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Integrating Air Pollution, Climate Change, and Economics in a Risk-Based Life-Cycle Analysis: A Case Study of Residential Insulation

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ABSTRACT

One of the ways in which risk assessment can inform life-cycle analysis (LCA) is by providing a mechanism to translate midpoint categories into common endpoints. Although this analytical step is complex and often highly uncertain, it can allow for prioritization among disparate midpoints and subsequent analytical refinements focused on the endpoints that dominate policy decisions. In this article, we present an approach to address three widely differing impact categories—particulate matter air pollution, greenhouse gas emissions, and personal income. We use the case of increased residential insulation as a measure to reduce energy consumption, which implies economic and public health tradeoffs across all three categories. We apply previously developed models that combined input-output LCA and risk assessment to address public health impacts from particulate matter, and extend the framework to address greenhouse gases and the public health consequences of changes in income. For a hypothetical loan program applied to both new and existing single-family homes, we find a payback period of approximately one year for the particulate matter and greenhouse gas–related midpoints and endpoints, with the structure of the loan implying that no economic payback is required. Our central estimates for avoided disability adjusted life years (DALYs) for a 50-year period are approximately 200,000 for particulate matter, 900,000 for greenhouse gases, and 300,000 for income changes, although values are highly dependent on discount rates and other model assumptions. We conclude that all three impact categories are potentially significant in this case, indicating that analytical refinements should be considered for all three impact categories to reduce model uncertainties. Our study demonstrates how LCA and risk assessment can work together in a framework that includes multiple impact categories, aiding in the evaluation of the net impacts of an energy policy change on society.

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INTRODUCTION

One of the most difficult issues in conducting life-cycle impact assessments (LCIA) is the decision of whether to focus on the quantification of midpoint categories, which are intermediate factors in the causal chain between emissions and endpoints, or to convert these midpoint categories into common endpoints (Bare *et al.* 2000; Jolliet *et al.* 2003, 2004). Although endpoints are generally more interpretable and are potentially more helpful from a decision-maker's perspective, the process of moving from midpoint to endpoint contains significant uncertainties, and there are questions about whether the information gained offsets the added uncertainties.

The incorporation of risk assessment concepts into life-cycle analysis provides an important mechanism for converting disparate midpoints into relevant endpoints, addressing the human health or ecological risks associated with a number of impact pathways. Although the application of risk assessment methods does not eliminate significant uncertainties, some key uncertainties can be quantified, and analyses using identical endpoints can allow for first-order determinations of impact pathways likely to be more or less significant in the decision-making process.

The decision about whether to increase residential insulation to reduce energy consumption is a classic example of a multifactorial decision that could be informed by a risk-based life-cycle analysis, as the costs and benefits of increased insulation and reduced energy consumption can span a number of different dimensions. For example, increased residential insulation will lead to greater consumer costs, either through direct expenses or indirectly through increased home prices. However, these economic costs will be offset by gains associated with reduced energy consumption. The net change in annual disposable income will clearly influence consumer decision-making, but may also have implications for public health via the relationship between health and wealth.

In addition, the reduced end-use energy will yield public health benefits through reduced emissions of criteria air pollutants or air toxics (either directly from residential fuel combustion or indirectly from power plant emissions for changes in electricity use). Lowered energy consumption will also influence greenhouse gas (GHG) emissions, with potential implications for climate change and associated impacts. However, increased insulation manufacturing will be needed to yield these benefits, which can have its own associated impacts on emissions in both categories. For both end use energy consumption decreases and insulation manufacturing increases, there will be life-cycle implications of the changes as well. This could include conventional life-cycle impacts (*i.e.*, the environmental impacts of extracting the coal needed for electricity generation) as well as pathways often omitted (*i.e.*, increased insulation manufacturing inducing wage increases for factory workers, leading to public health benefits). An analysis that only includes a subset of these components may provide an incorrect assessment of the societal payback periods of the investments and the homes and regions where increased residential insulation would be warranted. Because the different impact pathways may have differing payback periods, development of methods to reasonably move from midpoints to endpoints and to determine which impact pathways may dominate decisions is warranted.

In spite of the importance of this topic and the need for an integrated assessment of costs and benefits, few studies have provided the necessary scope to yield definitive policy conclusions. For example, the state of Iowa has focused on economic impacts of energy policies to evaluate the effectiveness of energy efficiency programs, in order to minimize the state's economic loss to out-of-state coal suppliers (Weisbrod *et al.* 1995). In effect, GHG emissions or public health impacts of energy were not the focus of their study. Many state and local greenhouse gas mitigation case studies complied by the U.S. Environmental Protection Agency (USEPA) show the cost effectiveness of implementing innovative energy programs and the related GHG reductions, simply in dollar terms and CO_2-equivalent tons (USEPA 2004a).

On the other hand, we previously developed a methodology to quantify the air pollution-related public health benefits of energy efficiency measures, applying an energy simulation model to determine regional energy savings, quantifying regional emission rates given heating fuel types and power plants affected on the margin, applying simplified dispersion models to evaluate aggregate exposure reductions, and connecting exposure changes with concentration response functions (Nishioka *et al.* 2002; Levy *et al.* 2003). We also developed an approach to incorporate exposure and risk concepts into input-output (I-O) life-cycle analysis, taking into account both geographic variability in emissions and exposure and addressing the economic ramifications across all sectors of the economy (Nishioka *et al.* 2005a, b). This was one of the first attempts to incorporate risk assessment concepts formally into an economic input-output analysis framework. Although these approaches solved some methodological issues, they did not capture all impact pathways and related public health impacts.

Although past studies have not adequately addressed the health endpoints of multiple key impact pathways in a single analysis, the analytical tools are now available to combine all necessary dimensions. We expand our earlier framework by incorporating two critical dimensions, which we hypothesize are as important as particulate matter-related impacts, namely greenhouse gases and economic impacts. By integrating these multiple impacts in the framework of combined LCA and risk assessment, we illustrate how three widely disparate midpoints—concentrations of fine particulate matter, global warming potential, and household income—can be converted into health-relevant endpoints.

