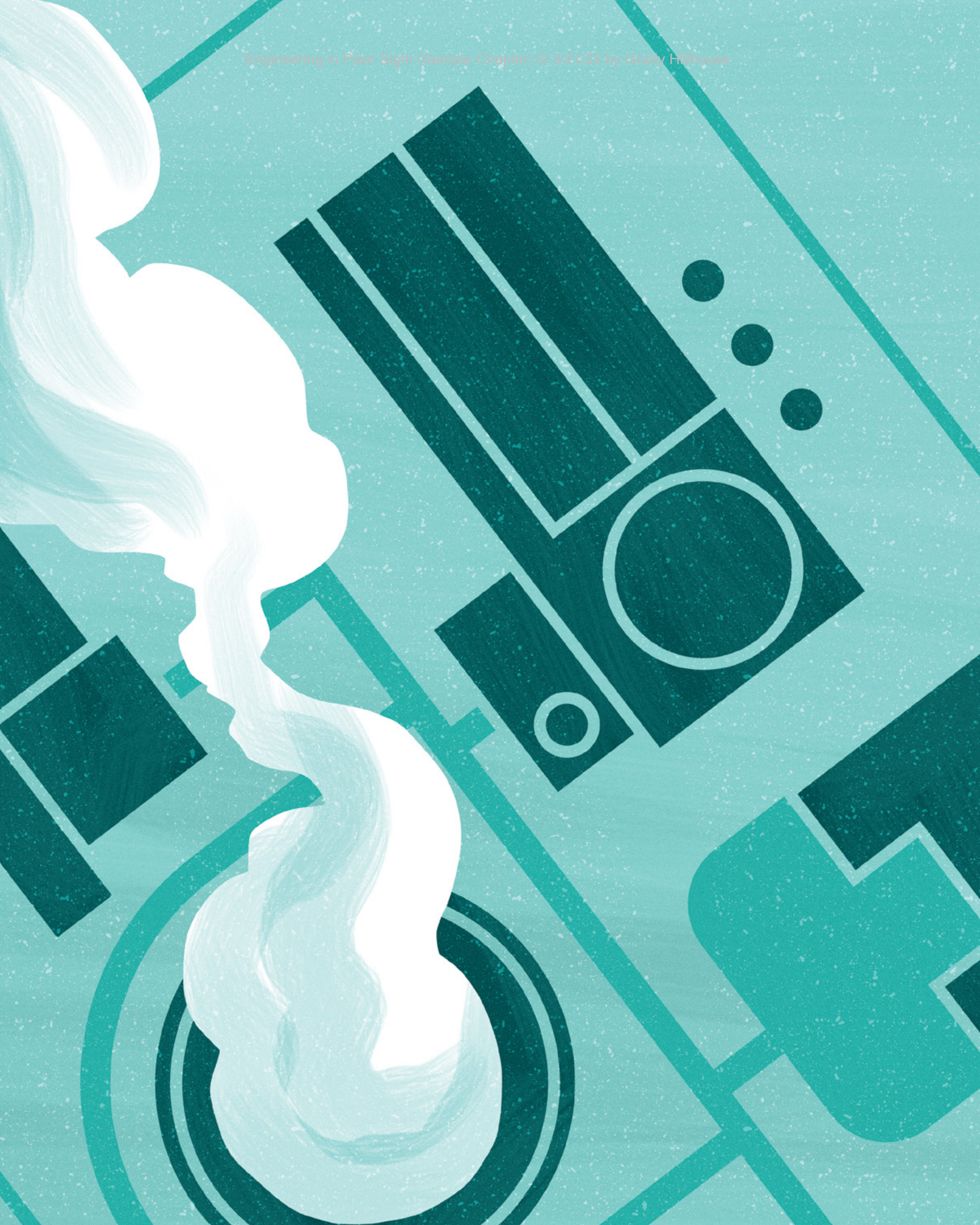


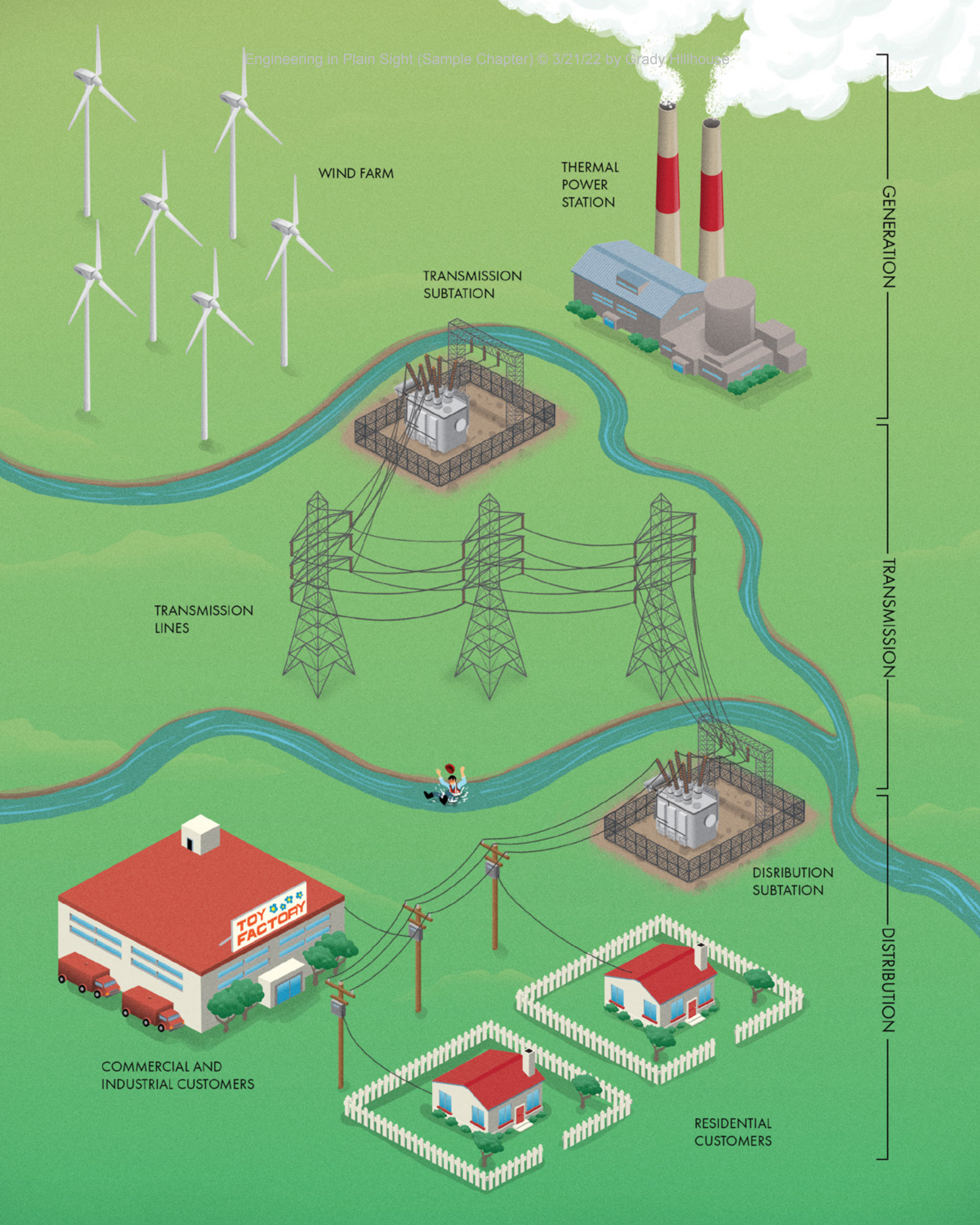
1

ELECTRICAL GRID

Introduction

Harnessing the power of electricity is one of humanity's greatest achievements. What was a luxury 100 years ago is now a critical resource for the safety, prosperity, and well-being of nearly everyone. In the not-too-distant past, manpower and horsepower were practically the only powers. Hard work was accomplished through the strength of living beings. It's no wonder we humans have sought to take control of energies beyond our own bodies. These days, "energy" gives life to almost every aspect of the contemporary world, enabling our most basic physiological needs to our most cutting-edge technologies.

Depending on how it is harnessed, stored, distributed, and used, energy can take many forms. On the earth, we can trace nearly all our energy back to the sun. Wind and waves are created by heating of the earth's atmosphere. Solar light can be harnessed directly. Even fossil fuels like gasoline got their energy from the sun. Prehistoric plants captured this solar power through photosynthesis and were buried over millions of years, only to be tapped into by wells, extracted, refined, and exploded in engines, releasing the sun's heat (along with many other foul byproducts) back to the planet again. Humans do a lot converting of energy from one form to another for convenience and practicality, but nothing compares to electricity, which makes having a personal source of power possible for nearly everyone.


WIND FARM
THERMAL
POWER
STATION
TRANSMISSION
SUBTATION
TRANSMISSION
LINES
DISRIBUTION
SUBTATION
TOY
FACTORY
COMMERCIAL AND
INDUSTRIAL CUSTOMERS
RESIDENTIAL
CUSTOMERS
GENERATION
TRANSMISSION
DISTRIBUTION

Overview of the Electrical Grid

