Outdoor Plus Indoor Air Pollution From Fossil Fuels, Biofuels, Bioenergy, and Biomass Burning is the Second Leading Cause of Death Worldwide, and a 100 Percent WWS World Will Eliminate Most of These Deaths

In
100% Clean, Renewable Energy and Storage for Everything
Textbook in press, Cambridge University Press
https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html

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April 18, 2019
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7.7.2. Avoided Health Costs From Air Pollution
Transitioning homes, towns, cities, states, provinces, and countries to WWS immediately reduces air pollution health problems. Fewer health problems result in cost savings due to lower hospitalization rates, fewer emergency room visits, fewer lost work days, fewer lost school days, lower insurance rates, lower taxes, lower workman’s compensation rates, and less loss of companionship, among other impacts.

Air pollution causes premature mortality in several ways. It contributes to death from heart disease, stroke, chronic obstruction pulmonary disease (COPD), lower respiratory tract infection, lung cancer, and asthma. Common types of COPD are chronic bronchitis and emphysema. Common types of lower respiratory tract infections are the flu, bronchitis, and pneumonia.

In 2016, 56.9 million people died from all causes worldwide (WHO, 2017a). Table 7.13 shows that air pollution caused between 24 and 45 percent of the deaths for each of five out of the six leading causes of death. About 4.5 million people died prematurely from outdoor air pollution and 7.1 million, from indoor plus outdoor pollution in 2016 (WHO, 2017b). Thus, about 12.5 percent of all deaths worldwide in 2016 were due to indoor plus outdoor air pollution, making it the second leading cause of death after heart disease. Twenty percent of premature air pollution deaths are of children age five and younger.

GBD (2015) similarly estimated that about 5.5 (5.1 to 5.9) million deaths worldwide in 2013 were caused by outdoor plus indoor air pollution. Of these, 2.8 to 3.1 million were from outdoor PM$_{2.5}$, 0.16 to 0.27 million were from outdoor ozone, and 2.5 to 3.3 million were from indoor air pollution from solid fuel burning.

Burnett et al. (2018) calculated 8.9 (7.5 to 10.3) million deaths per year worldwide in 2015 due to outdoor plus indoor air pollution. They hypothesized that the additional deaths from air pollution they found may have been due to the fact that previous studies considered only a limited number of categories of death that air pollution contributes to.

<table>
<thead>
<tr>
<th>Cause of death</th>
<th>Total all-cause$^a$ Number of deaths/y (millions)</th>
<th>Indoor plus outdoor air pollution</th>
<th>Outdoor air pollution only</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ischemic heart disease (coronary artery disease)</td>
<td>9.43</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>2. Stroke</td>
<td>5.78</td>
<td>24</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 7.13. Leading causes of death worldwide in 2016. Also shown are the percent and number of deaths in each category due to outdoor plus indoor air pollution and, separately, outdoor air pollution alone.
3. COPD (chronic bronchitis, emphysema)  3.04  43  1.31  25  0.76  
4. Lower respiratory infection (flu, bronchitis, pneumonia)  2.96  45  1.32  26  0.77  
5. Alzheimer’s disease/dementia  2.00  0  0  0  0  
6. Trachea, bronchus, lung cancers  1.71  29  0.50  16  0.27  
7. Diabetes  1.60  0  0  0  0  
8. Road accidents  1.40  0  0  0  0  
9. Diarrheal disease (cholera, dysentery)  1.38  0  0  0  0  
10. Tuberculosis  1.29  0  0  0  0  
Asthma  0.42  43  0.18  25  0.10  

**Total number of deaths worldwide**  56.9  12.5  7.1  7.9  4.5

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- **WHO (2017a).**
- **WHO (2017b),** except that the percentage of lower respiratory infection deaths that are due to indoor plus outdoor air pollution is estimated as the percent of respiratory deaths that are from outdoor air pollution from WHO (2017b) multiplied by the ratio of the percent of deaths from outdoor-plus-indoor to outdoor air pollution for COPD. The asthma percentage is assumed to be the same as the COPD percentage.
- **WHO (2017b),** except that the percentage of stroke deaths that are due to outdoor air pollution is estimated as the percent of stroke deaths that are from indoor plus outdoor air pollution from WHO (2017b) multiplied by the ratio of the percent of outdoor to indoor-plus-outdoor air pollution for ischemic heart disease. The asthma percentage is assumed to be the same as the COPD percentage.
- Chronic obstructive pulmonary disease (COPD) deaths are due to smoking and air pollution. They exclude asthma deaths, which are added separately.

