# Controlling Non-Energy Emissions in a 100 Percent Wind-Water-Solar (WWS) and Storage World

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## Table of Contents



## 6.10. Steel Manufacturing

Steel manufacturing requires significant electricity and heat and results in air pollution and carbon dioxide emissions. With steel manufacturing, carbon dioxide emissions arise not only from burning a fossil fuel or biomass for high-temperature heat but also from chemical reaction during the extraction of pure iron from iron ore. Carbon dioxide emissions arising from chemical reaction are called **process emissions**.

Steel can be produced from raw iron ore or recycled metal. Steel produced from iron ore is produced in two stages. The first is called ironmaking, and the second, steelmaking.

In the **ironmaking** step, molten pure iron metal is extracted from solid iron ore (iron oxide). A **blast furnace** is filled with iron ore, some relatively pure solid carbon in the form of coke (coal heated in the absence of air), and **limestone** (calcium carbonate). Hot air containing oxygen is then forced through the bottom of the blast furnace. It reacts with the coke to form carbon monoxide and heat. The carbon monoxide gas then reacts with the iron ore and the coke to produce molten pure iron metal and carbon dioxide. Due to the heat, the limestone simultaneously decomposes to calcium oxide and carbon dioxide. The calcium oxide then reacts with and removes sandy remnants of the iron ore to form a waste product, called slag. Slag is less dense than molten iron, so it floats above the pure iron. Slag is then cooled and removed for use in roads, leaving pure iron behind. Thus, traditional steelmaking releases carbon dioxide, not only through fossil-fuel and biofuel burning to produce high temperatures but also from chemical reactions during the production of pure iron.

**Steelmaking** is the second step in steel production. In this step, impurities are removed from the raw iron. Then, carbon and other alloying elements are added to make crude steel. Impurities removed include phosphorus, sulfur, and excess carbon. Alloying elements added include chromium, nickel, vanadium, and manganese.

Steelmaking is performed in one of two ways. **Primary steelmaking** involves the use of new iron from ironmaking. **Secondary steelmaking** involves the melting of recycled scrap steel in an electric-arc furnace to produce new steel.

The main method of primary steelmaking is the **basic oxygen steelmaking** method. With this method, the molten iron and impurities from the blast furnace are mixed with scrap steel and placed in a **basic oxygen furnace**. Oxygen is then blown through the furnace and reacts with carbon in the molten mix to form carbon dioxide, which is released to the air. Calcium oxide in the molten mix also reacts with phosphorous and sulfur, the products of which rise to the top as slag and are removed. Finally, alloys are mixed in, and the molten steel is poured into preshaped molds, where it cools and hardens.

With secondary steelmaking, scrap metal is melted in an arc furnace. Oxygen is blown through the metal to help remove the carbon and speed the meltdown of the metal by increasing combustion. Calcium, phosphorous, and sulfur are removed and alloys are mixed in in a manner similar to the process in the basic oxygen furnace.

In sum, the sources of carbon dioxide during the two-step steel formation process are (a) its emissions during fossil-fuel combustion to produce heat in the blast furnace and in the basic oxygen furnace, (b) its chemical release during reaction of carbon with iron ore, (c) its release upon the thermal decomposition of limestone during ironmaking, and (d) its release during the chemical reaction of carbon with oxygen during steelmaking. In addition, in an arc furnace, there is a small amount of carbon dioxide released due to the vaporization of graphite and its reaction with oxygen. The overall carbon emissions during the ironmaking plus steelmaking process using a blast furnace and basic oxygen furnace are about 1,870 kilograms of carbon dioxide per tonne of steel[146]. Of this, ironmaking produces about 70 to 80 percent of the carbon dioxide emissions.

