# 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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### 7.6.2. 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 save money by reducing hospitalization rates, emergency room visits, lost work days, lost school days, insurance rates, taxes, workman's compensation rates, and loss of companionship while improving quality of life.

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 (Table 7.13). 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 were children age five and younger.

Table 7.13. Leading causes of death worldwide in 2016. Also shown are the percentage and number of deaths in each category due to indoor plus outdoor air pollution and, separately, outdoor air pollution alone.

| Cause of death | Total all-cause [a] | Indoor plus outdoor air pollution | | Outdoor air pollution only | |
|---|---|---|---|---|---|
| | Number of deaths/y (millions) | Percent of all-cause deaths[b] | Number of deaths/y (millions) | Percent of all-cause deaths[c] | Number of deaths/y (millions) |
| 1. Ischemic heart disease (coronary artery disease) | 9.43 | 25 | 2.36 | 17 | 1.60 |
| 2. Stroke | 5.78 | 24 | 1.39 | 16 | 0.81 |
| 3. COPD (chronic bronchitis, emphysema)[d] | 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** |

[a]WHO (2017a).

[b]WHO (2017b), except that the percentage of lower respiratory infection deaths that are due to indoor plus outdoor air pollution is estimated as the percentage of respiratory deaths that are from outdoor air pollution from WHO (2017b) multiplied by the ratio of the percentage 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.

[c]WHO (2017b), except that the percentage of stroke deaths that are due to outdoor air pollution is estimated as the percentage of stroke deaths that are from indoor plus outdoor air pollution from WHO (2017b) multiplied by the ratio of the percentage 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.

[d]Chronic obstructive pulmonary disease (COPD) deaths are due to smoking and air pollution. They exclude asthma deaths, which are added separately.

Table 7.14 shows the 2016 mean number of deaths from indoor plus outdoor air pollution by country for 183 out of 195 countries of the world. China and India absorb the brunt of mortalities, a combined total of 2.6 million per year (37 percent of all deaths). In addition, Nigeria, Pakistan, Indonesia, Bangladesh, the Philippines, and Russia all suffer more than 100,000 air pollution deaths per year. The highest per capita air pollution death rates are in North Korea (Korea, DPR), Georgia, Chad, Nigeria, Bosnia and Herzegovena, Somalia, Sierra Leone, the Ivory Coast (Cote d'Ivoire), India, Bulgaria, the Central African Republic, China, Niger, and Montenegro, respectively.

Table 7.14. 2016 Mean number of indoor plus outdoor air pollution (AP) deaths, deaths per 100,000 population (WHO, 2017c), and population by country, for 183 countries of the world. Ranked from highest to lowest number of deaths.

