Regional Health Effects of Demand-Side Energy Management Using Exposure Efficiency

Nishioka Y.[1], Levy JI. [1], Hofstetter P.[1,2], Norris GA[1], Wilson A[1] , Spengler JD[1]
1. Harvard School of Public Health, Environmental Science and Engineering Program, 665 Huntington Ave. Boston, MA USA
2. ORISE Research Fellow at U.S. EPA (MS 466), 26W., Martin Luther King Dr., Cincinnati, Ohio 45268 USA

Key Words: Regional impact assessment, Damage pathway analysis, Exposure efficiency, Air pollution, Demand-side energy management, Public health

ABSTRACT

Life cycle impact assessment is usually plagued by the assumptions of site independence and uniform mixing of pollutants in a compartment (e.g., atmosphere), which are not valid for all air pollutants. In this paper we propose using the concept of exposure efficiency to simplify the damage pathway analysis without compromising the consideration of site-dependent characteristics. Our case study of increasing insulation in new homes in the US from the MEC1993 to IECC2000 level yields 6,442 TJ (6,111 GBTU) of energy savings potential in terms of energy content of the fuels. The energy savings are attributed to natural gas (72%), electricity (24%) and heating oil (3%). Using exposure efficiency, the electricity savings potentials correspond to an average ambient concentration reduction of 1.4E-5μg/m^3 in PM_{10}, 7.6E-5μg/m^3 in ammonium sulfate and 4.5E-4μg/m^3 in ammonium nitrate, spread across the US. Similarly, the household energy savings reduce 1.0E-4μg/m^3 of PM_{10}, 1.2E-7μg/m^3 of ammonium sulfate and 2.5E-4μg/m^3 of ammonium nitrate. Using a dose-response coefficient derived from a cohort study, the energy savings from increasing insulation in new homes avoid 7.5 cases of premature death each year due to the reduced population exposure to primary and secondary particulate matter. At the state level, the largest SO_2 emission reduction occurs in the state of Texas, followed by Ohio and Illinois. However, if we consider exposure to sulfates, Illinois experiences the largest amount of exposure reduction, followed by Texas and Ohio. This means that a unit of SO_2 emission in Illinois has more chance of being inhaled than in Texas, i.e., more chance of causing health damage. From a public health policy perspective, the exposure-based analysis is more relevant than emission-based if demand side energy management is targeted to reduce population health risks. Exposure efficiency and selective atmospheric dispersion modeling that we propose can improve a site-dependent life-cycle impact assessment for local pollutants.

INTRODUCTION

At present, a typical life cycle impact assessment is restricted by the assumption of site-independence and uniform mixing of pollutants in a compartment (e.g., the earth's atmosphere). While such assumptions may be valid for some pollutants such as greenhouse gases, these are not applicable to those pollutants that have local impacts (e.g., particulate matters, ozone, NOx, SOx) or that are transformed to secondary pollutants (e.g., sulfates and nitrates). Differences in population patterns and meteorological conditions will imply that a ton of emissions will have a health influence that varies by location.

For the assessment of public health impacts a site-dependent damage pathway analysis (or impact pathway analysis) is appropriate and has been applied widely for the power plants. In this approach, we need to understand how these emissions travel in the atmosphere, who they may influence, and what the effect per unit of pollution will be. However, dispersion modeling with detailed meteorological processing is often time-consuming and unrealistic to be used to account for the behavior of every pollutant from every emission source at the national or even regional level.

In this paper, we propose using the concept of exposure efficiency to simplify the damage pathway analysis without compromising the consideration of site-dependent characteristics. Exposure efficiency, simply defined as a fraction of emission that is inhaled, has an advantage in that it can be used directly to approximate risk without the need for national-level dispersion models. To demonstrate the application of exposure efficiencies in the context of damage pathway analysis, we present a case study of increasing insulation in new homes.

IMPACT ASSESSMENT USING EXPOSURE EFFICIENCY

Exposure efficiency is simply defined as the amount of pollutants inhaled by the population divided by amount of pollutants emitted per unit time. It is dimensionless and mathematically expressed as $EE = I/Q$. Q is the emission rate (g/s), and I is the intake rate, which is calculated as $I(g/s) = C*B*N$, where C is the concentration of pollutants (g/m^3), B is the breathing rate (20m^3/day for an adult male, on average), and N is the number of people affected by the pollutant emissions. Dr. Scott Wolff at Harvard School of Public Health (Wolff, 2000) investigated exposure efficiencies for forty US coal plants as well as forty 100-meter sections of US interstate highways. He used the state-of-the art atmospheric dispersion model CALPUFF, with a modeling domain across the entire US. For power plants, the mean exposure efficiencies for primary $PM_{2.5}$, ammonium sulfate (secondary particles obtained from SO_2 emissions) and ammonium nitrate (secondary particles obtained from NOx emissions) were

2.2E-6, 2.2E-7 and 2.7E-8 respectively. For mobile sources, the mean exposure efficiencies for primary PM$_{2.5}$, ammonium sulfate and ammonium nitrate were 9.4E-6, 1.8E-7 and 2.4E-8 respectively.