### 6.10.1. Reducing Carbon Emissions with Hydrogen Direct Reduction

An alternative to extracting molten iron from iron ore with coke during ironmaking is to extract the pure iron with hydrogen gas ($H_2$), where the hydrogen is produced with 100 percent WWS electricity[146]. Such hydrogen is **green hydrogen**. This process is called the **hydrogen direct reduction** process. The main extraction reaction involves mixing iron ore with hydrogen gas to produce pure molten iron plus steam. This reaction occurs optimally at a temperature of around 800 degrees Celsius, which is lower than the temperature needed in a blast furnace[146]. The reaction eliminates the process emissions of carbon dioxide produced from the purification of iron ore to iron during ironmaking. However, an injection of carbon into the molten iron during the steelmaking process is still needed to create an iron-carbon alloy (0.002 to 2.14 percent carbon) to strengthen the steel. In addition, some carbon is still emitted from the thermal decomposition of limestone and subsequent emission of carbon dioxide.

If the heat required for the hydrogen direct reduction ironmaking process is obtained with an electric-resistance furnace instead of with fossil fuels, if the hydrogen for the process is produced by electrolysis (passing of electricity through water), if an electric-arc furnace is used for the steelmaking process, and if all electricity is from 100 percent WWS, the hydrogen direct reduction process emits only 53 kilograms of carbon dioxide per tonne of steel, or only 2.8 percent of the emissions of the blast furnace/basic oxygen furnace process (1,870 kilograms of carbon dioxide per tonne of steel)[146]. The only carbon dioxide emissions during the hydrogen direct reduction process are from oxidation of injected carbon in the arc furnace, the thermal decomposition of limestone, and oxidation of the vaporized carbon in the arc furnace electrodes.

The system just described is a 100 percent clean, renewable energy system, but still results in a residual of 53 kilograms of carbon dioxide per tonne of steel (2.8 percent of the original emissions). The remainder will likely be released to the air. Capturing the remaining carbon dioxide requires electricity, and even if the electricity is from WWS, it is better to use that WWS electricity to displace a fossil-fuel electricity source than to capture carbon dioxide, since displacing a fossil-fuel source eliminates not only carbon dioxide from the source but also air pollution and upstream mining and emissions. Carbon capture does not reduce mining or air pollution.

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Transition highlight. During June 2021, a steel-manufacturing plant in Lulea, Sweden, created pure metallic iron (sponge iron) from hydrogen for the first time. The hydrogen was produced by electrolysis, where the electricity came from wind, thus the hydrogen was green hydrogen. The plant subsequently produced nearly-carbon-free steel commercially from the purified iron in July 2021. As of 2024, the plant had produced 5,000 tonnes of green steel. Based on the results of this plant, the Swedish steel industry plans to transition all steel factories to green steel ones.

To that end, a green steel plant being constructed in Boden, Sweden, is expected to open in 2025. This plant will produce 5 million tonnes of green steel per year by 2030 from the hydrogen direct reduction process. The hydrogen will come from an 800-megawatt electrolyzer. An electric-arc furnace will be used for steelmaking. Green steel plants are also being built in Finland, Spain, France, Germany, the United States, and China among other countries[147].

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### 6.10.2. Reducing Carbon Emissions with Lasers

Another way to separate pure iron from iron ore is to heat the iron ore directly with lasers[148]. With this process, an array of small lasers is pointed toward the iron ore, forming a spotlight, melting the iron ore in seconds. Lasers require only 70 percent of the energy needed for hydrogen direct reduction and result in the same emission reduction, so long as the electricity used for the lasers comes from WWS[148]. Lasers can also be applied to iron ore with low (below 67 percent) iron content, whereas hydrogen direct reduction is applied primarily to iron ore with higher iron content.

### 6.10.3. Reducing Carbon Emissions with Molten Oxide Electrolysis

Yet another method of extracting molten iron from iron ore during ironmaking is with **molten oxide electrolysis**[149]. With this technique, iron ore is first heated in a molten electrolyte soup above 1,961 degrees Celsius, where it decomposes to produce a different form of iron oxide, called magnetite, and oxygen. The molten electrolyte soup contains silicon, aluminum, and magnesium and helps electricity flow. The soup is heated further, past the melting point of pure iron, which is 2,084 degrees Celsius. Above this temperature, electricity that passes through the soup, turns magnetite into pure molten iron, which sinks to the bottom of the cauldron, where it is drained. As such, the molten oxide electrolysis process produces pure iron without emitting chemically-produced carbon dioxide.