The air pollution deaths in Table 7.13 are due almost entirely to combustion products of fossil fuels, biofuels, bioenergy, open biomass burning, and human-caused wildfires. The indoor mortalities are due to the indoor burning of bioenergy (e.g., wood, dung, waste), coal, and gas for home heating and cooking, primarily in developing countries. A 100 percent WWS world will eliminate most of the indoor and outdoor air pollution deaths. Controlling open biomass burning and human-caused wildfires will address most of the rest (Section 2.9.1).

Because premature mortalities arising from a BAU energy infrastructure results in a social health cost to society, it is important to quantify the avoided cost of reducing such mortalities, related morbidities, and non-health costs due to air pollution. This is done next.

The total annual damage cost ($/y USD) of air pollution due to conventional fuels (fossil fuel and biofuel combustion and evaporative emissions) in a country is estimated as

\[ AP_{C,Y} = D_{C,Y} VOSL_{C,Y} F_1 F_2 \]  \hspace{1cm} (7.5)

(Jacobson et al., 2017), where \( D_{C,Y} \) is the air pollution premature mortality rate (deaths/y) in country \( C \) in target year \( Y \), \( VOSL_{C,Y} \) is the value of statistical life in the country and for the target year, \( F_1 \) is the ratio of VOSL plus morbidity (illness) costs to VOSL, and \( F_2 \) is the ratio of VOSL plus non-health costs to VOSL. **Non-health costs** include costs due to lost visibility and agricultural output, for example. Table 7.14 gives low, medium, and high estimates of \( F_1 \) and \( F_2 \). These are held constant for all countries and years.

The premature mortality rate in a country in target year \( Y \) is projected from a base year (BYD) during which death rates from air pollution are available, with

\[ D_{C,Y} = D_{C,BYD} \left( \frac{e^{\Delta t_{C}[Y-BYD]}}{P_{C,Y} \dot{P}_{C,BYD}} \right)^{\kappa} \]  \hspace{1cm} (7.6)

where \( \Delta t_C \) (Table 7.14) is the fractional rate of change per year in the air pollution death rate in country \( C \) due to emission controls, \( P \) is population, and \( \kappa \) is the change in exposed population per unit change in population (Table 7.14).
The value of statistical life is the value economists calculate that a life is worth monetarily, based on what people are willing to pay to avoid health risks. It is determined from how much more employers pay their workers who have a higher risk of dying on the job. The VOSL varies with time and in each country. An estimate of the variation of VOSL (USD $million per death in 2013 USD) in country C during year Y is

$$VOSL_{C,Y} = VOSL_{US,Y} \left( T + \left[ 1 - T \right] \frac{G_{C,Y}}{G_{US,Y}} \gamma_{GDP,US,BY} \frac{G_{US,BY}}{G_{US,Y}} \right) \quad (7.7)$$

where

- $VOSL_{US,Y}$ is the VOSL in the U.S. in year Y (given in Table 7.14 for Y=2050);
- $T$ is the fraction of the country’s VOSL that is held constant at the U.S. VOSL for that year;
- $G_{C,Y}$ is the gross domestic product (GDP) per capita in the country in year Y;
- $G_{US,Y}$ is the U.S. GDP per capita in year Y (estimated in Table 7.14 for Y=2050);
- $G_{US,BY}$ is the U.S. GDP per capita in base year BYV for calculating VOSL (Table 7.14 for BYV=2006);
- $\gamma_{GDP,US,BY}$ is the elasticity of the GDP per capita in base year BYV (Table 7.14 for BYV=2006); and
- $\gamma_{GDP}$ is the elasticity of the GDP per capita for all years (Table 7.14).