An advantage of exposure efficiency is that it can be used directly to approximate risk. For a given change in emission rates, we can calculate the change in the population average pollutant concentration using exposure efficiency. Rearranging the equation, $EE = C*B*N/Q$ gives dC ($\mu g/m^3$) = $[(dQ*EE) / (B*N)]*C.F$; $dQ*EE$ represents change in exposure and C.F is a conversion factor (e.g., 2.5E+15 is used to convert μg/day from million tons/yr).

ENERGY CONSERVATION WITH INCREASING INSULATION

We have conducted a small-scale pilot study to estimate the approximate magnitude of energy savings when new homes are insulated according to the new International Energy Conservation Code (IECC2000) instead of the previous energy code published in 1993 (Model Energy Code or MEC1993). By going from the MEC1993 to IECC2000 levels, depending on the region, insulation R values are increased by–2 to +11 for the building envelope and –2 to +20 for the foundation. Using a residential energy consumption analysis program called REM/Design (Architectural Energy Corporation), we estimated energy savings of single-family homes located in 11 cities in the US and extrapolated the results for all the regions of the United States. Energy savings are expressed as the energy content of the fuels delivered to power plants or households. Those eleven cities are Providence for the East, Detroit and Minneapolis for the Midwest, Knoxville, Orlando and Shreveport for the South, and Los Angeles, Seattle, Denver, Fresno and Phoenix for the West. Based on the heating degree days and cooling degree hours, the contiguous states excluding Alaska and Hawaii were divided into 11 regions so that each city represents one sub-region. In the energy simulation, energy savings were calculated assuming all homes were heated with a natural gas furnace. Given the number of new homes built and the distribution of housing characteristics in 1997, the total energy savings were allocated into different fuel types. In this calculation, the seasonal equipment efficiencies were assumed to be 78% for the natural gas- and oil –fueled furnaces, 100% for electric heating units. For the cooling system, the seasonal energy efficiency ratio (SEER) of 10 BTU/Wh (i.e., 2.92 coefficient of performance) was assumed. The electricity conversion and transmission efficiency was assumed to be 35%. Consequently, our rough estimates of annual energy savings in terms of the energy content of the delivered fuels are 1,576 TJ (1,495 GBTU) for electricity and 4,865 TJ (4,616 GBTU) for heating fuels. The heating fuels saved are 122 million cubic meters (4.3 billion cubic feet) of natural gas and 33 thousand barrels (303 thousand gallons) of oil. The proportion of energy savings by natural gas, electricity and heating oil is 72%, 24% and 3% respectively. Therefore, a large part of our energy savings comes from natural gas. On a per house basis, the Midwest will most benefit from the updated energy codes, while the least energy benefit goes to the South. This implies that the increased insulation specified in IECC2000 will save heating energy more than cooling energy (Table 1).

Table 1. Energy Saving Potential by Region

	N=5	N=3	N=2	N=1
Region[#houses (000) using gas, elec. or oil for heating]	West [247, 29, 5]	South [265,48,4]	Midwest [223,19,2]	Northeast [75, 10,31]
Gas (TJ of fuel energy content)	1513.8	249.1	2484.3	397.4
Net elec. for cooling/heating (TJ of fuel energy content)	455.5	685.1	342.2	93.2
Oil (TJ of fuel energy content)	30.7	3.8	22.2	164.2
Total (TJ)	2000.0	938.0	2848.7	654.8
per house (TJ)	7.1	3.0	11.7	5.7