## 6.11. Concrete Manufacturing

**Concrete** is a mixture of **aggregate** (sand, gravel, and crushed stone) and paste (water and **ordinary Portland cement**). The paste binds the aggregate together, making a hard surface. Concrete is used for roads, foundations, buildings, runways, sidewalks, driveways, and a variety of other purposes.

**Joseph Aspdin** (1778 to 1855) of Leeds, England, invented ordinary Portland cement in the early nineteenth century. He formed it by burning powdered limestone and clay on his kitchen stove. Today, cement contains limestone, shells, or chalk, which all contain calcium carbonate mixed with clay, shale, slate, blast furnace slag, silica sand, or iron ore.

After being heated to 1,500 degrees Celsius, these ingredients form a hard substance that is ground into a fine, powdery cement.

The concrete industry produces about 8 percent of the world's fossil-fuel carbon dioxide emissions[150], or about 6.4 percent of all anthropogenic (fossil-fuel plus permanent-deforestation) carbon dioxide emissions. These emissions are equivalent to about 1.18 tonne of carbon dioxide per tonne of cement produced[150]. Of the total, 1.6 percent is from the quarrying of raw materials, 42.4 percent is from electricity and heat production during the cement manufacturing process, 46.3 percent is from chemical reaction (process emissions) during cement manufacturing, and 9.7 percent is from the production of concrete from cement and the transport of concrete[150]. As such, almost half of carbon dioxide emissions from concrete production are process emissions, and the rest are emissions related to energy (electricity production, heat production, and transport).

The process emissions during cement manufacturing arise due to the chemical reaction of calcium carbonate (limestone) with clay at a high temperature to produce clinker (a mix of oxides of silicon, iron, aluminum, and calcium) and carbon dioxide. The clinker is then mixed with gypsum (plaster of Paris) to form cement. The cement is subsequently mixed with water to form a paste, which is combined with the aggregate to form concrete.

Five ways of reducing process emissions and/or energy emissions from concrete manufacturing are to (1) use basalt instead of limestone to react with clay to produce clinker, (2) use geopolymer concrete instead of concrete derived from ordinary Portland cement, (3) use Ferrock instead of concrete, (4) recycle concrete, and (5) make concrete that traps carbon dioxide. In all cases, energy must be supplied by WWS to maximize carbon dioxide reductions.

### 6.11.1 Basalt-Based Concrete

All process emissions of carbon dioxide during concrete production are due to the reaction of limestone rock with clay. Limestone contains both calcium and carbonate. The calcium is needed to produce clinker. The carbonate in limestone is released as carbon dioxide gas upon the reaction of limestone with clay at high temperature. Basalt is a rock more common than limestone that contains calcium and other chemicals, but no carbonate. Basalt and other similar calcium silicate rocks with no carbonate can be ground, in the place of limestone, during cement production, eliminating process carbon dioxide emissions entirely while still producing the exact same ordinary Portland cement[152,153]. On March 14, 2024, the first basalt-based concrete in history was poured in Seattle, Washington State, for a foundation, wall, and ramp[153].

### 6.11.2. Geopolymer Concrete

**Geopolymer concrete** was named and developed in the 1970s by Joseph Davidovits (b. 1935), a French material scientist. It is a hardened mixture of geopolymer cement, aggregate, and water. **Geopolymer cement** consists of any natural or industrial waste material containing aluminosilicate minerals mixed with an alkali solution[153]. Waste materials include fly ash, granulated blast-furnace slag, rice-husk ash, or metakaolin. **Fly ash** is abundant in most countries since it is a waste product of 100 years of coal burning for electricity generation. **Slag** is a waste product of steel production. **Rice-husk ash** is an abundant waste product of rice milling. **Metakaolin** is a form of the clay mineral, kaolinite. Alkali solution options include sodium hydroxide, potassium hydroxide, and/or sodium silicate mixed with water. The cement is cured at a temperature of 100 degrees Celsius to provide strength. The cement is then mixed with aggregate and water to form concrete.

