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1 WHAT PROBLEMS ARE WE TRYING TO SOLVE?

Why do we want to transition all of our energy to clean, renewable energy? Why don't we just continue burning fossil fuels until they run out, which may be in 50 to 150 years? For three major reasons. Namely, fossil fuels today cause massive air-pollution health damage, climate damage, and risks to our energy security. These three problems, which have the same root cause, require immediate and drastic solutions. The longer we wait to solve these problems, the more the accumulated damage. This chapter examines each problem, in turn.

1.1 The Air Pollution Tragedy

Today, air pollution is the second-leading cause of human death and illness worldwide. It also kills and injures animals; impedes visibility; and harms plants, trees, crops, structures, tires, and art. Because air pollution causes such enormous loss and cost, controlling it is one of the greatest challenges of our time.

What is air pollution? **Air pollution** occurs when

> *gases or aerosol particles in the air build up in concentration sufficiently high to cause direct or indirect damage to humans, plants, animals, other life forms, ecosystems, structures, or works of art.*

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What are gases and aerosol particles? A **gas** is a group of atoms or molecules that are not bonded to each other. Whereas a liquid occupies a fixed volume and a solid has a fixed shape, a gas is unconfined and freely expands with no fixed volume or shape.

An **aerosol particle** consists of 15 or more gas atoms or molecules, suspended in the air, that have bonded together and changed phase to become a liquid or solid. An aerosol particle can contain one chemical or a mixture of many different chemicals. An **aerosol** is an ensemble, or cloud, of aerosol particles.[1] Aerosol particles are distinguished from cloud drops, drizzle drops, raindrops, ice crystals, snowflakes, and hailstones, in that the latter all start as an aerosol particle but grow far more water on them than the former.

Gases and aerosol particles may be emitted into the air naturally or by humans (**anthropogenically**). They may also be produced chemically in the air from other gases or aerosol particles. Natural air pollution problems on the Earth are as old as the planet itself. Volcanos, natural fires, lightning, desert dust, sea spray, plant debris, pollen, spores, viruses, bacteria, and bacterial metabolism have all contributed to natural air pollution.

Humans first emitted air pollutants when we burned wood for heating and cooking. Today, anthropogenic air pollution arises primarily from the burning of fossil fuels and bioenergy fuels used for energy, and from the burning of open biomass for land clearing or ritual, or due to arson or carelessness. Air pollutants also arise from the release of chemicals to the air, such as from industrial processes or leaks.

The main **fossil fuels** burned today are coal, natural gas, and crude oil. Crude oil is refined into multiple products, including gasoline, diesel, kerosene, heating oil, naphtha, liquefied petroleum gas, jet fuel, and bunker fuel. **Bioenergy** fuels burned are either solid fuels, such as wood, vegetation, or dung, or liquid fuels, such as ethanol or biodiesel. **Open biomass** includes forests, woodland, grassland, savannah, and agricultural residues. Anthropogenic emissions have contributed not only to indoor and outdoor air pollution, but also to acid rain, the Antarctic ozone hole, global stratospheric ozone loss, and global warming.

In 2019, 55.4 million people died from all causes worldwide.[2] Air pollution enabled about 7 million (12.6 percent) of the deaths, making it the second-leading cause of death after heart disease.[3] Of the air pollution deaths, about 4.4 million were due to outdoor air pollution and about 2.6 million were due to indoor air pollution.[3] Indoor

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air pollution arises because 2.6 billion people burn solid fuels (wood, dung, crop waste, coal) and kerosene indoors for cooking and heating.[4] Air pollution also causes hundreds of millions of illnesses each year.

The deaths and illnesses arise when air pollution particles (mostly) and gases trigger or exacerbate heart disease, stroke, chronic obstruction pulmonary disease (chronic bronchitis and emphysema), lower respiratory tract infection (flu, bronchitis, and pneumonia), lung cancer, and asthma.