For calculating the reduced pollutant concentrations due to energy savings, we somewhat simplistically assume the exposure efficiency for PM$_{10}$ and PM$_{2.5}$ are approximately the same. We also assume that the national average exposure efficiencies for PM$_{2.5}$ from mobile sources are a reasonable proxy for particles emitted at the ground level (i.e., household). Using the equation and exposure efficiencies given above, the average concentration reductions in PM$_{10}$ due to electricity savings and household heating fuel savings are 1.4E-5 μg/m^3 and 1.0E-4 μg/m^3 respectively. Similarly, the ammonium sulfate concentration reduction is 7.6E-5μg/m^3 due to electricity savings and 1.2E-7μg/m^3 due to household heating fuel savings. The ammonium nitrate concentration is reduced by 4.5E-4μg/m^3 due to electricity savings and 2.5E-4μg/m^3 due to household heating fuel savings. It should be noted that this concentration is effectively spread across the entire US. Also, it should be pointed out that there are significant uncertainties associated with these exposure efficiency estimates, including the fact that impacts from automobiles and household heating systems assessed with smaller grids in urban areas would most likely increase exposure efficiency and therefore increase the estimated concentration reductions. The implications of assessing sources at appropriate scales will be discussed later.

On the state level, we can identify those states that contribute the most health benefits by increasing insulation in new homes, using state-by-state exposure efficiencies derived from the sources modeled in each state or region. We examine SO_2 emissions converted to sulfate particle exposures. The largest SO_2 emission reduction occurs in the state of Texas, followed by Ohio and Illinois. However, if we consider exposure to sulfates, Illinois provides the largest amount of exposure reduction, followed by Texas and Ohio. This means that a unit of SO_2 emission in Illinois has more chance of being inhaled than in Texas-- i.e., more chance of causing health damage--either due to a higher population density or meteorological conditions (e.g., wind blowing towards densely populated area). From the public health policy perspective, an exposure-based analysis is more relevant than emission-based if the demand-side energy management was targeted to reduce the population health risks (Table 2). A comprehensive assessment would also include morbidity and mortality effects of all associated pollutants.

Table 2. Rank order of States by Emission Saved and by Exposure Reduced

	Ordered by Emission			Ordered by Exposure		
	State	SO_2 emissions saved (Mton/yr)	% total	State	Exposure to Sulfate reduced (Mton/yr)	%total
1	TX	7.9E - 05	13.8%	IL	9.3E - 12	10.8%
2	OH	4.6E - 05	8.0%	TX	8.7E - 12	10.1%
3	IL	4.3E - 05	7.5%	OH	7.5E - 12	8.7%

The added insulation in our study would save consumers heating/cooling costs of approximately 35 million dollars US annually—60% from natural gas, 37% from electricity and 3% from heating oil. However, from the public health perspective, such cost reduction is not an appropriate measure of benefits. The benefit should include the value of health benefits that result from increased insulation, either in health terms or potentially the monetary value associated with the net statistical lives saved (i.e., the amount of money that people would be willing to pay to reduce a mortality risk divided by the magnitude of that risk). From the societal perspective, the benefit calculation should also consider any increased mortality due to the increased production levels of insulation materials. Alternatively, the effectiveness can be expressed simply with the net change in premature deaths in the population.

LIVES SAVED PER YEAR

A prospective cohort study by Pope et al. (1995) reports the mortality-rate ratio for $PM_{2.5}$ to be 1.17 (95%CI; 1.09-1.26) for a $24.5\mu g/m^3$ change after adjusting for age, sex, race, cigarette smoking, pipe and cigar smoking, exposure to passive cigarette smoke, occupational exposure, education, body mass index, and alcohol use. This mortality rate ratio is interpreted as a 0.4% increase in mortality per $1\mu g/m^3$ increase in PM_{10}, assuming that 60% of PM_{10} consists of $PM_{2.5}$. The annual death rate in the US is 8.65/1000, so a $1\mu g/m^3$ increase in PM_{10} will increase death by 3.5/100000. Consequently, the total premature death avoided with the given decrease in the primary and secondary particulate matter concentrations, assuming a linear relationship with risk and exposure at current ambient concentrations, is approximately 7.5 persons per year, calculated as #death avoided from reduction in PM_{10} concentrations from electricity and household fuel energy savings = $8.8E\text{-}4\mu g/m^3$ * 247million population * 0.00865* 0.004. Here we assume that different species of $PM_{2.5}$ have the same toxicological potency regardless of the constituents.