In theory, this could provide a comprehensive, integrated analysis that would be directly relevant for decision-makers. However, there are substantial uncertainties related to each of these midpoints, complicating the analysis. We adopt an iterative risk assessment paradigm, in which we conduct a screening-level analysis for a first-order determination of dominant pathways, after which point more refined assessments can focus on the most influential pathway(s).

We focus on primary PM, NOx, and SO_2 for particulate matter, fossil carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) for greenhouse gases, and the consumers purchasing insulation for economic impacts. We acknowledge that there are other impact categories that may be relevant for energy policy (*e.g.*, eutrophication, acidification, eco-toxicity, ozone depletion, land use, smog formation, water use). However, we only focus on the human health impact category and limit the number of midpoints and endpoints for this illustrative example.

METHODS

Background and Case Study Framework

Previously, we evaluated energy savings and the health impacts associated with particulate matter exposure as a result of increasing fiberglass insulation from current practice to the levels recommended by the 2000 International Energy Conservation Codes or IECC 2000 (International Code Council, 2000) in both new and existing single-family homes (Nishioka *et al.* 2002; Levy *et al.* 2003; Nishioka *et al.* 2005a, b). In those cases, we assumed that the 2000 IECC were applied to all new single-family homes, and that all existing homes with adequate or poor insulation (63% of the total) were retrofitted. This resulted in our hypothetical intervention affecting 1.2 million new housing units per year and 46 million existing homes nationally.

Although these assumptions helped us determine the maximum potential benefits, they ignored some key economic dimensions of the problem. First, it is practically infeasible to retrofit all existing homes at once—the potential increase in insulation demand for the retrofit cohort is an order of magnitude greater than the current amount of fiberglass insulation manufactured in the United States. Additionally, homeowners would likely only choose to retrofit if it were economically beneficial to do so. However, consumers generally must bear the up-front costs of these measures, and empirical evidence has shown that extremely high effective discount rates are applied when making decisions about energy efficiency (Hausman 1979; Dubin and McFadden 1984; Dermot 1980; Ruderman *et al.* 1987).

Thus, for this case, we assume that loans are available to homeowners that would allow them to defray the initial cost and pay back the loan with the resulting stream of energy savings. We assume that these are variable term loans, with payments equal to energy savings until the loan is paid in full. In this way, there would be no net economic impact on the homeowner during the payback period, avoiding the issue of high effective discount rates. This is similar to the construct used by energy service contractors in commercial settings. To make the loan structure realistic, we assume a maximum loan term of 20 years (*i.e.*, paybacks of over 20 years will not be financed). We assume an interest rate of 2.5% for the loan and test alternative discount rates of 5% and 3% for the future stream of net savings over 50 years.

Given this assumed loan availability, we expand our original insulation case analysis by incorporating impacts from climate change as well as incremental disposable income into the risk-based framework. The overall framework of our integrated analysis consists of several steps for each impact pathway model, which are described in Figure 1 and in more detail later:

- Given the initial target cohort of new and existing single family homes for each state based on the current practice of installed insulation levels relative to IECC 2000, quantify the incremental insulation required for the target cohorts by income level and state and estimate the resulting energy savings.

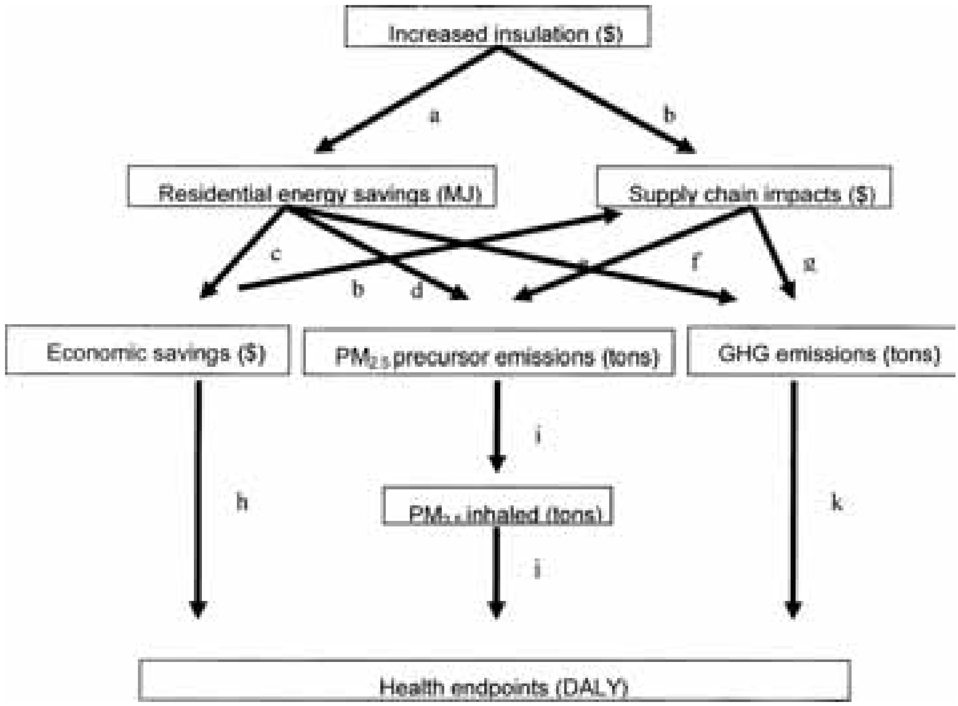

Figure 1. Analytical framework of impact pathway analyses. (a) REM/Design™ (Architectural Energy Corporation 2000); IECC 2000 (International Code Council 2000); 2000 actual R-values (Norland 2000); Housing characteristics (EIA 1999); (b) 1998 I-O table (US Department of Commerce 2002), OpenLC (Sylvatica 2003); (c) Energy prices (EIA 2004a, b, c); (d) AP-42 data (USEPA 1995); 1998 E-GRID database (USEPA 2004b); (e) AP-42 data (USEPA 1995); 1998 E-GRID database (USEPA 2004b); Global warming potentials (USEPA 2004c); (g) National Emission Inventory database (USEPA 2000b); 1998 I-O table (Bureau of Economic Analysis 2002); (h) Simapro™ (PRé Consultants 2004); I-O based GHG emission factors (Suh and Huppes 2003); (i) Income-health model (Keeney 1997); (j) Intake fractions (Levy *et al.* 2002; Nishioka *et al.* 2005a, b) Concentration-response functions derived from epidemiologic studies (Pope *et al.* 2002; Whittmore and Korn 1980; Ostro and Rothchild 1989); DALYs associated with PM-related health effects (De Hollander 1999; Hofstetter 1998); (k) EcoIndicator (Goedkoop and Spriensma 2001).