The GDP per capita in Equation 7.7 is the GDP at purchasing power parity (PPP). The GDP at PPP means that the GDP is determined by equalizing the value of a basket of goods in one country versus another, taking into account the currency exchange rate. For example, suppose countries A and B have a normal GDP per capita of $20 and $40, respectively, but a cup of coffee costs $5 in country A and $20 in country B. In that case, a consumer in country B can purchase only one-fourth the goods that a consumer in country A can for the same amount of money. If we make country A the reference country, then its GDP at PPP is still $20 per person, but the GDP at PPP of the second country is $40 per capita $\times$ ($5 per cup in country A / $20 per cup in country B) $=$ $10 per person. So, although the normal GDP per capita is higher in Country B, the GDP at PPP is higher in Country A.

Equation 7.7 and the corresponding values of $T$ in Table 7.14 indicate that a small portion of the VOSL is assumed to be constant across all countries. This constant portion is the fraction of the VOSL that is independent of relative wealth, productivity or consumption. The equation also indicates that the VOSL is a function of change in income. In addition, the elasticity of the GDP per capita is itself a function of the GDP per capita ratio between the country and the U.S.

Example 7.4. Estimating the value of statistical life.

Estimate the medium number of premature air pollution deaths in Country C in 2050 if the number of deaths in base year 2018 is 10,000/y, the population in the base year is 30 million, and that in 2050 is estimated to be 50 million. Also, estimate the VOSL and cost of air pollution in 2050 in the country assuming the GDP per capita in 2050 in the country is USD $40,000/person.

Solution

From Equation 7.6, the number of premature deaths in the country is estimated to increase to about 10,909/y. Thus, the impact of the increase in population was offset partly by the impact of better emission controls. From Equation 7.7, the value of statistical life in the country in 2050 is estimated to be $6.59 million in 2013 USD. Finally, from Equation 7.5, the air pollution mortality, morbidity, and non-health effects cost is $90.9 billion/y.


<table>
<thead>
<tr>
<th>Parameter</th>
<th>LCHB</th>
<th>Middle</th>
<th>HCLB</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. VOSL in base year 2006 ($VOSL_{US,BY}$) (Smil/health USD 2006)</td>
<td>9.00</td>
<td>7.00</td>
<td>5.00</td>
</tr>
<tr>
<td>U.S. VOSL in target year 2050 ($VOSL_{US}$) (Smil/health USD 2013)</td>
<td>15.37</td>
<td>10.40</td>
<td>6.47</td>
</tr>
<tr>
<td>Approximate global average VOSL (Smil/health USD 2006)</td>
<td>4.00</td>
<td>3.48</td>
<td>3.43</td>
</tr>
<tr>
<td>U.S. GDP per capita in 2006 ($G_{US,BY}$) (USD $/person 2006)</td>
<td>52,275</td>
<td>52,275</td>
<td>52,275</td>
</tr>
<tr>
<td>U.S. GDP per capita target year 2050 ($G_{US}$) (USD $/person 2013)</td>
<td>96,093</td>
<td>96,093</td>
<td>96,093</td>
</tr>
<tr>
<td>Multiplier for morbidity impacts ($F_{I}$)</td>
<td>1.25</td>
<td>1.15</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Table 7.15