| | Country | 2016 AP deaths | 2016 AP deaths per 100,000 | 2016 Population | | Country | 2016 AP deaths | 2016 AP deaths per 100,000 | 2016 Population |
|---|---|---|---|---|---|---|---|---|---|
| 1 | China | 1,912,570 | 140 | 1,366,119,400 | 93 | Tajikistan | 5,830 | 70 | 8,328,400 |
| 2 | India | 1,785,870 | 141 | 1,266,575,400 | 94 | Azerbaijan | 5,430 | 55 | 9,866,000 |
| 3 | Nigeria | 299,500 | 159 | 188,363,000 | 95 | Canada | 5,300 | 15 | 35,357,400 |
| 4 | Pakistan | 228,270 | 113 | 202,012,600 | 96 | Netherlands | 5,270 | 31 | 17,014,400 |
| 5 | Indonesia | 209,070 | 81 | 258,113,600 | 97 | Kyrgyzstan | 4,430 | 74 | 5,993,200 |
| 6 | Bangladesh | 176,940 | 103 | 171,788,200 | 98 | Belgium | 4,080 | 39 | 10,456,200 |
| 7 | Philippines | 130,520 | 117 | 111,558,600 | 99 | Dominican Rep. | 4,030 | 38 | 10,605,000 |
| 8 | Russian Fed. | 116,320 | 86 | 135,256,400 | 100 | Australia | 3,910 | 17 | 22,988,600 |
| 9 | Ethiopia | 87,400 | 82 | 106,591,200 | 101 | Croatia | 3,830 | 86 | 4,457,400 |
| 10 | Congo, DR of | 82,160 | 101 | 81,350,000 | 102 | Moldova | 3,760 | 107 | 3,510,400 |
| 11 | United States | 78,060 | 24 | 325,264,000 | 103 | Congo | 3,570 | 73 | 4,892,800 |
| 12 | Brazil | 66,460 | 31 | 214,398,400 | 104 | Liberia | 3,570 | 83 | 4,302,200 |
| 13 | Myanmar | 65,980 | 116 | 56,881,200 | 105 | Ecuador | 3,540 | 22 | 16,075,400 |
| 14 | Egypt | 65,730 | 73 | 90,041,600 | 106 | Honduras | 3,470 | 39 | 8,890,600 |
| 15 | Vietnam | 61,900 | 65 | 95,223,400 | 107 | Mongolia | 3,260 | 97 | 3,361,400 |
| 16 | Ukraine | 59,900 | 137 | 43,719,400 | 108 | Mauritania | 3,240 | 88 | 3,678,600 |
| 17 | Thailand | 58,150 | 85 | 68,406,800 | 109 | Slovak Republic | 3,240 | 59 | 5,495,600 |
| 18 | Korea, DPR | 58,020 | 231 | 25,115,000 | 110 | Austria | 3,210 | 39 | 8,223,200 |
| 19 | Japan | 54,450 | 43 | 126,637,400 | 111 | Albania | 3,190 | 105 | 3,038,200 |
| 20 | Sudan | 53,640 | 105 | 51,082,400 | 112 | Paraguay | 3,160 | 46 | 6,864,800 |
| 21 | Nepal | 42,670 | 133 | 32,082,600 | 113 | Libya | 3,120 | 43 | 7,257,400 |
| 22 | Mexico | 39,560 | 33 | 119,882,000 | 114 | Portugal | 3,030 | 28 | 10,828,400 |
| 23 | Turkey | 38,350 | 46 | 83,369,800 | 115 | Lithuania | 2,860 | 82 | 3,483,000 |
| 24 | Germany | 36,320 | 45 | 80,715,200 | 116 | Turkmenistan | 2,700 | 51 | 5,290,600 |
| 25 | Tanzania | 35,170 | 75 | 46,896,200 | 117 | Macedonia | 2,620 | 125 | 2,099,400 |
| 26 | Cote d'Ivoire | 34,180 | 144 | 23,736,800 | 118 | El Salvador | 2,590 | 42 | 6,156,200 |
| 27 | Afghanistan | 31,710 | 95 | 33,380,000 | 119 | Nicaragua | 2,570 | 43 | 5,967,000 |
| 28 | Uganda | 30,700 | 74 | 41,491,000 | 120 | Armenia | 2,420 | 81 | 2,990,600 |
| 29 | Italy | 30,360 | 49 | 61,964,600 | 121 | Singapore | 2,250 | 39 | 5,781,200 |