Slag-based geopolymer cement consists of fly ash, ground-granulated blast-furnace slag, and an alkali solution. Rock-based geopolymer cement consists of volcanic rock, fly ash, slag, and an alkali solution.

Because geopolymer concrete does not use calcium carbonate and because it does not need energy for high-temperature kilns, producing it results in about 80 percent lower carbon dioxide emissions than producing concrete from ordinary Portland cement[154]. Most of the carbon dioxide emission reduction is due to eliminating the off-gassing of carbon dioxide from calcium carbonate chemical reaction. The remaining reduction is due to the fact that geopolymer concrete does not require the use of extreme high-temperature kilns, thus it reduces energy consumption by about 50 percent versus concrete derived from ordinary Portland cement. If the remaining energy is provided by WWS, geopolymer concrete emissions of carbon dioxide are almost eliminated. Other benefits of geopolymer concrete are that it is more resistant to freezing and thawing cycles and to corrosion by acid rain than is concrete from ordinary Portland cement. The costs of the two types of concrete are similar.

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Transition highlight. Geopolymer concrete has been used in many projects to date. For example, 70,000 tonnes of it were used to construct the Toowoomba Wellcamp airport in Queensland, Australia.

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### 6.11.3. Ferrock

Another commercialized alternative to concrete is **Ferrock**, or iron carbonate ($FeCO_3$)[155]. Ferrock is derived by first mixing waste steel dust containing iron oxide with crushed glass containing silicon dioxide, limestone, kaolinite or another clay, stabilizers, promoters, and a catalyst into a mixer at room temperature. The mixture is then poured into a mold containing seawater. The filled mold is put into a curing chamber, where carbon dioxide from a furnace is injected. The iron, carbon dioxide, and saltwater react together to form Ferrock and hydrogen gas. When the final product dries, it is about 5 times harder and more flexible than ordinary Portland cement. The production of Ferrock not only avoids the chemical carbon dioxide emissions and most energy emissions from concrete production, but it also traps carbon dioxide and produces hydrogen, which can be used for other applications.

### 6.11.4. Concrete Recycling

Another method of reducing carbon dioxide emissions from concrete manufacturing is with **concrete recycling**. Concrete structures or roads are often demolished. Historically, such concrete has been sent to a landfill. However, if the concrete is uncontaminated (free of trash, wood, and paper), it can be recycled. Rebar (steel reinforcement) in concrete can also be recycled, as magnets can remove it. The rebar can then be melted and used for other purposes. The broken concrete is crushed. Crushed concrete is often used as gravel in new construction projects or as aggregate in new concrete.

### 6.11.5. Sequestering Carbon Dioxide in Concrete

Trapping carbon dioxide in a material, as done in Ferrock, is a method of offsetting emissions of chemically produced carbon dioxide emissions from the concrete production process. Trapping carbon dioxide within concrete itself is another option[156]. The clinker in ordinary Portland cement contains calcium oxide. If carbon dioxide from any source is mixed with the clinker, it will react with the calcium oxide to form calcium carbonate within the cement. Upon drying, the solid calcium carbonate strengthens the cement. Even if the cement breaks, the carbon dioxide, trapped in the calcium carbonate, will not break free because calcium carbonate is a solid bound to the cement.

Remaining carbon dioxide emitted chemically during the cement formation process can theoretically be captured upon emissions. However, capturing carbon dioxide requires equipment, electricity, and pipelines. Even if the electricity is from WWS, it is far better to use that WWS electricity and the money for the equipment to displace coal or fossil-gas electricity than to capture carbon dioxide. This is because displacing a fossil-fuel electricity source with WWS electricity (a) eliminates more carbon dioxide than does using the WWS electricity to run carbon-capture equipment and (b) eliminates the air pollution, upstream mining and emissions, and fossil-fuel infrastructure, which carbon-capture equipment does none of. In addition, carbon-capture equipment extracts only 10 to 80 percent of carbon dioxide from a source in the annual average. Further, of the captured carbon dioxide, 82 percent worldwide is used for enhanced oil recovery. During that process, 47 to 109 percent of the captured carbon is released back to the air (Section 8.4). Thus, carbon capture attached to cement is an opportunity cost that increases carbon dioxide, air pollution, mining, and fossil infrastructure and is not recommended for reducing process emissions during cement manufacturing.

