, which vary over space and time. Most energy conservation projects also require an initial investment in order to receive a future stream of energy-saving benefits. The value of such an investment depends greatly on the choice of discount rate, and private discount rates may vary from social discount rates, which could give greater weight to the welfare of future generations than individuals do (Ackerman, 2009).

We assume that decarbonizing building energy use is a necessary step for controlling climate change. The IPCC estimates that keeping atmospheric greenhouse gas levels in the year 2100 below 450 ppm CO_2e will require reducing world emissions 40–70% from 2010 levels by 2050, and achieving near-zero emissions by 2100 (IPCC, 2014). If decarbonization must occur, it should be accomplished in the least expensive way. In economic terms, this is a cost-effectiveness analysis: we identify the least-cost path to the exogenous goal of controlling climate change, since the benefit of controlling climate change is difficult and perhaps impossible to completely quantify. We adopt a social perspective, where the objective is to minimize total decarbonization costs for society. We assume that aggregate decarbonization targets are achieved in a decentralized way, i.e. through the actions of individual households. In the absence of appropriate policies, minimizing household cost may differ from minimizing social cost.

Framed as a cost-effectiveness question, the optimal building energy conservation problem is simpler than a benefit-cost analysis. Instead of comparing conservation cost to unknown future fossil fuel prices, we compare to the cost of a carbon-free renewable-energy alternative. If renewable energy prices decline over time (as expected), they are bounded by today's prices, while future fossil-fuel prices are unbounded. In this case, cost-effectiveness analysis is also less sensitive to choice of discount rate, since both energy conservation and carbon-free energy alternatives (like solar panels) require large initial investments and have decades-long useful lives. When the same discount rate is used for both investment alternatives, choice of discount is not critical (though discount rate still makes some difference when alternatives have different useful lives). Finally, uncertainty about the costs of climate change does not affect the cost-effectiveness question: even if we are unable to identify and quantify the precise benefits of decarbonization, they will be the same whether achieved through energy conservation or by replacing fossil energy with carbon-free energy.