| 30 | South Africa | 29,480 | 61 | 48,334,800 | 122 | Lesotho | 2,210 | 113 | 1,952,200 |
| 31 | Poland | 29,060 | 76 | 38,231,400 | 123 | Lebanon | 2,170 | 52 | 4,169,400 |
| 32 | Iran | 28,970 | 35 | 82,767,800 | 124 | Latvia | 2,090 | 98 | 2,137,000 |
| 33 | Niger | 27,690 | 140 | 19,777,000 | 125 | Gambia | 1,950 | 97 | 2,009,200 |
| 34 | Ghana | 27,300 | 101 | 27,024,800 | 126 | Switzerland | 1,930 | 25 | 7,708,600 |
| 35 | Romania | 26,560 | 123 | 21,593,400 | 127 | Guinea-Bissau | 1,900 | 108 | 1,759,400 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 36 | Cameroon | 25,730 | 118 | 21,803,800 | 128 | Israel | 1,850 | 23 | 8,043,800 |
| 37 | Yemen | 24,550 | 90 | 27,279,000 | 129 | Jordan | 1,760 | 26 | 6,754,000 |
| 38 | Chad | 21,460 | 181 | 11,856,000 | 130 | Denmark | 1,680 | 30 | 5,594,000 |
| 39 | United Kingdom | 20,620 | 32 | 64,422,600 | 131 | Namibia | 1,670 | 75 | 2,222,200 |
| 40 | Madagascar | 20,320 | 80 | 25,395,600 | 132 | Sweden | 1,650 | 18 | 9,171,400 |
| 41 | Sri Lanka | 19,780 | 89 | 22,220,200 | 133 | Costa Rica | 1,320 | 27 | 4,870,800 |
| 42 | Kenya | 18,680 | 40 | 46,711,600 | 134 | Botswana | 1,170 | 53 | 2,208,800 |
| 43 | Burkina Faso | 18,170 | 93 | 19,541,200 | 135 | Slovenia | 1,130 | 57 | 1,976,600 |
| 44 | Peru | 17,830 | 58 | 30,739,000 | 136 | Uruguay | 1,070 | 32 | 3,351,200 |
| 45 | Mali | 17,280 | 107 | 16,152,400 | 137 | Kuwait | 1,050 | 37 | 2,830,000 |
| 46 | Korea, Rep. of | 17,210 | 35 | 49,164,400 | 138 | Finland | 1,000 | 19 | 5,271,200 |
| 47 | France | 16,640 | 25 | 66,544,400 | 139 | Swaziland | 1,000 | 69 | 1,451,400 |
| 48 | Mozambique | 16,620 | 64 | 25,963,000 | 140 | Timor-Leste | 1,000 | 77 | 1,295,400 |
| 49 | Somalia | 16,480 | 152 | 10,844,200 | 141 | Ireland | 990 | 20 | 4,949,000 |
| 50 | Argentina | 16,210 | 37 | 43,821,400 | 142 | Panama | 960 | 26 | 3,704,400 |
| 51 | Colombia | 16,050 | 34 | 47,206,600 | 143 | Jamaica | 950 | 32 | 2,970,200 |
| 52 | Uzbekistan | 15,920 | 54 | 29,473,000 | 144 | United Arab Emir. | 950 | 16 | 5,923,000 |
| 53 | Guinea | 15,380 | 127 | 12,108,000 | 145 | Norway | 910 | 19 | 4,770,400 |
| 54 | Algeria | 14,810 | 40 | 37,030,800 | 146 | Montenegro | 900 | 140 | 645,400 |
| 55 | Cambodia | 13,880 | 87 | 15,952,600 | 147 | Gabon | 890 | 51 | 1,739,400 |
| 56 | South Sudan | 13,680 | 109 | 12,546,200 | 148 | Djibouti | 840 | 99 | 846,800 |
| 57 | Angola | 13,530 | 67 | 20,196,800 | 149 | Equatorial Guinea | 760 | 100 | 760,000 |
| 58 | Morocco | 13,460 | 40 | 33,649,600 | 150 | Comoros | 750 | 94 | 794,000 |
| 59 | Spain | 13,100 | 27 | 48,520,000 | 151 | Estonia | 740 | 60 | 1,239,800 |
| 60 | Haiti | 12,990 | 127 | 10,226,600 | 152 | Oman | 740 | 22 | 3,356,600 |