## 6.12. Silicon Purification

Pure silicon is a common chemical in alloys and semiconductors. Alloys, including aluminum-silicon and iron-silicon alloys, are the major end-use of pure silicon. Such alloys are used to make transformer plates, engine blocks, cylinder heads, and machine tools. Semiconductors are used in computers, microelectronics, and solar photovoltaic cells.

Pure silicon (Si) is extracted from silicon dioxide ($SiO_2$), also called silica and quartz. The source of silicon dioxide is either sand or a mine. The most common process of silicon extraction is **carbothermic reduction of silica**. It involves heating silicon dioxide together with pure graphitic carbon up to a temperature of 2,200 degrees Celsius in an electric-arc furnace. The reaction produces pure silicon and carbon dioxide gas. The silicon is extracted, and the carbon dioxide is released to the air as process emissions. If electricity for the arc furnace is derived from a fossil-fuel energy source, additional carbon dioxide is emitted. For some applications, such as photovoltaics, the silicon is still not pure enough and more purification is needed.

Several alternative methods of purifying silicon from silica exist that do not involve releasing carbon dioxide. These methods involve either dissolving silica in a mixture of organic alcohol and a base; reacting silica with aluminum or magnesium at moderate temperature (450 to 650 degrees Celsius); or placing silica in a molten salt electrolyte solution and running electricity through the solution[156]. Alternatively, pure silicon can be obtained from calcium silicate instead of from silica. The calcium silicate is dissolved in a mixture of 3 salts - calcium chloride, magnesium chloride, and sodium chloride - at a warm temperature. In solution, the calcium silicate dissociates into pure silicon[157]. All materials for this process are relatively inexpensive. Developing one of these alternative methods and using WWS electricity to provide the heat needed eliminates energy and process carbon dioxide emissions from silicon production.

## 6.13. Ammonia Manufacturing

About 80 percent of ammonia ($NH_3$) manufactured worldwide is used to make fertilizer. The rest is used for cleaning; purifying water; refrigerating; and manufacturing plastics, explosives, textiles, pesticides, dyes, and chemicals[96]. The most common way to produce ammonia is the Haber-Bosch process, which involves combining one molecular nitrogen ($N_2$) gas molecule from the air with 3 molecular hydrogen ($H_2$) gas molecules produced chemically to produce two ammonia molecules. In 2020, about 146.85 million tonnes per year of nitrogen in ammonia were produced among 145 countries. This necessitated about 31.7 million tonnes per year of hydrogen. Almost all hydrogen for ammonia today is from steam methane reforming, where the methane originates from fossil gas. Such hydrogen is referred to as gray hydrogen. Gray hydrogen results in two sets of $CO_2$ emissions: from the use of fossil gas for both energy and the chemical source of hydrogen.

If hydrogen is instead produced from WWS electricity through electrolysis (green hydrogen), all carbon dioxide and air-pollution emissions during ammonia production are eliminated. Using green instead of gray hydrogen does not affect the process of manufacturing ammonia. It affects only how the hydrogen is produced. Creating and compressing hydrogen for ammonia production using WWS electricity is estimated to require about 170.5 gigawatts of annually averaged power in 2050, an 18.8 percent decrease versus producing hydrogen from steam methane reforming[96].

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Transition highlight. In September 2024, 3 Danish companies (Topsoe, Skovgaard Energy, and Vestas) joined forces in Ramme, Denmark, to begin manufacturing 5,000 tonnes of ammonia per year directly from WWS electricity (12 megawatts of wind and 50 megawatts of solar PV). This was the first time a hybrid wind and solar farm had been connected to both an electrolyzer to produce hydrogen and a plant that manufactures ammonia from hydrogen. This plant avoids the production of hydrogen for ammonia from fossil gas.