Almost half of all pneumonia deaths worldwide among children aged five and younger are due to air pollution.[4] Many children who die live in homes in which solid fuel or kerosene is burned for home heating and cooking. Their little lungs absorb a high concentration of aerosol particles in the air that result from fuel burning. They die of pneumonia because their immune systems weaken owing to the assault of air pollutants on their respiratory systems. Most of the casualties are in developing countries, where indoor burning often still occurs on a large scale. These deaths and illnesses not only devastate families, but also incur tremendous cost. The worldwide cost of all air pollution death and illness is estimated to be over US$30 trillion per year today.[5]

Transition highlight

In 2019, 7 million people died from air pollution worldwide. China and India absorbed the brunt of mortalities, with a combined total of 3.6 million deaths (52 percent of the total). Nigeria, Pakistan, Indonesia, Bangladesh, the Philippines, and Russia all suffered more than 100,000 air pollution deaths that year. The highest per capita air pollution death rates were in North Korea, Georgia, Chad, Nigeria, Bosnia and Herzegovina, and Somalia, respectively.

Around half the mass of aerosol particles emitted worldwide is in natural particles. However, natural particles are mostly large and thus do not penetrate deep into people's lungs. On the other hand, combustion particles, which are almost all from human sources today, are mostly small and penetrate deep into the lungs. Most combustion particles are also emitted near where people live, so people breathe in these particles. As a result, about 90 to 95 percent of air pollution deaths today are caused by anthropogenic air pollution. Of these deaths, about 90 percent are due to air pollution particles; the rest are due to air pollution gases, primarily ozone.

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Because combustion during energy production is the world's major source of air pollution, changing the world's energy infrastructure to eliminate combustion will largely eliminate air pollution death and illness worldwide. This goal can be accomplished by transitioning to 100 percent clean, renewable energy and storage for everything.

1.2 Global Warming

1.2.1 The Natural Greenhouse Effect

Global warming is the human-caused increase in the average temperature of the Earth's lower atmosphere since the Industrial Revolution above and beyond the temperature due to the natural greenhouse effect. The **natural greenhouse effect** is the increase in the Earth's average temperature above its temperature without an atmosphere. The natural greenhouse effect is due to the build-up of natural greenhouse gases in the atmosphere since the formation of the Earth. **Greenhouse gases** are gases that are mostly transparent to sunlight but that absorb some of the heat emitted by the surface of the Earth. All objects in the universe, including the Earth, emit heat.

The Earth has three main sources of heat. The first and, by far, the most important, is sunlight, also called **solar radiation**. The Earth absorbs sunlight and converts it to heat, also called **infrared radiation**. About 99.97 percent of the heat emitted by the surface of the Earth originates from sunlight. The remaining 0.03 percent of heat originates from the interior of the Earth from two sources, each in relatively equal proportions. One is heat left over from the formation of the Earth, called **primordial heat**. Owing to gravitational compression of the Earth's interior during its formation, and despite heat loss over time, the temperature at the center of the Earth is still about 4,300 degrees Celsius. This heat transfers slowly to the surface of the Earth by **conduction**, which is the process by which molecules transfer energy to each other when they collide. Primordial heat also gets to the surface by volcanic activity. The other source of interior heat is heat released during the decay of radioactive elements in the Earth's interior. The main elements that decay are uranium, thorium, and a small fraction of potassium. The decay products of these elements decay further as well. The resulting heat transfers slowly to the surface, also by conduction.

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Greenhouse gases in the Earth's atmosphere are transparent to sunlight, allowing it to penetrate to the Earth's surface. However, the same gases trap a portion of the Earth's outgoing heat, warming the ground and air near the ground. The more greenhouse gases present, the greater the trapping of heat and warming of the air. When the greenhouse gases are natural, the resulting warming is called the natural greenhouse effect.

The primary natural greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide (CO_2), ozone, nitrous oxide, methane, and oxygen gas. Oxygen gas is a weak greenhouse gas, but it is so abundant in the air (20.95 percent of all air molecules) that it has a non-trivial natural warning impact. Nitrogen gas, which comprises 78.08 percent of the molecules in the Earth's atmosphere, is not a greenhouse gas.

If the Earth had no atmosphere, thus no natural greenhouse effect, its average surface temperature would be about minus 18 degrees Celsius (zero degrees Celsius is the freezing temperature of water). At that temperature, little life would exist on Earth's surface.