| 61 | Benin | 12,790 | 119 | 10,750,400 | 153 | Fiji | 690 | 76 | 914,400 |
| 62 | Burundi | 11,950 | 100 | 11,945,000 | 154 | Bhutan | 660 | 88 | 750,000 |
| 63 | Iraq | 11,910 | 35 | 34,025,800 | 155 | Mauritius | 650 | 48 | 1,347,800 |
| 64 | Saudi Arabia | 10,980 | 39 | 28,165,400 | 156 | New Zealand | 630 | 14 | 4,473,400 |
| 65 | Malaysia | 10,830 | 35 | 30,941,600 | 157 | Guyana | 560 | 76 | 742,000 |
| 66 | Senegal | 10,600 | 74 | 14,328,000 | 158 | Trinidad & Tobago | 550 | 45 | 1,219,400 |
| 67 | Kazakhstan | 10,460 | 57 | 18,344,000 | 159 | Solomon Islands | 430 | 67 | 634,600 |
| 68 | Belarus | 10,340 | 110 | 9,401,000 | 160 | Cyprus | 400 | 33 | 1,204,600 |
| 69 | Syria | 10,230 | 44 | 23,252,000 | 161 | Cape Verde | 380 | 69 | 553,400 |
| 70 | Zambia | 10,160 | 63 | 16,128,200 | 162 | Suriname | 300 | 51 | 586,000 |
| 71 | Cuba | 9,910 | 90 | 11,011,200 | 163 | Qatar | 290 | 13 | 2,244,800 |
| 72 | Malawi | 9,830 | 54 | 18,212,800 | 164 | Bahrain | 210 | 15 | 1,378,600 |
| 73 | Zimbabwe | 9,750 | 67 | 14,550,400 | 165 | Malta | 180 | 44 | 415,000 |
| 74 | Bulgaria | 9,600 | 141 | 6,807,400 | 166 | Vanuatu | 180 | 76 | 239,000 |
| 75 | Togo | 8,930 | 115 | 7,763,200 | 167 | Barbados | 170 | 57 | 291,800 |
| 76 | Sierra Leone | 8,920 | 148 | 6,029,000 | 168 | Sao Tome+Principe | 160 | 82 | 197,400 |
| 77 | Serbia | 8,720 | 122 | 7,144,000 | 169 | Belize | 120 | 35 | 353,600 |
| 78 | Venezuela | 8,610 | 29 | 29,675,200 | 170 | Luxembourg | 120 | 23 | 532,800 |
| 79 | Georgia | 8,290 | 184 | 4,508,000 | 171 | Samoa | 120 | 62 | 199,200 |
| 80 | Greece | 8,290 | 77 | 10,769,200 | 172 | Micronesia | 100 | 93 | 104,400 |
| 81 | Hungary | 8,190 | 83 | 9,872,800 | 173 | Kiribati | 90 | 88 | 107,200 |
| 82 | Cent. Afr. Rep. | 7,770 | 141 | 5,511,800 | 174 | Bahamas | 70 | 22 | 327,600 |
| 83 | Laos | 7,720 | 110 | 7,019,000 | 175 | Saint Lucia | 60 | 38 | 164,400 |
| 84 | Rwanda | 7,670 | 59 | 12,995,000 | 176 | Tonga | 60 | 57 | 106,800 |
| 85 | Guatemala | 7,590 | 50 | 15,188,000 | 177 | Grenada | 50 | 44 | 111,400 |
| 86 | Bosnia & Herz. | 7,330 | 159 | 4,612,800 | 178 | Iceland | 50 | 17 | 321,000 |
| 87 | Czech Republic | 6,470 | 64 | 10,106,600 | 179 | Maldives | 50 | 14 | 392,800 |
| 88 | Eritrea | 6,340 | 95 | 6,674,400 | 180 | St. Vinc. & Grenad. | 50 | 48 | 102,600 |
| 89 | Tunisia | 6,340 | 57 | 11,128,400 | 181 | Seychelles | 50 | 56 | 92,800 |
| 90 | Chile | 6,150 | 35 | 17,559,600 | 182 | Brunei Darussalam | 40 | 9 | 436,800 |
| 91 | Papua New Guinea | 6,110 | 90 | 6,789,400 | 183 | Antigua & Barbuda | 30 | 28 | 93,200 |
| 92 | Bolivia | 6,030 | 55 | 10,968,800 | | | | | |
| | | | | | | **Total** | **7.01 mil.** | **95.6** | **7.33 billion** |

