No Miracles Needed
How Today's Technology Can Save Our Climate and Clean Our Air

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Chapter 6

WWS Solutions for Industry

The industrial sector creates products made of metal, plastic, rubber, concrete, glass, and ceramics, among other materials. Energy is needed in industry for heating, cooling, drying, curing, melting, and electricity. In the United States, energy for creating industrial heat comprises about 70 percent of industrial energy demand. Energy for cooling and refrigeration comprises about 3.4 percent; energy for machines, about 19 percent; energy for electro-chemical processes, 2.6 percent; and energy for all other processes, five percent[98]. Industrial heat ranges from low to high temperature heat. About half of industrial heat is high-temperature heat (above 400 degrees Celsius) and the other half, low- (30 to 200 degrees Celsius) and medium- (200 to 400 degrees Celsius) temperature heat[99]. High temperature heat is used for plastics and rubber manufacturing, casting, steel production, other metal production, glass production, lime calcining in cement manufacturing, metal heat-treating and reheating, ironmaking, and silicon extraction from sand. Low and medium-temperature heat are used for drying and washing during food production, chemical manufacturing, distilling, cracking, pulp and paper manufacturing, and petroleum refining, among other processes. This chapter first discusses the current sources of energy used in industry then discusses WWS replacements for these sources. The chapter also includes methods of eliminating chemical emissions from steel, concrete, and silicon manufacturing.

6.1. Current Energy Sources for Industry

Energy for industrial heat is currently obtained from fuels, electricity, and steam.

Fuels producing industrial heat include natural gas, coal, fuel oils, liquefied gases, and biomass. These fuels are burned in ovens, fired heaters, kilns, and melters. The resulting heat is transferred either directly or indirectly to the material being melted. With **direct (convection) heating**, combusted gases come in direct contact with the material. With **indirect (radiant) heating**, the hot gases pass through radiant burner tubes or panels separated from the material, and the heat is transferred radiantly.

Electricity-based heating technologies include electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters (including radio frequency driers and microwave processors), and electron beam heaters. The first three produce high temperature heat (greater than 400 degrees Celsius). The remaining technologies produce primarily medium and low temperature heat. All technologies use either direct or indirect electric heating. With direct electric heating, an electric current is sent directly to a material, heating the material by resistance heating. With indirect electric heating, high-frequency energy is inductively coupled with a specific material to heat it.

Steam-based heating technologies heat materials directly with steam or indirectly through a heat-transfer mechanism. Almost all steam heating is for low-temperature (less than 200 degrees Celsius) processes, such as pulp and paper manufacturing, chemical manufacturing, and petroleum refining. Currently, most of the steam for these processes is generated simultaneously (co-generated) with electricity produced by the burning of a fossil fuel or biomass.

In the U.S. in 2010, fuels comprised 48.5 percent of energy supplied to industry; electricity supplied 22.7 percent, and steam provided 28.8 percent[98]. Of all the energy consumed, only 58 percent was applied usefully, and the rest was lost as waste heat.

Transitioning industrial-sector energy to 100 percent clean, renewable WWS energy and storage requires moving high, medium- and low-temperature fuel-based combustion to electric alternatives. Such alternatives include electric arc furnaces, induction furnaces, resistance furnaces, dielectric heaters, electron beam heaters, heat pump steam, and CSP steam.

In addition, it is necessary to eliminate non-energy carbon dioxide emissions (called **process emissions**) produced chemically during steel manufacturing, concrete production, and silicon extraction from sand. This requires alternative methods of producing steel, concrete, and silicon. Industrial-sector electrification and alternatives to steel, concrete, and silicon manufacturing are discussed next.

6.2. Arc Furnaces

An **electric arc furnace** is a spherical-shaped furnace for melting metal. It has a retractable roof and contains three graphite electric rods. The floor of the furnace is coated with a heat-resistant material that is used for collecting the molten metal. Scrap steel or iron is fed into the furnace, the roof is closed, and the electric rods (cathodes) are lowered onto the metal. An electric current that passes between the rods and an anode mounted at the bottom of the furnace creates an arc (extremely hot, bright light). The current that passes from the negatively-charged cathode rods to the positively-charged anode base melts the metal, as does the radiant heat emitted by the arc. When the metal is melted, the metal alloy, slag (stony waste matter separated from metals during smelting), and oxygen formed by the process are removed through side doors.

The arc furnace derives from the carbon arc lamp. In 1800, Sir Humphrey Davy invented the **carbon arc lamp**, which consists of two carbon rods with an electric current running through them. When the rods first contact each other, a spark is ignited. The rods are then pulled apart slowly. The current forms an extremely bright arc of light across the air gap. The bright arc forms because the hot (3,600 to 6,300 degrees Celsius) carbon rod tips vaporize and ionize, creating a plasma that contains positive carbon ions and free electrons at high temperature. The electrons turn the gas into a good conductor that can be maintained at the high temperature. When the current strikes the ionized carbon vapor, the result is a bright light. The carbon rods slowly burn away as they gasify, requiring the distance between them to be adjusted as well. Carbon arc lamps were the only form of light used for street lighting and industrial indoor lighting from 1801 to 1901. Their disadvantages are that they produce short ultraviolet wavelengths of radiation, which are dangerous to humans; they create a buzzing sound; and they produce flickering light and sparks, which can set fires.