- Quantify the economic expenditure and savings for the homeowners, determining the final cohort of existing homes that would install additional insulation.
- Quantify the particulate matter-related life cycle impacts of increased residential insulation and energy savings.
- Quantify the incremental life-cycle greenhouse gas emissions and resulting health effects associated with potential climate change.

- Quantify the health effects associated with the incremental disposable income of home owners.
- Evaluate impacts from each impact pathway in Disability Adjusted Life Years (DALYs).

Energy Savings by Income Level

We derive estimates of energy savings for five income levels in each state based on Nishioka *et al.* (2002), using housing characteristics information from RECS 97 microdata (a survey of housing and household characteristics of 5,901 single-family households, each of which represents 3,800 to 80,000 U.S. households, totaling about 100 million households in the United States) (EIA 1999). In brief, in Nishioka *et al.* (2002), REM/Design (Architectural Energy Corporation, Boulder, CO, USA) was used to calculate heating and cooling energy consumption for prototype homes representing various combinations of housing characteristics such as insulation level, floor area, heating system, foundation type, and number of stories. Based on the model outputs and ASHRAE (American Society of Heating, Refrigerating and ir-conditioning Engineers) standard heat loss equations, Nishioka *et al.* (2002) developed regression models, which were applied to calculate energy savings associated with incremental R-values for each state for the given distribution of housing characteristics. In the current study, we adjust the previous energy savings for the average floor space of five annual income levels based on RECS 97 microdata.

Economic Costs and Benefits of Added Insulation

Based on the R-value increments for various regions, housing sizes and average density of fiberglass insulation, the required amount of additional insulation to meet the IECC 2000 code would be 300 kg per new unit and 600 kg per existing unit. To estimate the cost of insulation in consumer's price, the cost of material and installation was estimated on a square foot basis from RSMeans (Chandler and Mewis 2000), assuming batt insulation is used in the new homes and poured insulation is used for the retrofit cohort. RSMeans provides cost estimates for a range of thicknesses for batt and poured insulation on a square foot basis. Because the incremental insulation is added at the time of construction for the new homes, the lowest cost per square foot was selected to represent the marginal cost of added insulation. Based on the marginal cost estimates, the total cost of added insulation in consumer's price would be $1.3 per kg for batt insulation and $0.02 per kg of poured insulation. The estimated total cost of insulation for the new homes is lower than that previously estimated in Nishioka *et al.* (2005a, b), who used value of shipment and the annual production in 1997 to estimate the average cost of insulation per unit. The difference may be due to the fact that use of the industry-wide value of shipment and the annual production would reflect the average cost of production for the industry, whereas the current cost estimate based on RSMeans data would be close to the marginal cost. For an I-O analysis, the producer's price was estimated to be 45% less than the material cost in consumer's price, assuming that the median value of wholesale and retail margins would apply to the mineral wool industry.

To obtain the incremental dollar value of the fuel savings, we first calculated the demand reduction in consumer's price based on the total energy savings from our previous analysis and the unit price of fuel sources as reported by the Energy Information Administration (EIA) for 2003 (EIA 2004a, b, c). We then applied the price content of fuel sources to derive the economic value in producer's price to be used in an I-O analysis.

Both cost of loan and economic savings were determined based on the incremental R-value by state, average floor space by income level for the corresponding census division and the estimated incremental energy savings by state. For both new and existing housing cohorts in each income group in each state, the payback period was calculated as a function of the interest rate (2.5%), cost of loan and annual savings. The number of affected homes was determined assuming that all households with payback periods less than 20 years will participate in the loan program and install additional insulation. For the existing homes, an annual participation rate of 2% was assumed based on a residential retrofit program in Vermont (Vermont Gas Systems, Inc, 2003).

Health Impacts from Particulate Matter

Our analytical methods for this pathway have been described in detail elsewhere (Nishioka *et al.* 2002; Levy *et al.* 2003; Nishioka *et al.* 2005a, b). Key aspects of our methods included residential fuel and power sector analyses to determine region-specific emission rates, application of intake fractions linking site-specific emissions to population exposure as a function of population patterns and meteorology, and linkage with epidemiological evidence to develop concentration-response functions. In this article, we add to this framework the estimation of DALYs for both mortality and morbidity outcomes. DALYs is a common measure used in LCA and elsewhere to assess the global burden of disease (Murray and Lopez 1996), which combines years of life lost due to mortality and years lived with disability due to morbidity. Conversion of mortality and morbidity associated with $PM_{2.5}$, GHGs, and economic impacts into DALYs allows a first-order comparison of the magnitude of endpoints from each impact pathway.

For the midpoint approach, the incremental concentrations of particulate matter in the United States were estimated based on incremental emissions and intake fractions, which is the fraction of a pollutant or its precursor emitted that is eventually inhaled or ingested(Levy *et al.* 2002). Mathematically, intake fraction is defined as:

$$iF = C \times BR \times N/Q$$

where C = incremental concentration of pollutant in the affected area ($\mu g/m^3$); (BR = breathing rate (20 m^3/day on average); N = number of exposed people; Q = emission rate of pollutant or pollutant precursor (μg/day). Nishioka *et al.* (2002) developed intake fractions for each state, which indicate the fraction of particles or particle precursors originating from a state that result in eventual inhalation of particles by someone in the U.S. population. Applying the previously developed intake fractions and rearranging the formula, the mean incremental concentration of particulate matter was derived as a function of emission rate of primary $PM_{2.5}$, NOx, and SO_2, intake fractions, breathing rate and the exposed U.S. population. These mean incremental concentrations were then linked with concentration-response functions derived from the published literature. For premature mortality, we used the American Cancer Society (ACS) cohort study (Pope *et al.* 2002) for our central estimate, and for morbidity, we used Whittmore and Korn (1980) for asthma attacks and Ostro and Rothchild (1989) for restricted activity days (RADs).