The Global Burden of Disease study (GBD, 2015) similarly estimated that about 5.5 (5.1 to 5.9) million deaths worldwide in 2013 were caused by indoor plus outdoor 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.

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

The air pollution deaths in Tables 7.13 and 7.14 are due almost all to combustion products of fossil fuels, biofuels, bioenergy, open biomass burning, and human-caused wildfires. The indoor mortalities are additionally 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 about 90 percent of the outdoor plus indoor 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 result 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

$$AP_{C,Y} = D_{C,Y} VOSL_{C,Y} F_1 F_2 \tag{7.5}$$

(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 ($/death) in the country and for the target year, $F_1$ is the ratio of mortality plus **morbidity** (illness) costs to mortality costs alone, and $F_2$ is the ratio of health cost (mortality plus morbidity costs) plus non-health costs to health costs alone. **Non-health costs** include costs due to animal health impacts, lost visibility, reduced agricultural output, and corrosion to building materials and works of art. Table 7.15 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

$$D_{C,Y} = D_{C,BYD}\left(e^{\Delta A_C[Y-BYD]}\right)\left(\frac{P_{C,Y}}{P_{C,BYD}}\right)^{\kappa} \tag{7.6}$$

where $\Delta A_C$ (Table 7.15) 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 7.15). Figure 7.1 shows the application of Equation 7.6 to 24 world regions encompassing 143 countries. These countries were home to 96 percent of 2016 indoor plus outdoor air pollution mortalities worldwide.

Figure 7.1. Year 2016 and projected year 2050 indoor plus outdoor air pollution mortalities per year in 24 world regions encompassing 143 countries (see Table 8.5 for a list of countries in each region). Year 2016 data are obtained by multiplying country-specific indoor plus outdoor air pollution deaths per 100,000 population from WHO (2017c) by 2016 country population. 2050 estimates are obtained from Equation 7.6. BAU energy is responsible for about 90 percent of the mortalities. Most of the rest are from open biomass burning, wildfires, and dust.

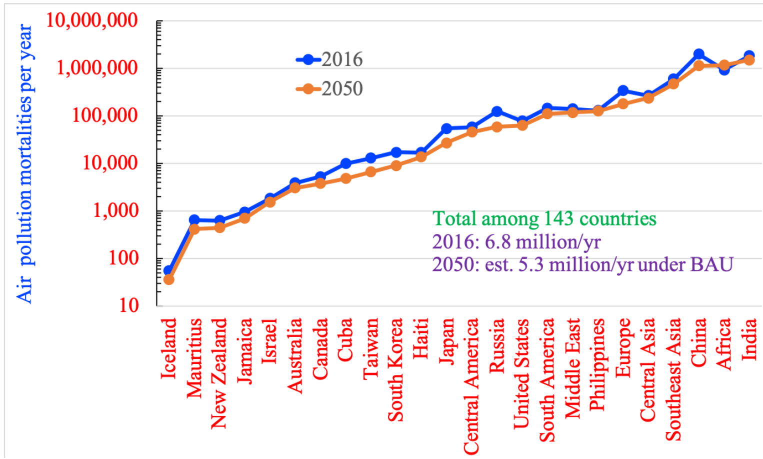


Figure 1 indicates that BAU mortalities may be, on average, about 22 percent less in 2050 than in 2016. Reductions occur in almost all world regions despite higher populations in all regions in 2050. The reason is that improvements in BAU emission-reduction technologies between 2016 and 2050 outpace population growth in almost all regions. The only exception is in Africa, where population growth is so high, it outpaces technology improvements, resulting in higher air pollution mortality in 2050 than in 2016.

The **value of statistical life** is a widely used metric determined by economists to assign the cost of reducing mortality risk. It is the value of reducing 1 statistical mortality in a population. For example, if the average person in a city of 100,000 is willing to pay \$75 to reduce her or his mortality risk by 1/100,000th, the statistical value of reducing one mortality is \$7.5 million. The value of statistical life is also 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 country. An estimate of the variation of VOSL (USD \$million per death in 2013 USD) in country $C$ during year $Y$ is

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

where

$VOSL_{US,Y}$ is the VOSL in the U.S. in year $Y$ (given in Table 7.15 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 7.15 for $Y$=2050);
$G_{US,BYV}$ is the U.S. GDP per capita in base year $BYV$ for calculating VOSL (Table 7.15 for BYV=2006);
$\gamma_{GDP,US,BYV}$ is the elasticity of the GDP per capita in base year $BYV$ (Table 7.15 for BYV=2006); and
$\gamma_{GDP}$ is the elasticity of the GDP per capita for all years (Table 7.15).