In 1878, **Carl W. Siemens** extended the idea of the arc lamp to build and patent an electric arc furnace. James B. Readman subsequently invented (1888) and patented (1889) an arc furnace in Edinburgh, Scotland and applied it to produce phosphorus. Paul Heroult of France developed a commercial arc furnace for steel production in 1900. In 1905, he went to the U.S. to work with several steel companies, including the Sanderson Brothers Steel Company in Syracuse, New York, which installed the first commercial arc furnace worldwide in 1906.

Arc furnaces are used in foundries (workshops in which metals are melted and cast into different shapes), steel mills, and silicon extraction facilities. In steel mills, they are used to produce steel from recycled, scrap metal, reducing the energy needed versus making steel from raw ores. Because arc furnaces require a lot of energy, they are often used

when electricity prices are low, thus their use responds well to electricity pricing, which is a central feature of demand response management of the grid.

In a 100 percent clean, renewable energy world, arc furnaces are one technology that will replace fossil fuels and biomass to produce heat for making steel and for casting metals.

6.3. Induction Furnaces

Another method of melting metals, such as iron, steel, copper, aluminum, and precious metals, is with an electric **induction furnace**. Induction furnaces can melt from a kilogram to a hundred tonnes of metal at a time.

An induction furnace consists of a nonconductive crucible surrounded by a large coil of copper wire. Metal is placed inside the crucible to be melted. A strong alternating electric current is sent through the wire coil, creating a rapidly reversing magnetic field that induces circular electric currents (called eddy currents) inside the metal. The metal heats by resistance heating as the eddy currents pass through it. Because the heating of the targeted material results from electric currents that are induced by a magnetic field created from electricity passing through a coiled wire, the heating is by electromagnetic induction.

Because the metal is heated by induction, the temperature of the metal rises to no higher than the temperature required to melt the metal. This prevents the loss of some alloying elements. Thus, an induction furnace differs from an arc furnace, where the temperature rises above that required to melt the metal.

In a 100 percent WWS world, induction furnaces are another electric technology that will replace fossil fuels and biomass for producing high-temperature heat.

6.4. Resistance Furnaces

A third method of obtaining high-temperature heat is with an electric resistance furnace. With this technology, direct current (DC) electricity passes from a negative electrode (cathode), through a conducting material, to a positive electrode (anode). The conducting material heats up due to resistance within the material. In **direct resistance heating**, the material targeted for heating or melting is itself the conductor of electricity. In **indirect resistance heating**, a separate heating element is heated and transfers its heat by a combination of conduction, convection, and radiation to the material targeted for heating or melting.

The most common applications of direct resistance heating are the heating of long rods, the heating of iron-containing metals prior to forging, and the continuous annealing (heating followed by slow cooling) of wire[100].

Indirect resistance heating is used to heat solids, liquids, and gases in many industries. It is used in the heating and metals industries for melting, hot working, plasma-heating processes, stress relieving, and preheating. It is also used in the food, paper, print, textile, rubber, plastic, glass, and ceramic industries.

6.5. Dielectric Heaters

A fourth method of electric heating is **dielectric heating**, which is what microwave ovens use to cook food. Dielectric heating is used for low-temperature applications.

Dielectric heating, also referred to as electronic heating, uses electromagnetic radiation in the frequency range covering either radio frequencies or microwave frequencies. The former type of dielectric heating is referred to as **radio frequency heating** and the latter, **microwave heating**.

In a dielectric heater, the radio wave or microwave is used to heat a **dielectric material**, which is a poor conductor of electric current. Radio frequency heating is often applied to heat large materials because the heating is more uniform than with microwave heating. As such, radio frequency heating is used for most dielectric industrial heating applications, including gluing, welding, plastic production, preheating, bread baking, textile drying, adhesive and paper drying, microwave preheating, and vulcanizing rubber. Microwave heating is used primarily for the tempering of meat and other food processing applications[101].

6.6. Electron Beam Heaters

Electron beam heating is a method of melting metals or modifying materials with a fine beam of electrons. When the high concentration of electrons hits a solid material, the kinetic energy of the electrons is converted to heat, which melts the material. The electrons are produced with an **electron gun**, which ejects a narrow stream of electrons from a heated cathode and accelerates them using high voltage. The beam is obtained by using electric and magnetic fields to force free electrons in a vacuum into a straight line. The power per unit area of electron beam heating is one-thousand times that of peak sunlight reaching the surface of the Earth. Around 50 to 80 percent of the energy in the electron beam is transferred to the material.

Electron beam heating takes place in a large vacuum furnace and is applied to mass-produce steel and purify metals, such as titanium, vanadium, tantalum, molybdenum, tungsten, zirconium, niobium, and hafnium. The electronics industry uses many of these metals. A **vacuum furnace** is a furnace in which the material being operated on is surrounded by a vacuum, or absence of air. Temperatures in a vacuum furnace reach up to 3,000 degrees Celsius. Electron beam heating is also used in vacuum chambers to weld and precisely cut materials to make machines, evaporate and deposit thin layers of metal on solar cells, and modify surface layers of metals.