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# Chapter 7

# Solutions for Non-Energy Emissions

WWS technologies eliminate energy-related emissions of air pollutants that affect health and climate. Energy-related emissions are responsible for about 90 percent of anthropogenic air-pollution health problems worldwide and 75 to 80 percent of anthropogenic greenhouse gas emissions. As such, some emissions that affect human health and climate do not come from energy sources, but they must still be reduced or eliminated in order to help solve the air-pollution and climate problems the world faces. Such nonenergy emissions include gases and particles from open biomass burning; methane from agriculture and landfill waste; halogens from leaks and their reckless disposal; and nitrous oxide from fertilizers, industry, and wastewater treatment. This chapter discusses these sources of emissions and methods of controlling them.

## 7.1. Open Biomass Burning and Waste Burning

**Open biomass burning** is the burning of evergreen forests, deciduous forests, woodland, grassland, and agricultural land, either to clear land for other use, to stimulate grass growth, to manage forest growth, or to satisfy a ritual. Agricultural fields are often set on fire after a harvest to remove straw, thus clearing land for a new crop the next spring. Sugarcane fields are often burned before harvest to remove the outer leaves around the sugarcane stalks to facilitate sugarcane extraction. **Waste burning** is the burning of trash, such as in a landfill, open pit, garbage can, or backyard incinerator. Such waste burning is illegal in many countries but still occurs in others. **Wildfires** are fires triggered accidentally by a campfire, debris burning, an electrical spark from a transmission line, or a cigarette; or intentionally, by arson. About 17 percent of all global carbon-dioxide emissions worldwide are from fires (open biomass burning, waste burning, and wildfires). Humans cause 100 percent of open-biomass-burning and waste-burning fires and about 93 percent of all fires. Nature causes the rest[6].

All fires produce not only gases that warm the climate (carbon dioxide, methane, ozone precursors, nitrous oxide, carbon monoxide, and water vapor), but also climate-warming particles (black and brown carbon) and direct heat. Black and brown carbon, along with other particles emitted during open biomass burning (ash, organic carbon aside from brown carbon, and sulfate) cause substantial health impacts to people and animals who breathe them in. In addition, the oxides of nitrogen and organic gases from open biomass burning result in elevated levels of ozone, formaldehyde, and other gases that affect human health. Waste burning emits the same chemicals as biomass burning but also toxic chemicals from burning plastics, paints, varnishes, pesticides, medical waste, and chemical byproducts.

While some argue that open biomass burning followed by regrowth of vegetation produces no net increase in carbon dioxide to the air, that contention is incorrect. Although the carbon dioxide released upon burning is offset by carbon dioxide taken from the air during photosynthesis to regrow the vegetation burned, the time lag between burning and regrowth (from one to ten years for savannah and 80 years for a forest, for example), always increases carbon dioxide in the air[158]. The contention is also misleading because biomass burning emits black and brown carbon, water vapor, methane, ozone precursors, nitrous oxide, carbon monoxide, and heat, all of which increase global temperatures. These are not recycled like carbon dioxide is. As such, biomass burning always causes net global warming[6].

The only solution to open biomass burning is to stop it. No technology can control its emissions. An alternative to burning agricultural waste straw is to till it into the soil. An alternative to sugarcane burning is to cut away the leafy parts of the sugarcane before harvest and mix them into the soil. Since humans cause 100 percent of open biomass burning and waste burning, both types of fires are largely preventable through government policies restricting burning and discouraging the conversion of forest land to agricultural land or another land use type.

Similarly, the only method of reducing the impacts of waste burning is to stop it. If waste is burned in an incinerator, many of the resulting emissions can theoretically be controlled with emission-control technologies; however, no technology eliminates all emissions, including of carbon dioxide. Thus, even incinerators with emission controls produce substantial pollution. The best control of waste burning is to instead recycle the waste or put it in a landfill. Waste should not be dumped into the oceans since plastics do not degrade for centuries. The accumulation of plastics in the oceans has caused an environmental catastrophe, resulting in the **Great Pacific Garbage Patch**. This is a plastic wasteland that consists of two distinct garbage patches in the North Pacific Ocean, one near Japan (Western Garbage Patch) and the other between California and Hawaii (Eastern Garbage Patch). Collectively, the two are 3 times the area of France.