For the endpoint approach, DALYs were estimated based on the number of endpoint cases, and the corresponding severity weights and years of life lost or disabled. De Hollander *et al.* (1999) report DALYs associated with environmental exposure in the Netherlands, including particulate matter pollution. Hofstetter. (1998) reports DALYs associated with air pollution in Europe. We use the severity weights and duration of conditions reported in De Hollander *et al.* (1999) for premature mortality and asthma attacks and those reported in Hofstetter (1998) for RADs, assuming the conditions are similar between the Netherlands, Europe, and the United States. Thus, DALYs per case for premature mortality, asthma attacks and restricted activity days are 10.9, 0.001193, and 0.000271, respectively.

For the life-cycle emissions we use OpenLC (Sylvatica, North Berwick, ME, USA) to estimate the incremental economic outputs induced by increased insulation and reduced fuel consumption and calculate emissions from a sector-specific pollution intensity matrix. For mortality and morbidity associated with the supply chain emissions, we used previously developed sector-specific intake fractions (Nishioka *et al.* 2005a, b).

Greenhouse Gas Emissions

The greenhouse gases considered in this article are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The emissions from household heating systems were estimated based on the fuel-specific emission factors derived from AP-42 (USEPA 1995) and the energy savings by income and fuel type for each state. For the power plant emissions, we assume that only noncombined cycle fossil-fuel plants with less than 80% capacity factors are affected on the margin in response to the short-term demand changes. We use the Emissions and Generation and Resource Integrated Database (E-GRID) (USEPA 2004b) to determine the state-level CO_2 emission factors for a subset of 553 power plants that would hypothetically be affected by the demand increments. To estimate methane and nitrous oxide factors, we use the fuel mix information for the affected power plants and the fuel-specific emission profiles of the average electricity generation in the United States (USEPA 1995, 2004b). To interpret the GHG emissions in terms of global warming potential, CH_4 and N_2O are both quantified as "CO_2-equivalent" emissions, based on the relative heat trapping potential over 100 years. The characterization factors used for CO_2, CH_4, and N_2O are 1, 21, and 310, respectively (USEPA 2004c).

For the supply chain emissions we use an Input-Output (I-O) approach with commodity specific GHG emission factors developed by Sangwon Suh. Suh and Huppes (2002) used 1998 U.S. supply and use tables to derive a commodity-by-commodity (496×496) total requirement matrix based on an industry-technology assumption. For the GHG emissions, Suh derived GHG emission factors for each commodity based on energy consumption and emission data for various industries compiled by the USEPA and the EIA (USEPA 2000a; EIA 1991, 1997, 1998, 2000a, b).

In this study, SimaPro™ (PRé Consultants, Amersfoot, Netherlands) is used to compute the I-O-based GHG emissions. For our incremental final demand of insulation and energy, SimaPro uses Suh's model to estimate the total GHG emissions based on the total incremental commodity output estimates.

Health Impacts from Climate Change

A range of health damages associated with climate change has been modeled in the past. They include heat- and cold-related illnesses and deaths associated with heat stress, changes in incidence of vector-borne diseases (*i.e.*, malaria), and infectious disease and psychological disorders related to sea-level rise, population displacement and damage to infrastructure. For the endpoint analysis of climate change in this article, we rely on the EcoIndicator approach, a damage-oriented LCA impact assessment method developed by Goedkoop and Spriensma (2001). To estimate the marginal health damages of GHG emissions, Goedkoop and Spriensma (2001) used an approach developed by Tol (1999), who used the FUND model, a benchmarking model that calculates damage associated with doubling of rm CO_2 concentrations, and estimated the marginal impacts of GHG emissions. For our analysis, we used the damage factors for the Egalitarian perspective, which include the effects of all damages modeled by Tol for the time horizon of 200 years with no age discounting. As a result, the premature deaths per associated ton of CO_2, CH_4 and N_2O are 1.1E-5, 5.2E-5, and 1.1E-3, which are equivalent to 2.1E-04, 4.4E-06, and 6.9E-05 of DALYs, respectively. Tol's analysis contains numerous assumptions about the nature and distribution of health impacts associated with climate change, and these DALY estimates should be considered extremely uncertain in light of these assumptions and the general state of the science. Although we could formally quantify uncertainties or evaluate the sensitivity of the damage per ton estimates to Tol's assumptions, this is beyond the scope of our illustrative analysis. We consider our analysis to be a first-order comparison among impact pathways, and further refinements can be made if this impact pathway proves to be significant relative to particulate matter and health-wealth.

Health Impacts from Income Changes

The third impact pathway in our analysis involves the public health consequences of changes in income for the homeowners who bear the direct economic impacts. Although a comprehensive LCA would also include the indirect impacts on workers in the supply chain, this was beyond the scope of our current analysis (and, as mentioned earlier, this dimension could be incorporated if this pathway proved significant).

Few previous analyses combining LCA and risk assessment have addressed the socioeconomic impact pathway, which may be crucial in an evaluation of the net impacts of an energy policy on society. As with the particulate matter and GHG impacts, the magnitude of the relationship between income and health is highly uncertain. For example, some studies (Graham *et al.* 1992; Ruhm 1999, 2000, 2003) determined that transitory income loss or unemployment was health-beneficial, whereas permanent income loss was detrimental to health. Moreover, the impact of income changes likely depends on the distribution of incomes within the society (Marmot 2002), income may be a proxy for a number of other factors influencing health, and changes in household expenses may not be perceived identically to changes in income.