On the other hand, using a dose-response coefficient derived from time-series studies leads to a smaller estimate of avoided premature deaths. Given a mortality rate increase of 0.7% per $10ug/m^3$ of PM_{10} (Levy, 2000), the avoided number of deaths is calculated to be 0.17 people per year from primary PM_{10} emissions only. Both of these study types have potential uncertainties associated with them. For time-series studies, factors that can vary on a daily basis and that are correlated with particulate matter concentrations can potentially act as cofounders. This might include weather or other air pollutants. However, these factors are generally considered within the time-series studies, and the large number of available studies strengthens our belief in this evidence. For cohort studies, since individuals are followed over time, all other risk factors (i.e., smoking, socioeconomic status, body mass index) must be rigorously included, since any can potentially influence health. It is also difficult to understand the true lifetime exposure, and a limited number of studies are available. For both types of studies, there is a need to understand the constituents of particulate matter (both chemicals and size fractions) that influence health. In general, it is thought that particles from combustion sources have more toxicological potency than dust or other crustal elements. Our future analyses will explore these issues through a survey of the relevant literature.

DISCUSSION AND CONCLUSIONS

So far we have considered only changes in end-use energy consumption. However, increasing insulation implies increasing production. Using a conventional life cycle assessment coupled with a damage pathway analysis using exposure efficiency, the costs and benefits of increasing insulation throughout its life-cycle will be estimated. For the national-level average, economic input-output models of glass and rock wool as well as annual emission rates of the manufacturing sectors are available for 1992. Given the total change in initial costs of insulation and the average pollution emission per dollar of inputs, the total change in pollution emission can be estimated using matrix operations. A further limitation also includes the exclusion of emissions during the pre-combustion stages, which usually happen during the extraction and transportation of fuels, which underestimates the overall health benefits. On the other hand, the omission of the life-cycle emissions for insulation materials overestimates the overall health benefits.

Clearly, a more refined procedure for estimating site-dependent exposure efficiency would be warranted. At the local-level, one approach for estimating exposure efficiency is to run rigorous air dispersion models for a unit emission rate (e.g., 1g/s) from various stack heights and locations throughout the US for relatively fine-scale grids (e.g., 10km). This could be done by running dispersion models for industry-dependent pollutant mixes using REMSAD, which has the capability to run all sources in the United States simultaneously. With its database of all source profiles and meteorological parameters throughout the country, REMSAD allows us to model additive effects of both short-range and long-range pollutants emitted from multiple sources. Given the exposure efficiency value for a dependent location, one can estimate the health effects of industrial processes without running a dispersion model; one needs only to know the source characteristics (e.g., emission rates, stack heights, pollution mix), population density and the dose-response coefficients.

Alternatively, we could run dispersion models for a selected set of sources (i.e., less sample size than the approach above) but use a regression approach to predict exposure efficiency at the local level. With some additional dispersion modeling with varying input parameters to reach a sufficiently large sample size, we can test the explanatory power of some parameters (e.g., population density, stack heights, etc) for predicting exposure efficiency. We have conducted a preliminary regression analysis with population and stack heights as the key parameters. Using Wolff's exposure efficiencies for both power plants and mobile sources, the derived model checks sensitivity for inputs such as release heights and distance. The preliminary regression model shows that stack heights and population within 500 km of the source alone can explain 84% of the variation in the exposure efficiency values, with both parameters being statistically significant predictors. When we have more data, we will be able to examine scaling factors of models to determine the implication of stack heights and population distribution near sources.

Regardless of the approach, it is clear that an exposure efficiency model can inform life cycle impact assessment by introducing local characteristics without burdensome detail. Our refinements will help reduce the uncertainties in exposure efficiency and risk calculations and can be used to introduce risk- and exposure-based concepts into life cycle impact assessment.

REFERENCES

1. Architectural Energy Corporation. REM/Design v.8.2
2. DOE/EIA Household Energy Consumption and Expenditures 1993 (October 1995). #0321(93)
3. Department of Housing and Urban Development and Department of Commerce. "Characteristics of New Housing"(1998)
4. EPA. Emissions & Generation Resource Integrated Database (EGRID). January 2000
5. EPA. National air quality and emissions trends report (1996). EPA 454 /R-97-013
6. International Code Council. International Energy Conservation Code 2000 (1999)
7. Levy JI, Hammitt JK, Spengler, JD. "Estimating the Mortality Impacts of Particulate Matter: what can be learned from between-study variability?" *Environmental Health Perspectives* Vol.108, No. 2 pp109-117 (2000).
8. Pope CA III, Thun MJ, Namboodiri MM, Dockery DW, Evans JS, Speizer FE, Heath CW Jr. "Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults" (1995). Am J Respir Crit Care Med. Vol 151. pp 669-674.
9. Wolff, SK. "Evaluation of Fine Particle Exposures, Health Risks, and Control Options" (May 2000). Doctoral Thesis, Harvard School of Public Health. Boston, MA