## 7.2. Methane from Agriculture and Waste

**Methane** is a long-lived greenhouse gas that selectively absorbs specific long wavelengths of heat radiation, trapping some of that radiation near the surface of the Earth. Methane not only increases global warming, but it also increases background levels of ozone, another greenhouse gas, through chemical reaction.

Anthropogenic sources of methane include open biomass and waste burning, fossil-gas mining leaks and pipeline venting, fossil-fuel combustion, and biological sources enabled by human activity. Biological sources include bacterial production of methane in landfills, rice paddies, the stomachs and manure of farm animals, and sewage treatment plants. Policies controlling biomass and waste burning are needed to reduce methane from those sources. A 100 percent WWS energy system eliminates the need for methane for, thus emissions of methane from, energy systems. This section discusses controlling methane from human-enabled biological sources.

The root biological source of most methane is **methanogenic (methane-producing) bacteria**, which live in environments lacking oxygen. Methanogenic bacteria consume organic material and excrete methane. Ripe oxygen-depleted environments include the digestive tracts of cattle, sheep, and termites; manure from cows, sheep, pigs, and chickens; rice paddies; landfills; and wetlands. All of these sources aside from termites and wetlands, are human-enabled.

The main method of reducing methane from bacteria in the digestive tracks and manure of animals is to reduce human consumption of meat and poultry. This requires people changing their diets, which can have additional health benefits. Another method is to change the diet of animals that release methane. For example, studies indicate that feeding cattle red or brown seaweed can reduce methane emissions from them substantially[160].

Methane from manure can also be captured with a methane digester. A **methane digester**, or manure digester, is an airtight tank in which manure is processed after water is separated from it. The manure is heated and stirred to simulate the inside of a cow's stomach. Methane emitted by bacteria within the manure rises from the manure to the top of the tank, where it is captured in a bag or piped out of the digester, into a storage tank.

Methane gas from landfills, like from a digester, can be captured directly. **Landfill gas** is often a mixture of nearly 50 percent methane, nearly 50 percent carbon dioxide, and trace amounts of nonmethane organic gases. Landfill gas is extracted by drilling multiple half-meter-wide boreholes up to 30 meters deep into a section of the landfill. Trash is then removed so that a well, which consists of a perforated or slotted siding with a cap on the bottom, can be installed. Most of the top of the well is sealed to prevent gas escape. A wellhead is installed at the top through which gas is piped to its end destination. In some cases, a network of multiple vertical and horizontal pipes can capture the landfill gas. Once captured, the landfill gas is usually filtered to separate out the methane from the other gases.

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Transition highlight. **Rice paddies** release a significant amount of methane globally, both through the leaves of rice plants themselves and in the oxygen-depleted environment of the flooded soil in which rice plants usually grow. On average, rice-paddy soil is flooded for 4 months of the year. Direct seeding of rice plants, instead of transplanting rice plants into already-flooded paddies, can reduce the time needed for flooding down to one month. This reduces methane emissions from rice paddies by 15 to 90 percent. A system of pipes can also be used to capture rice paddy methane just as it captures methane from landfill gas.

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Once biological methane from a digester, landfill, or rice paddy is captured, what should be done with it? In a 100 percent WWS world, the best use of captured biological methane may be to produce hydrogen through methane pyrolysis. The hydrogen should then be used in a hydrogen-fuel-cell-electric vehicle for long-distance transport, in a hydrogen fuel cell to produce grid or microgrid electricity, or for steel or ammonia manufacturing.

With **methane pyrolysis**, methane ($CH_4$) is heated to above 1,000 degrees Celsius in the absence of oxygen until the bonds between the carbon atom and its 4 attached hydrogen atoms are broken[161]. If a metal catalyst, such as nickel or iron is present, the temperature needed can be lowered to about 600 or 800 degrees Celsius, respectively[161]. Adding a small amount of cobalt can further lower the temperature needed. In all cases, the carbon atoms from multiple methane molecules coalesce into carbon nanotubes, solid carbon, graphite or carbon black[161], all of which are solids that can be used for industry or buried. The free hydrogen atoms combine into molecular hydrogen ($H_2$) gas molecules.