<table>
<thead>
<tr>
<th>Relative risk (β)</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lung Cancer mortality</td>
<td>0.0035</td>
<td>0.0055</td>
<td>0.0076</td>
</tr>
<tr>
<td>Cardiopulmonary mortality</td>
<td>0.0100</td>
<td>0.0129</td>
<td>0.0159</td>
</tr>
<tr>
<td>Ischemic heart disease mortality</td>
<td>0.0175</td>
<td>0.0217</td>
<td>0.0259</td>
</tr>
<tr>
<td>All-cause mortality</td>
<td>0.0055</td>
<td>0.0129</td>
<td>0.0203</td>
</tr>
<tr>
<td>All-cause mortality (1-h max O₃)</td>
<td>0.0002</td>
<td>0.0004</td>
<td>0.0006</td>
</tr>
<tr>
<td>All-cause mortality (8-h max O₃)</td>
<td>0.00027</td>
<td>0.00053</td>
<td>0.0008</td>
</tr>
<tr>
<td>Cancers over 70 years</td>
<td>U.S. EPA CURES</td>
<td>OEHHA CURES</td>
<td></td>
</tr>
</tbody>
</table>

LCHB = low cost, high benefit. HCLB = high cost, low benefit. VOSL = value of statistical life. GDP = gross domestic product at purchasing power parity (PPP).

Equation 7.6 requires a premature mortality rate from air pollution in a base year in each country. Such an estimate can be obtained from data, such as that shown in Table 7.13, but for individual countries. Those data include the number of actual deaths occurring in each country due to a specific cause, as denoted on death certificates, and an approximation of how many deaths of each cause were due to air pollution.

A second way is first to obtain measurements or computer model simulation estimates of the concentrations of PM₂.₅ and O₃, throughout each country. The advantage of using measurements is that they are fairly accurate. However, such data are usually scattered sparsely throughout a country, and concentrations measured in one location may not be representative of concentrations nearby. The advantage of using a model is that it has complete horizontal and vertical coverage of a country. The disadvantage is that the model estimates are usually less accurate than the measurements.

Concentrations of PM₂.₅ and O₃ over a country are combined with estimates of the population exposed to those concentrations and with relative risk estimates of premature mortality as a function of concentration of PM₂.₅ and O₃, in a health-effects equation. The equation estimates premature mortalities due to PM₂.₅ and O₃.

The health effects equation gives the death rate (e.g., deaths per year), cancer rate, hospitalization rate, etc., due to exposure to a pollutant as

\[ y = y_0 P \left[ 1 - \exp \left[ -\beta \times \max \left( x - x_{th}, 0 \right) \right] \right] \]

(7.8)

(e.g., Jacobson, 2010b), where \( x \) is the average concentration or mixing ratio of the pollutant, \( x_{th} \) is the threshold concentration or mixing ratio below which no health effect occurs, \( \beta \) is the relative risk, or fractional increase in the risk of the health effect occurring per unit concentration \( x \), \( y_0 \) is the baseline health effect rate per unit population (e.g., all-cause deaths per year per 100,000 population), and \( P \) is the population. Table 7.15 gives relative risks and threshold values for PM₂.₅, O₃, and carcinogens.

Equation 7.8 can be applied over very small regions, such as a neighborhood, or large regions, such as a whole country. When it is applied to each of multiple small regions adjacent to each other, results are summed over all regions to obtain a total number of premature mortalities per year, for example.
### Example 7.5. Estimating the number of premature mortalities due to ozone.

Estimate the number of premature mortalities in the United States per year due to short-term ozone exposure if the entire population of 300 million were exposed to 40 ppbv ozone over a year. Assume the all-cause death rate is approximately $y_0 = 833$ deaths per year per 100,000 population.

**Solution**

Substituting $y_0=0.00833$ deaths per person, $P=300,000,000$ people, $\beta=0.0004$ per ppbv, $x=40$ ppbv, and $x_0=35$ ppbv into Equation 7.8 gives $\gamma=5000$ additional premature deaths per year due to ozone in the U.S.

Table 7.11 estimates the avoided premature mortalities from air pollution by country in 2050 upon a conversion to 100 percent WWS. The table also shows the resulting avoided health cost by country from Equation 7.5 per unit of BAU energy eliminated. The table indicates that transitioning to 100 percent WWS will avoid millions of premature deaths each year and save the equivalent of $0.127/kWh$ (USD 2013), which is more than the direct cost of energy.

### References