Setting those caveats aside, we apply one functional relationship between income and health to provide a rough sense of the magnitude of this impact relative to climate change or particulate matter. Keeney (1997) used data from the U.S. National Longitudinal Mortality Study to develop a model linking annual mortality risk with household income, stratified by race and gender. Keeney hypothesized that mortality risk would be related to income through an exponential relationship. This addressed the notion that mortality risk is highest at low levels of income, and that the mortality risk increases due to a reduction in income would be greater for low-income individuals and relatively small for high-income individuals. Formally, annual mortality risk $r(x)$ was estimated as $ae^{-bx} + d$, where x is the annual household income and a, b, and d are parameters fit separately for different races and genders.

We use the distribution of race by income group by state to estimate the change in mortality risk for each income group. Because the income-mortality relationships in Keeney were based on income distributions in 1991 dollars, we use 1990 Census data (US Census Bureau 1992) for comparability with these relationships. Of note, this implicitly assumes that the relationship between race and mortality risk is identical across all states, which is unlikely given the multitude of factors represented by race. Regardless, the assumption is reasonable for the purpose of this illustrative calculation. We assume 10.9 DALYs per premature death, as done in the case of particulate matter.

RESULTS

As mentioned earlier, we assume all new homes participate every year, and 2% of existing homes are retrofit each year. In this section we present the combined results for new and existing homes, unless noted otherwise. Under the scenario of our loan program, we assume that those single family homes whose economic payback period is over 20 years would not participate. As a result, the participation rate would be 58% for the new single family households and 81% for the existing households. Assuming a single-year cohort of all of the eligible households install additional insulation to meet IECC 2000, an insulation policy shift would save 9E + 14 British thermal units or BTU per year. On a per unit basis the average annual energy savings is 24 million BTUs. Assuming that all homes save energy at the same rate for 50 years after insulation is installed, the total lifetime energy savings for the cumulative cohort that are built or retrofit over the next 50 years would be 5E + 16 BTUs.

The reduced end use energy consumption of a single year cohort and the upstream fuel production processes lead to a population average $PM_{2.5}$ concentration reduction of 7E-4 $\mu g/m^3$ each year including both primary and secondary sources of $PM_{2.5}$. The potential greenhouse gas emission reduction is 2E + 6 CO_2-equivalent metric tons per year. In terms of the endpoints, we estimate that the reduced concentrations of particulate matter lead to 7 fewer fatalities, 200 fewer asthma attacks, and 3,000 fewer restricted activity days avoided per year, which adds up to approximately 70 DALYs saved annually. The reduced greenhouse gas emissions would lead to 20 fewer premature deaths or 400 fewer DALYs each year. Looking across a 50-year period of our loan program for new and existing homes, the reduced endpoint impacts would be 200,000 DALYs from particulate matter and 900,000 DALYs from GHGs with a 0% discount rate. If the future impacts are discounted, the endpoint impacts would be 52,000 DALYs (3% discount rate) or 28,000 DALYs (5% discount rate) from particulate matter and 250,000 DALYs (3% discount rate) or 130,000 DALYs (5% discount rate) from GHGs.

On the other hand, the increased supply chain activities associated with insulation manufacturing for a single year cohort of homes lead to an increased population average $PM_{2.5}$ concentration of 9E-4 $\mu g/m^3$ and the added greenhouse gas emissions of 4E + 5 CO_2-equivalent metric tons per year. In terms of the health endpoints, the increased concentrations of particulate matter from the insulation supply chain lead to 9 premature deaths, 200 asthma attacks, and 4,000 restricted activity days nationwide for one year of increased fiberglass output, which adds up to 100 added DALYs. To this, the greenhouse gas effect from the increased fiberglass output would add approximately 5 premature deaths, which is equivalent to 80 DALYs. For a cumulative 50-year cohort, the added endpoint impacts would be 5,000 DALYs from particulate matter and 4,000 DALYs from GHGs with a 0% discount rate. If the future impacts are discounted, the cumulative endpoint impacts would be 2,500 DALYs (3% discount rate) or 1,800 DALYs (5% discount rate) from particulate matter and 2,200 DALYs (3% discount rate) or 1,600 DALYs (5% discount rate) from GHGs.

Given the adverse impacts associated with insulation manufacturing and the subsequent stream of benefits, for the midpoint indicators, the payback period is about 1 year for $PM_{2.5}$ concentrations and less than 1 year for CO_2-e GHGs. For the endpoint indicators, the payback period for DALYs is about 1 year for $PM_{2.5}$ and less than a year for GHGs.

Considering the economic effect, we first examine the payback period in the absence of a loan program. The total added cost of insulation for the single-year cohort would be nearly \$1 billion per year (\$1500 per home), whereas the annual economic savings from reduced energy consumption would be \$100 million (\$200 per home). The average economic payback period is 11 years with a 3% discount rate and 13 years with a 5% discount rate. Note that the payback period varies significantly by state, ranging from 6 to 20 years for a 5% discount rate.

Given the loan program, each homeowner would have zero net economic impact until their loan was paid in full, after which point they would receive the economic benefits from reduced energy consumption. Using the health-wealth relationship described earlier and assuming that the rate of new construction for the next 50 years remains at the current level, the avoided DALYs for the cumulative 50-year cohort would be 340,000 with a 0% discount rate, 140,000 with a 3% discount rate, and 90,000 with a 5% discount rate.

Figure 2 shows the midpoint effects in $PM_{2.5}$ concentrations, GHG emissions and economic costs for the added insulation compared with the avoided annual energy consumption for the aggregated single-year cohort of new and existing homes. For the $PM_{2.5}$ impact category, the relative magnitude of avoided effects is smaller than the added effects, indicating a payback period of slightly more than a year for the impact category. Note that there are no additional economic costs of insulation given the loan program (zero net impact until the loan is paid in full).