During Earth's 4.6-billion-year history, several processes released to the air all of the Earth's natural greenhouse gases, except for ozone. These processes included emissions (through volcanos, fumaroles, and geysers) of greenhouse gases from the Earth's interior, bacterial metabolism, bacterial photosynthesis, and green-plant photosynthesis. Ultraviolet sunlight cooked some oxygen to produce ozone, most of which formed high above the ground, in what is now called the stratospheric ozone layer. The formation of the ozone layer was critical for protecting the surface of the Earth from harmful ultraviolet sunlight, permitting life to move from underwater and underground to above the ground.

Natural greenhouse gases raised the temperature of the Earth substantially compared with the Earth without an atmosphere, permitting life to flourish on the Earth. Just before the start of the Industrial Revolution, around 1760, Earth's average temperature was about 15 degrees Celsius. That is 33 degrees Celsius higher than Earth's temperature without greenhouse gases (minus 18 degrees Celsius). This warming was due to the natural greenhouse effect. Of this temperature rise, about 66 percent was due to water vapor, about 25 percent was due to background carbon dioxide, and about 6.2 percent was due to background ozone, most of which is in the upper atmosphere.[6]

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1.2.2 Global Warming

Global warming is the rise in the Earth's globally averaged ground and near-surface air temperature above and beyond that due to the natural greenhouse effect, due to human activity. The Earth's average global warming in the period 2011 to 2020 compared with the period 1850 to 1900 was about 1.09 degrees Celsius.[7] Since this is an average value, some places on Earth have warmed more, whereas others have warmed less or cooled. For example, the Arctic has warmed by over 5 degrees Celsius. Many other high-latitude locations (parts of Canada, Northern Europe, and Russia) have warmed by 2 to 5 degrees Celsius. The North Atlantic Ocean has cooled slightly.

1.2.3 Causes of Global Warming

Global warming is due to four major warming processes partially offset by one major cooling process (Figure 1.1). The four major warming processes are anthropogenic greenhouse gas emissions, anthropogenic warming particle emissions, anthropogenic heat emissions, and the urban heat island effect. The cooling process is anthropogenic cooling particle emissions.

1.2.3.1 Anthropogenic Greenhouse Gas Emissions

The primary anthropogenic greenhouse gases contributing to global warming are carbon dioxide, methane, halogens, ozone, nitrous oxide, and anthropogenic water vapor.

The primary anthropogenic sources of **carbon dioxide** are fossil-fuel combustion, bioenergy combustion, open biomass burning, and chemical reaction during industrial processes, such as cement manufacturing, steel production, and silicon extraction. Owing to these emissions, carbon dioxide in the air has increased from about 275 parts per million (ppm) to 420 ppm, or by 53 percent, between 1750 and 2021. One part per million of carbon dioxide means that, for every million molecules of total air, one molecule is carbon dioxide. Carbon dioxide has been increasing in the air, not only owing to its emissions from human activity, but also because it stays in the air a long time. The major removal methods of carbon dioxide from the air are its dissolution into the oceans and other water bodies and green-plant

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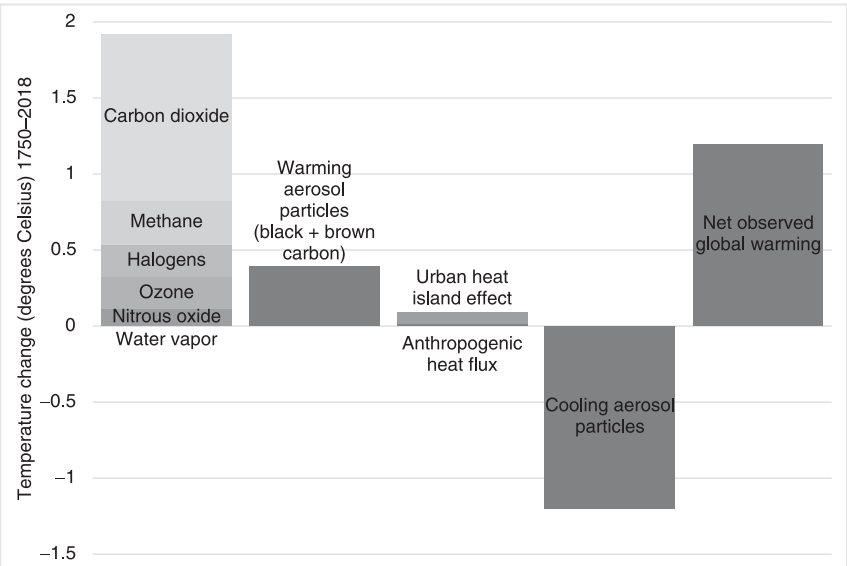