If the methane comes from a biological source and the heat comes from a WWS source, no carbon dioxide is emitted during methane pyrolysis. However, standard methane pyrolysis converts only about 80 to 95 percent of the input methane into solid carbon and hydrogen[161]. The rest is released to the air. The process also produces some air pollutants due to incomplete decomposition of some methane during heating. Tests suggest that methane conversion can approach 100 percent efficiency when microwave heating instead of conventional heating is used during pyrolysis[161].

In sum, using methane captured from a digester, landfill, or rice paddy and heat from a WWS source to produce hydrogen through methane pyrolysis reduces climate-relevant emissions more than does allowing the methane to be released to the air, while slightly increasing air pollution. However, using methane from fossil gas to produce hydrogen by methane pyrolysis is not good for either the climate, air quality, or the environment. This is because the mining, transporting, and processing of fossil gas results in substantial land damage and emissions of gaseous air pollutants, black carbon particles, methane, and carbon dioxide beyond the emissions associated with methane pyrolysis itself[161].

## 7.3. Halogens

Anthropogenically-emitted halogens are responsible for about nine percent of global warming (Figure 1.1). Halogens are still used today as refrigerants, solvents, blowing agents, fire extinguishants, and fumigants. They enter the atmosphere primarily upon evaporation when they leak or when the appliances containing them are drained. Their persistence in the atmosphere and their strong warming per molecule make them potent greenhouse gases.

The main methods of reducing halogen emissions and their impacts on climate are (a) replacing halogens used in equipment and appliances that have high global warming potentials with halogens that have low warming potentials, (b) requiring tougher standards for sealing halogens in the equipment and appliance, and (c) requiring tougher standards for disposing of halogens at the end of the life of the equipment or appliance they are contained in. For these suggestions to be effective, they need to be implemented and enforced worldwide.

## 7.4. Nitrous Oxide

Nitrous oxide is a potent greenhouse gas with a long lifetime. It is produced largely by bacteria and contributes to about 4.3 percent of global warming. In fact, 67 to 80 percent of anthropogenic nitrous oxide originates from agriculture[163]. In particular, bacteria in nitrogen-containing fertilizers expel substantial amounts of nitrous oxide. In addition, the cultivation of legumes (plants in the pea family) results in the conversion, by bacteria, of atmospheric nitrogen gas to nitrous oxide, which is released to the air. A third agricultural source of nitrous oxide is the bacterial conversion of solid waste of domesticated animals.

Some methods of reducing nitrous oxide emissions from fertilizers are (a) using less nitrogen-based fertilizer, (b) cultivating leguminous crops that don't require fertilizer in the crop rotation, and (c) reducing tillage to reduce the breakdown of organic fertilizer, thereby reducing reaction and release of chemicals.

The remaining anthropogenic sources of nitrous oxide are fossil-fuel combustion, open biomass and waste burning, industrial processes, and wastewater treatment. Transitioning fossil energy to 100 percent WWS will eliminate fossil combustion sources of nitrous oxide. Reducing biomass and waste burning will reduce nitrous oxide from these sources.

The two main industrial sources of nitrous oxide are the production of nitric acid for use in fertilizers and the production of adipic acid for use in the production of nylon fibers and plastics. To date, nitrous oxide emissions from adipic acid production have been reduced effectively with emission-control technologies in several plants, so the expansion of such technologies to adipic acid plants worldwide will help reduce nitrous oxide emissions. Similarly, nitrous oxide emission-control technologies for nitric acid production plants are available and could be implemented worldwide with stringent policies[164].

The source of nitrous oxide in wastewater is organic material from human or animal waste. Modulating the dissolved oxygen content in the wastewater treatment process can control the nitrous oxide content of wastewater[165,166].

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