For the midpoint approach, normalization can be performed in order to relate the environmental impacts of each pathway to global emissions or expenditure. In

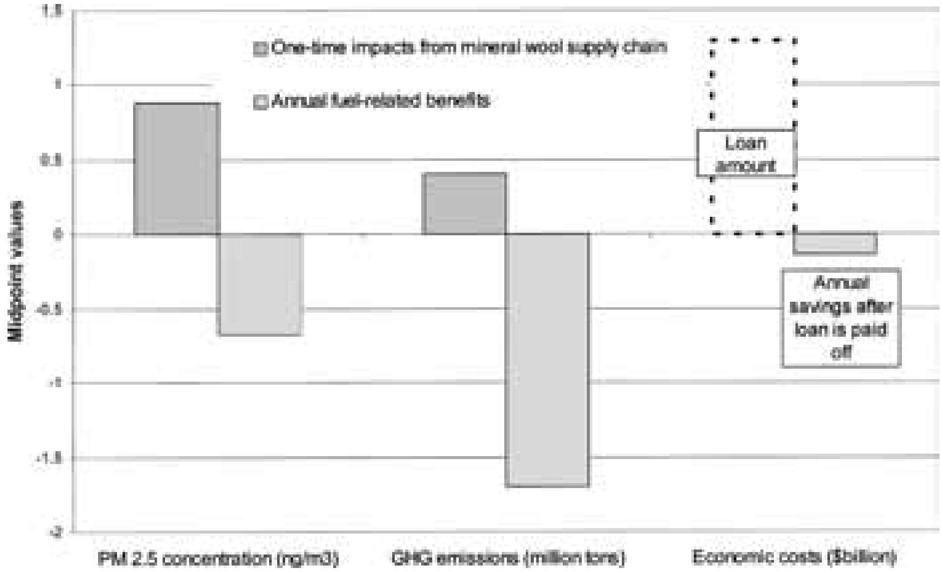

Figure 2. Midpoint results from added insulation *vs.* annual fuel savings for a single-year cohort of new and retrofit homes under the loan program.

other words, by putting all of the categories on even footing, normalization allows an evaluation of the relative magnitude of each impact relative to a reference system. Figure 3 shows the normalized results using the U.S. annual average $PM_{2.5}$ concentrations, GHG emissions and GDP as the reference values. The one-time impacts of

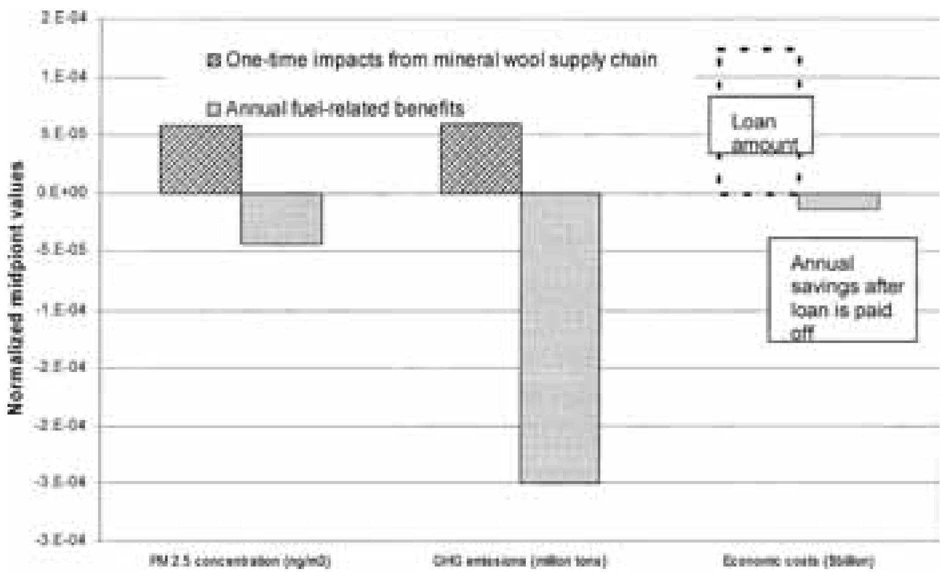

Figure 3. Normalized results for midpoint impacts from added insulation compared with reduced annual energy consumption by a single-year cohort of new and retrofit homes under the loan program.

$PM_{2.5}$, GHG and economic impacts from the mineral wool supply chain for a single-year cohort of new and retrofit homes relative to the reference system are 6E-5, 6E-5, and 1E-4, respectively. On the other hand, the annual fuel-related benefits of $PM_{2.5}$, GHG and economic impacts relative to the reference system are 4E-5, 2E-4, and 1E-5, respectively. In general, the normalized results indicate that the magnitude of each impact relative to the corresponding annual impact by the United States would be similar across all impact categories.

Using DALYs, the health effects associated with each midpoint impact category can be compared and aggregated. On the aggregated level for a single-year cohort, the total DALYs saved from the fuel supply chain is four times larger than the total DALYs added from the mineral wool supply chain, indicating the payback period of less than a year (Figure 4). Among the impact categories, climate change is the largest contributor to the total DALYs avoided, although the difference relative to the PM and wealth-related health effects is within an order of magnitude.

In Figure 5 are shown the cumulative DALYs over 50 years for the aggregated cohort of new and existing homes that would meet the IECC levels of insulation today, assuming 2% annual participation for the existing homes and with a 5% discount rate. The plot shows that after the loan is paid off, the cohort starts saving financially, leading to additional DALY savings associated with the added disposable income. Although the economic payback period is estimated to be 12 years, the health payback occurs within a year after the retrofit.