Figure 1.1 Estimated primary contributors to net observed global warming from 1750 to 2018. Warming aerosol particles include black and brown carbon from fossil-fuel burning, biofuel burning, and open biomass burning. Cooling aerosol particle components include sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, non-brown organic carbon, and water. Of the gross warming (warming before cooling is subtracted out), 45.7 percent is due to carbon dioxide, 16.3 percent is due to black plus brown carbon, 12 percent is due to methane, 9 percent is due to halogens, 8.8 percent is due to ozone, 4.3 percent is due to nitrous oxide, 3 percent is due to the urban heat island effect, 0.7 percent is due to anthropogenic heat flux, and 0.23 percent is due to anthropogenic water vapor. Source: Jacobson, *100% Clean, Renewable Energy*.[8]

photosynthesis (the conversion of carbon dioxide and water vapor into oxygen and cell material by plants and trees). However, these sinks remove carbon dioxide very slowly over many decades.

The primary anthropogenic sources of **methane** are natural gas, coal, and oil mining leakage; fossil-fuel combustion, bioenergy combustion; open biomass burning; and leakage from landfills, rice paddies, livestock, and manure. Methane is removed from the air primarily by chemical reaction in the air itself and by bacterial metabolism at the surface of the Earth.

Halogens are a series of synthetic chemicals whose main uses are as refrigerants, solvents, degreasing agents, blowing agents, fire

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extinguishants, and fumigants. The first halogen was invented in 1928. Halogens enter the atmosphere when appliances or tubes sealing them in liquid form leak or are drained, and the liquid evaporates.

Most halogens are **halocarbons**, which are chemicals that contain carbon and possibly hydrogen, but also either chlorine, bromine, fluorine, or iodine. The main types of halocarbons are the following. **Chlorofluorocarbons** (CFCs) are halocarbons containing carbon, chlorine, and fluorine. **Halons** are halocarbons containing carbon and bromine. **Perfluorocarbons** are halocarbons containing carbon and fluorine. **Hydrofluorocarbons** are halocarbons containing carbon, fluorine, and hydrogen. Some halogens, such as sulfur hexafluoride, have no carbon, so are not halocarbons.

Because chlorofluorocarbons and halons contain stratospheric-ozone-destroying chlorine and bromine, most countries outlawed them through international agreement starting with the 1987 Montreal Protocol. Hydrofluorocarbons and perfluorocarbons were developed as ozone-layer-friendly replacements. However, because many of them are greenhouse gases with long lifetimes in the air, such chemicals, while not directly damaging to the ozone layer, have the unintended consequence of enhancing global warming.

Ozone is the only greenhouse gas with no emission source. It forms chemically in the air. About 90 percent of ozone resides in the upper atmosphere (stratosphere), and the rest resides in the lower atmosphere (troposphere). The troposphere is the layer of air between the ground and 8 kilometers above sea level at the North and South Poles and between the ground and 18 kilometers above sea level at the equator. The stratosphere is the layer of air just above the troposphere and extends to about 48 kilometers above sea level. Because of the substantial abundance of ozone in the stratosphere, the stratosphere is also called the ozone layer.

In the stratosphere, ozone (which has three oxygen atoms) forms chemically following the breakdown of oxygen gas (made of two oxygen atoms bonded together) into two unbonded oxygen atoms, by ultraviolet sunlight. Atomic oxygen then combines with oxygen gas to form ozone.

In the troposphere, ozone is produced chemically following the breakdown, by ultraviolet sunlight, of nitrogen dioxide into atomic oxygen. The atomic oxygen then combines with the oxygen

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gas that we breathe (molecular oxygen) to form ozone. The nitrogen dioxide comes either from direct emissions or from chemical reaction between nitric oxide and certain reactive organic gases. Most emissions of nitric oxide, nitrogen dioxide, and reactive organic gases result from the burning of fuels by humans. Some comes from natural forest burning and bacterial metabolism. Some nitric oxide comes from lightning.