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 × (\$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 7.15 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.

Table 7.15. Parameters in the calculation of the value of statistical life over time and by country.

| Parameter | LCHB | Middle | HCLB |
|---|---|---|---|
| U.S. VOSL in base year 2006 ($VOSL_{US,BYV}$) (\$mil/death USD 2006) | 9.00 | 7.00 | 5.00 |
| U.S. VOSL in target year 2050 ($VOSL_{US,Y}$) (\$mil/death USD 2013) | 15.37 | 10.40 | 6.47 |
| 2006 global average VOSL (\$mil/death USD 2006) | 4.00 | 3.48 | 3.43 |
| 2050 global average VOSL (\$mil/death USD 2013) | 8.15 | 7.09 | 6.99 |
| U.S. GDP per capita in 2006 ($G_{US,BYV}$) (USD \$/person 2006) | 52,275 | 52,275 | 52,275 |
| U.S. GDP per capita target year 2050 ($G_{US,Y}$) (USD \$/person 2013) | 96,093 | 96,093 | 96,093 |
| Multiplier for morbidity impacts ($F_1$) | 1.25 | 1.15 | 1.05 |
| Multiplier for non-health impacts ($F_2$) | 1.10 | 1.10 | 1.05 |
| Fractional reduction in mortalities per year ($\Delta A_c$) | -0.014 | -0.015 | -0.016 |
| Exponent giving change in mortality with population change ($\kappa$) | 1.14 | 1.11 | 1.08 |
| Fraction of country's VOSL fixed at U.S. TY value ($T$) | 0.10 | 0.00 | 0.00 |
| GDP/capita elasticity ($\gamma_{GDP,US,BYV}$) of VOSL, U.S. base year 2006 | 0.75 | 0.50 | 0.25 |
| GDP/capita elasticity ($\gamma_{GDP}$) of VOSL, all years | -0.15 | -0.15 | -0.15 |

LCHB = low cost, high benefit. HCLB = high cost, low benefit. VOSL = value of statistical life. GDP = gross domestic product at purchasing power parity (PPP). From Jacobson et al. (2017), except that the low and high fraction reduction in mortalities per year are updated here.

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 the population in 2050 is 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 is offset partly by the impact of better emission controls. From Equation 7.7, the value of statistical life in the country in 2050 is \$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.

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 those data shown in Table 7.13, but for individual countries. Such 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 by each cause were due to air pollution.

Table 7.11 estimates the avoided premature mortalities from air pollution by country in 2050 upon a conversion to 100 percent WWS. The mortalities are determined from Equation 7.6 using base-year death rates from 2016. Base-year indoor plus outdoor air pollution death rates are determined for each country by multiplying the country-specific total number of air pollution mortalities per 100,000 population from WHO (2017b) by the population of the country.

Table 7.11 also shows the resulting avoided health cost (from Equation 7.5) per unit of BAU energy eliminated due to switching to WWS. Transitioning to 100 percent WWS will avoid millions of premature deaths each year and save the equivalent of 16.9 ¢/kWh (USD 2013), which is more than the direct cost of energy. The cost savings per unit energy translates to an aggregate avoided air pollution mortality, morbidity, and non-health cost in 2050 of about \$30 trillion/y.

A second way to determine premature air pollution mortalities by region or country is with a health effects equation. The equation combines concentrations of $PM_{2.5}$ and $O_3$ with estimates of the population exposed to those concentrations and with relative risk estimates of premature mortality as a function of $PM_{2.5}$ and $O_3$ concentrations.