6.7. Steam Production From Heat Pumps and CSP

Steam is needed for many low and some medium-temperature processes in a 100 percent WWS world. Such steam is currently obtained as a co-product of burning fossil fuels or biomass for electricity production. These sources will be replaced by steam from an electric heat pump or steam co-generated with electricity at a CSP plant. A heat pump can produce heat up to 160 degrees Celsius[102]. This heat can be used to boil water to produce steam of a similar temperature.

Parabolic trough CSP plants produce temperatures of 60 to 350 degrees Celsius. Parabolic dish CSP plants produce temperatures of 100 to 500 degrees Celsius. Central tower receiver CSP plants produce temperatures of up to 600 degrees Celsius[103]. The heat in all cases, if not used to produce electricity, can be used to produce steam directly. However, a manufacturing plant that uses such steam needs to be nearby, otherwise, heat losses from pipes transporting the steam long distance will be significant.

6.8. Steel Manufacturing

Steel manufacturing is a significant user of energy and source of air pollution and carbon dioxide. 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 gas and heat. The carbon monoxide 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 is 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 pre-shaped 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[104]. Of this, ironmaking produces about 70 to 80 percent of the carbon dioxide emissions.

6.8.1. Reducing Carbon Emissions with Hydrogen Direct Reduction
An alternative to extracting molten iron from iron oxide with coke during ironmaking is to extract the pure iron with hydrogen gas (H_2), where the hydrogen is produced with 100 percent WWS[104]. This process is called the **hydrogen**

direct reduction process. The main extraction reaction involves mixing iron oxide 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[104]. The reaction eliminates chemical carbon dioxide produced from the purification of iron oxide 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 provided with 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 (1870 kilograms of carbon dioxide per tonne of steel) [104]. 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.

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 WWS sources, thus the hydrogen was **green hydrogen**. The plant subsequently produced nearly-carbon-free steel commercially from the purified iron in July 2021.

6.8.2. Reducing Carbon Emissions with Molten Oxide Electrolysis

A second alternative method for extracting molten iron from iron ore during ironmaking is with **molten oxide electrolysis**[105,106]. 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 dioxide, aluminum oxide, and magnesium oxide 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 is passed through the soup, turning magnetite into pure molten iron. The pure liquid iron 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.

6.9. Concrete Manufacturing

Concrete is a mixture of **aggregate** (sand, gravel, and crushed stone) and paste (water and **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 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, all of which contain calcium carbonate mixed with clay, shale, slate, blast furnace slag, silica sand, or iron ore. These ingredients are heated to 1,500 degrees Celsius to form a hard substance that is ground into a fine, powdery cement.

The concrete industry produces about eight percent of the world's fossil-fuel carbon dioxide emissions[107], 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[108]. 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[108]. 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 chemical reaction of calcium carbonate 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.

Four ways of reducing both process emissions and energy emissions from concrete manufacturing are to (1) use geopolymer concrete instead of concrete derived from Portland cement, (2) use a material called Ferrock instead of concrete, (3) recycle concrete, and (4) make concrete that traps carbon dioxide. In all cases, energy must be supplied by WWS to maximize carbon dioxide reductions.

6.9.1. Geopolymer Concrete
Geopolymer concrete was named and developed in the 1970s by Joseph Davidovits, 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[109]. Waste materials include fly ash, granulated blast-furnace slag, rice husk ash, or metakaolin. **Fly ash** is abundant in most countries since it 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 Portland cement[109]. Most of the carbon dioxide reduction is due to eliminating the offgassing 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 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 Portland cement. The costs of the two types of concrete are similar.

6.9.2. Ferrock

Another commercialized alternative to concrete is **Ferrock**, or iron carbonate ($FeCO_3$)[110,111]. 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 five times harder and more flexible than 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.

6.9.3. 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.

6.9.4. 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[112]. The clinker in 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 be captured upon emissions. However, capturing carbon dioxide requires equipment and electricity. 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 natural gas electricity than to capture carbon dioxide. This is because displacing a fossil fuel electricity source eliminates not only carbon dioxide from the source but also air pollution, upstream mining and emissions, and fossil-fuel infrastructure. Capturing carbon dioxide eliminates only some carbon dioxide.

6.10. Silicon Purification

Pure silicon is a common chemical in alloys and semiconductors. Alloys, including aluminum-silicon and iron-silicon alloys, are the major application 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. The silicon is extracted, and the carbon dioxide is released to the air. 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 producing pure silicon from silica exist that do not involve releasing carbon dioxide. These methods generally 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[113].

Alternatively, pure silicon can be obtained from calcium silicate instead of from silica. The calcium silicate is dissolved in a mixture of three salts; calcium chloride, magnesium chloride, and sodium chloride, at a warm temperature. In solution, the calcium silicate dissociates into pure silicon[114]. 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.

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