Since the Industrial Revolution, the mass of tropospheric ozone has increased by about 43 percent because of the worldwide increase in air pollution (the anthropogenic emissions of nitric oxide, nitrogen dioxide, and reactive organic gases). Since the late 1970s, stratospheric ozone has declined by about 5 percent owing to the increased presence of chlorofluorocarbons and halons within the stratosphere.

Ozone has a relatively short lifetime in the air. Most of its loss is due to chemical reaction. Just as its concentration has grown rapidly in the troposphere owing to increases in air pollution, its tropospheric concentration and warming impact can decrease rapidly if air pollution levels decrease. This is one reason that a strategy to eliminate air pollution can help to decrease global warming as well.

Nitrous oxide (laughing gas) is a colorless gas emitted naturally by bacteria in soils and in the oceans. Because it is long-lived, nitrous oxide stays in the air for up to hundreds of years once emitted. It is a powerful greenhouse gas, so it causes substantial warming per molecule during this period. Humans have increased the abundance of nitrous oxide in the air through fertilizer use, agricultural waste, sewage, legumes (plants in the pea family), bioenergy burning, biomass burning, jet-fuel burning, nylon manufacturing, and aerosol spray can manufacturing. Agriculture (fertilizers, agricultural waste, and legumes) is the largest source of human-emitted nitrous oxide today.

Anthropogenic water vapor comes from two main sources. The first is evaporation of water that is used to cool power plants and industrial facilities that run on coal, natural gas, oil, biomass, or uranium. The second is emission of water vapor during the burning of fuels for energy. Water vapor emitted annually from these sources is only about 1/8,800 of the 500 million metric tonnes of water vapor emitted per year from natural sources. Nevertheless, this relatively small anthropogenic emission rate of water vapor contributes a modest 0.23 percent of global warming.[6]

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1.2.3.2 Anthropogenic Warming Particle Emissions

Dark aerosol particles may contribute more to today's global warming than any other chemical aside from carbon dioxide (Figure 1.1).[9,10,11,12,13] Dark particles, also called **warming particles**, contain primarily black and brown carbon.

Black carbon is an agglomerate of solid spherules made of pure carbon and attached to each other in an amorphous shape. The source of black carbon is incomplete combustion of diesel, gasoline, jet fuel, bunker fuel, kerosene, natural gas, biogas, solid biomass, and liquid biofuels. Black carbon is often visible to the eye and appears black because it absorbs all wavelengths of sunlight, transmitting none to the eye. Black carbon particles convert the absorbed light to heat, raising the temperature of the particles and causing them to re-radiate some of the heat to the surrounding air.

Black carbon and greenhouse gases warm the air in different ways from each other. Greenhouse gases are mostly transparent to sunlight. They warm the air by absorbing heat emitted by the surface of the Earth. They then re-emit half of that heat upward and half downward, raising the ground and near-surface air temperatures.

Black carbon particles, on the other hand, heat the air primarily by absorbing sunlight, converting the sunlight to heat, then re-emitting the heat upward and downward, like with greenhouse gases. Black carbon particles also absorb and re-emit heat itself, but that process is important for them only at night and when black carbon concentrations are high.

When other aerosol material, such as sulfuric acid, nitric acid, water, or brown carbon, coats the outside of a black carbon particle, the black carbon heats the air 2 to 3 times faster than without a coating because more light hits the larger particle, thus more light bends (refracts) into the particle. Inside the particle, this light bounces around until it hits and is absorbed by the black carbon core.

Black carbon not only warms the air but also evaporates clouds and melts snow. When black carbon enters a cloud, it absorbs sunlight that bounces around in the cloud, converts the sunlight to heat, then emits the heat to the cloud, warming the cloud. If a sufficient number of black carbon particles is present, this warming can cause the cloud to evaporate completely. When black carbon falls on snow or sea ice, it similarly absorbs sunlight, converts the sunlight to heat, then emits the heat to the ice or snow, melting it.

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