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

$$y = y_0 P\left(1 - \exp\left[-\beta \times \max\left(x - x_{th}, 0\right)\right]\right) \tag{7.8}$$

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, β 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 (e.g., Jacobson, 2010b).

The concentrations are obtained from measurements or computer model simulation. 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 less accurate than the measurements.

Table 7.16 gives relative risks and threshold values for $PM_{2.5}$, $O_3$, and carcinogens.

Table 7.16. Relative risks (β) of premature mortality due to $PM_{2.5}$ and $O_3$, and of cancers over 70 years for various carcinogens.

| | Low | Medium | High |
|---|---|---|---|
| Long-term $PM_{2.5}$ exposure[a] | | | |
| All-cause mortality | 0.0035 | 0.0055 | 0.0076 |
| Cardiopulmonary mortality | 0.0100 | 0.0129 | 0.0159 |
| Ischemic heart disease mortality | 0.0175 | 0.0217 | 0.0259 |
| Lung Cancer mortality | 0.0055 | 0.0129 | 0.0203 |
| Short-term $O_3$ exposure[b] | | | |
| All-cause mortality (1-h max $O_3$) | 0.0002 | 0.0004 | 0.0006 |
| All-cause mortality (8-h max $O_3$) | 0.00027 | 0.00053 | 0.0008 |
| All-cause mortality (24-h $O_3$) | 0.0005 | 0.001 | 0.0015 |
| Cancers over 70 years[c] | U.S. EPA CURES | | OEHHA CURES |
| Formaldehyde | $1.3 \times 10^{-5}$ | | $6.0 \times 10^{-6}$ |
| Acetaldehyde | $2.2 \times 10^{-6}$ | | $2.7 \times 10^{-6}$ |
| Butadiene | $3.0 \times 10^{-5}$ | | $1.7 \times 10^{-4}$ |
| Benzene | $5.0 \times 10^{-6}$ | | $2.9 \times 10^{-5}$ |

[a]The relative risks due to the long-term effects of $PM_{2.5}$ are the fractional increases in the cause of death specified per μg/m$^3$ increase in annual average outdoor $PM_{2.5}$ concentration (Krewski et al., 2009, based on data for 1999 to 2000; CARB, 2010). The relative risks apply only above a threshold concentration of $x_{th}$ = 5.8 μg/m$^3$, the lowest annual averaged $PM_{2.5}$ concentration measured in Krewski et al. (2009). The relative risks apply only for people older than 30 years. The low threshold due to health problems from $PM_{2.5}$ is 0 μg/m$^3$, but the relative risk down to zero is uncertain. Jacobson (2010b) estimate the relative risk down to zero as one-fourth that above $x_{th}$. The low and high values in the table represent 95 percent confidence intervals. Ischemic heart disease is a subset of cardiopulmonary causes of death. Those two and lung cancer are a subset of the all-cause death rate.

[b]The relative risks (for all ages) due to the short-term effects of $O_3$ are the fractional increase in all-cause daily mortality that is due to short-term exposure to a 1 ppbv increase in the highest 1-hour average ozone level during a day, the highest 8-hour average ozone level during a day, or the 24-hour average ozone during a day (Ostro et al., 2006). The low threshold for ozone health effects is $x_{th}$ = 35 ppmv.

CURES are cancer unit risk estimates. They are 70-year cancer risks per μg/m$^3$ sustained concentration change of a carcinogen. Thus, divide the CURES by 70 years for use in Equation 7.8 to obtain the number of new cancers (not necessarily cancer deaths) per year due to exposure to the carcinogen. No low thresholds apply. The two sources of CURES are the U.S.

Environmental Protection Agency (U.D. EPA) and the California Office of Environmental Health Hazard Assessment (OEHHA) (Jacobson, 2010b).

Equation 7.8 can be applied over very small regions, such as a neighborhood, or a whole country. When it is applied to each of many 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, β=0.0004 per ppbv, $x$=40 ppbv, and $x_{th}$=35 ppbv into Equation 7.8 gives $y$≈5,000 additional premature deaths per year due to ozone in the U.S.

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