DISCUSSION

We have extended our framework of combined LCA and risk assessment by incorporating climate change and the public health impacts of income changes in the

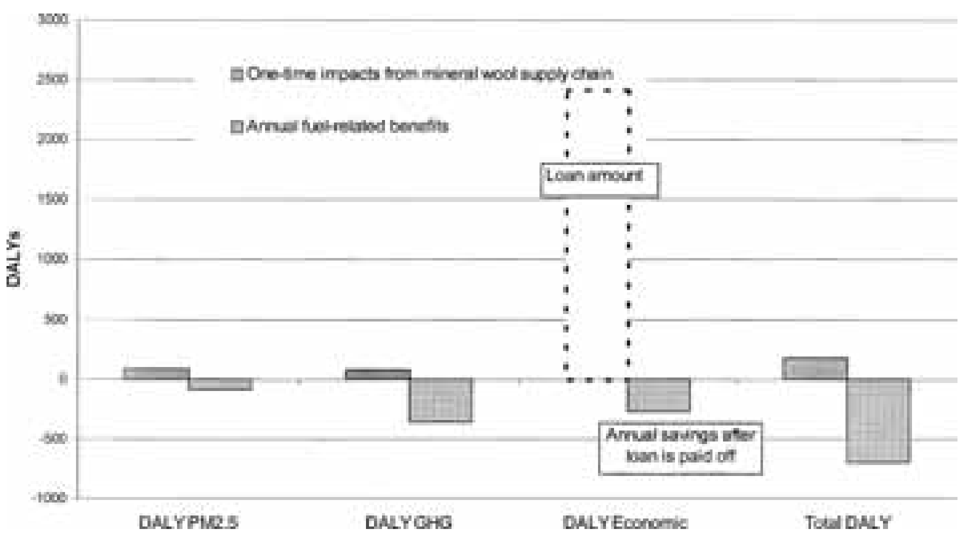

Figure 4. DALYs added from the mineral wool supply chain *vs.* DALYs saved from fuel and economic savings for an aggregated single-year cohort of new and retrofit homes under the loan program.

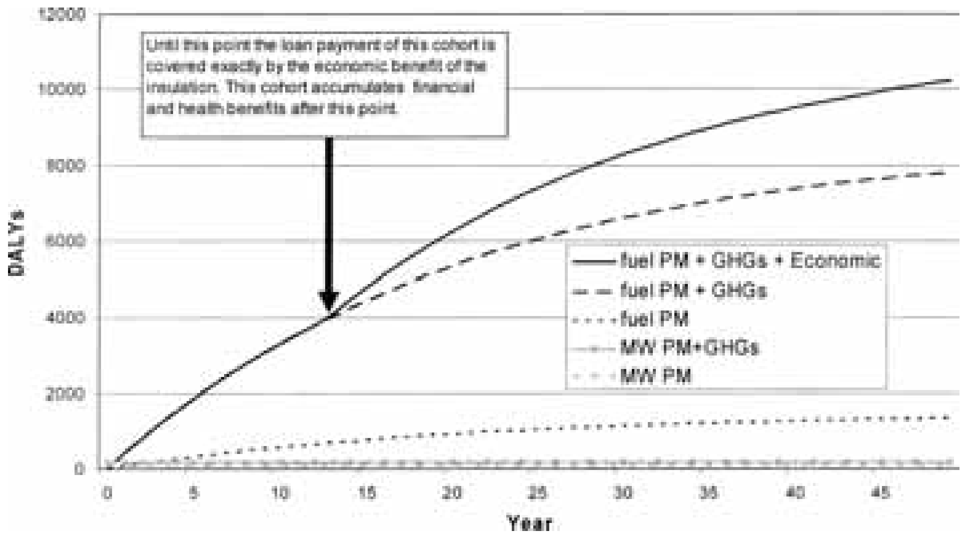

Figure 5. Cumulative DALYs avoided from energy savings and DALYs added from increased insulation for the first year new and retrofit cohort assuming 2% annual participation for the existing homes under the loan program.

context of residential energy policy. Using existing models and publicly available data, we have demonstrated that it is feasible to incorporate those potentially important health impact pathways into LCA. To our knowledge this is the first study to attempt to capture health endpoints associated with both environmental and economic changes in the context of energy policy.

Both midpoint and endpoint approaches were used to evaluate the payback periods and to interpret the relative importance of the impact categories. Based on the midpoint analysis, our normalized values show that all three impacts are of the same orders of magnitude relative to the annual U.S. levels. However, the level of "importance" depends on the reference system, and therefore it is impossible to compare the importance of impacts across impact categories. If a reference value is relatively high for a particular impact category, the normalized values imply "low" impacts, and vice versa, even if the endpoint impacts indicate otherwise. For particulate matter, this could well happen if direct and/or upstream pollutants are emitted into densely populated areas, whereas the incremental concentrations are calculated simply as national averages regardless of the population distributions. (Note that in our analysis, the incremental concentrations were exposure-weighted, therefore the payback period for the midpoint indicator is the same as the endpoint payback periods.) For climate change, whereas the United States is one of the major emitter of GHGs, the potential impacts would be global. Therefore, it is impossible to tell whether the magnitudes of normalized impacts are over or underestimated. For the economic impacts, likewise, we have no way of knowing what it means to have more or less disposable income.

Although endpoint modeling provides insights about the relative magnitude and significance of impacts across impact categories, it involves more sources of uncertainty than midpoint modeling. In this study, we have presented only the central estimates of the results from each impact pathway analysis. For all impact pathways, the additional uncertainty sources in going from midpoints and endpoints pertain to risk calculations and valuation in DALYs.

Uncertainty pertains at every stage of the impact pathway modeling. For the particulate matter impact pathway, an uncertainty importance analysis in Nishioka *et al.* (2002) shows that, for the impact pathway from energy savings to health endpoints, the most influential uncertainty was the uncertainty in the concentration-response function, regardless of pollutant or region. Second in importance in most cases was the total uncertainty in estimates of avoided exposures (*i.e.*, the intake fractions applied), followed by more minor uncertainties due to issues regarding affected population and background rates of disease. Because our current risk analysis framework is built on our previous analysis, we can infer that the same factors are likely important for the current analysis as well. For the concentration-response uncertainty, for example, the magnitude of impacts depends on the understanding of acute *vs.* chronic mortality as well as the relative toxicity of different forms of particulate matter. Nishioka *et al.* (2005,b) show that under an alternative assumption that increases in particulate matter concentration only cause acute mortality of a sensitive population and not chronic mortality, the monetary value of total health effects from both the insulation manufacturing supply chain and the end-use energy savings decrease by 97%. This indicates the importance of understanding the concentration-response relationships and the number of life-years lost,although the alternative assumptions do not affect the public health payback period. As to the question of differential toxicity of various forms of particulate matter, alternative assumptions could be significant in both risk estimates and payback periods (*e.g.*, if primary particles emitted by insulation manufacturing were more or less toxic than secondary particles from power plant emissions).

For GHGs, the level of uncertainty is assumed to be much larger than PM because the model is largely theoretical and no observational study is possible to validate the causal relationship from emission to global warming and from global warming to health effects and natural disasters. Even if the global warming effect is real, the current model cannot estimate a number of direct and indirect effects such as deaths from extreme weather events, diarrhea related to local water quality, malnutrition from altered food productivity, allergic reaction to increased bioaerosols, and public health consequences associated with social economic and demographic dislocations (Goedkoop and Spriensma 2001). Moreover, even if the theoretical model is correct, GHGs have long-term effects, which may be sensitive to technology, economy, and social structures. The long-term effects are also sensitive to discount rates. Note that assuming that the health impacts of GHGs do not start immediately, Tol's model implies that application of a 5% discount rate would reduce the total impacts by a factor of 5 over the next 100 years.

As mentioned previously, the magnitude and even direction of the relationship between small changes in household expenses and mortality risks is highly uncertain. We applied a relationship derived from a single study, although there is an extensive literature debating this effect with a wide array of estimates. As for particulate matter and GHGs, the findings are quite sensitive to assumed discount rates. Thus, substantial uncertainties can exist for this pathway as well.

DALYs may be subject to the bias of experts who state their values of disability weights in a series of panel sessions. Although the disability weights are elicited from health professionals, their judgment cannot be 100% objective and therefore are subject to biases of unknown magnitude. However, it should be noted that uncertainty in disability weights should not affect the public health payback period because the magnitude and direction of bias would be independent of the three impact categories in our analysis.

Although it is impossible to quantitatively compare uncertainty across different impact categories without a formal uncertainty analysis, we can qualitatively assume that, for our risk framework, the uncertainty is the largest in the economic impacts, because even the direction of the impact is fairly uncertain. GHG impacts can be theoretically established, although the magnitude may be larger or smaller depending on the magnitude of endpoints for which models are currently unavailable, the future technology, economy, and social structure as well as discount rate. Between the GHG and PM impact pathways, GHG would likely involve larger uncertainty than PM, because no observation study is possible, whereas the health impacts of PM have been well established in epidemiological studies.

Finally, the I-O analysis involves some uncertainties as well. Lenzen (2001) lists six categories of uncertainties in I-O analysis. The sources of uncertainty for I-O analysis include: (1) reporting errors in the economic transactions; (2) assumptions that factor inputs to domestic industries are identical for foreign industries; (3) assumption of homogeneity of foreign industries; (4) assumption of linearity between monetary and physical flow; (5) aggregation of different producers into one industry; and (6) aggregation of different commodities produced by each industry. Because I-O results are composted of the sums of a very large number of products of the coefficients in the I-O table, the relative standard error in the final result is much smaller than that of the separate coefficients (Lenzen 2001). In general, adapting hybrid approaches (Suh and Huppes 2000; Joshi 2000; Suh *et al.* 2004; Suh 2004) where process-specific information for the core processes are incorporated with input output information can improve the I-O analysis by reducing the uncertainties from the aforementioned sources.

Although each of the impact pathways is relatively uncertain, our first-order central estimates of DALY endpoints are all of similar orders of magnitude, and we therefore cannot eliminate any pathway at this stage. Although this does not simplify the task for future analyses, it does reinforce that each pathway may be potentially significant. As more evidence becomes available, each impact pathway should be iteratively refined, and uncertainties should be more formally addressed. In particular, for our analytical framework, a better understanding of the relationship between changes in household expenses and resulting mortality risks, detailed spatial and temporal impacts of climate change, and concentration-response functions of particulate matter would be essential to further characterize the relative magnitudes of uncertainty. Once uncertainties can be quantitatively addressed across impact categories, the most important sources can be identified and further improved so that the overall uncertainty is reduced.

In spite of the numerous limitations and caveats in the earlier estimates, it is important to note that the level of uncertainties in decisions based on endpoint modeling can be productively addressed in theory, whereas the uncertainty in decisions based on the midpoint approach would be simply unknown. It can be argued that the endpoint approach with the uncertainty levels well quantified makes more information available to decision-makers than the midpoint approach, which would lead to less informed decisions involving more judgment.

Despite the uncertainties in the endpoint modeling, our study demonstrates the feasibility of a comparison of three different pathways through a combined risk assessment and life-cycle assessment. The endpoint approach can help decision-makers evaluate the costs and benefits of policy options from a combined public health, socioeconomic, and life-cycle perspective. Although it is impossible to conclude that increasing insulation saves certain numbers of DALYs without a formal uncertainty analysis, the comparison of the central estimates of energy savings benefits and supply chain costs indicates that the payback period for particulate matter, GHGs and economic impacts all result in positive net benefits over the lifetime of the home. More importantly, our approach has introduced a new societal dimension to LCA, which can apply to other energy efficiency measures. Our analytical framework allows incorporation of both LCA and RA to characterize numerous dimensions of problems around energy policy, helping analysts and decision-makers to prioritize among the various impact pathways and focus on more detailed assessments in the future.

CONCLUSION

We have incorporated impacts from fine particulate matter, greenhouse gases, and income changes into a framework of risk-based LCA. The endpoint approach allows for a comparison and aggregation of three disparate impact pathways for particulate matter, greenhouse gases, and disposable income with common health metrics. The central estimates of all three pathways have DALY impacts within an order of magnitude of one another. Given significant uncertainties in all pathways, we conclude that none can be ruled out at this time and that any may contribute to a refined LCA. Our study demonstrates how LCA and risk assessment can work together in a framework that includes multiple impact categories, aiding in the evaluation of the net impacts of an energy policy change on society.

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