Electricity is remarkably different from all the other types of energy. We can't hold it in our hands, and we can't see it directly. Yet, it can accomplish incredible work—from physical feats to computations—nearly instantaneously. Rather than being a tangible manifestation of energy, such as fuels, electricity takes a more transient form, requiring only a connection by metal wires for transmission. The simplicity of moving it from one place to the next has given rise to *electrical grids*, huge, interconnected networks of electricity producers and users. To get a sense of scale, only five major power grids cover all of North America, and many of the world's largest power grids encompass multiple countries.

In general, electricity makes its way through a series of discrete steps on the grid divided into three parts: GENERATION (production of power), TRANSMISSION (moving that electricity from centralized plants to populated areas), and DISTRIBUTION (delivering the electricity to every individual customer). Establishing these large interconnections solves a lot of challenges at once. Allowing a greater number of users and producers to share expensive infrastructure creates efficiency. Because power can take many different paths to each location, and individual power plants can step in if another one falls offline, reliability increases. Finally, interconnections help smooth out the flow of electricity.

Unlike other utilities, electricity is quite challenging to store on a large scale, which means power must be generated, transported, supplied, and used all in the same moment. The energy coursing through the wires of your home or office was a ray of sunshine on a solar panel, an atom of uranium, or a bit of coal or natural gas in a steam boiler only milliseconds ago. The electricity a single household uses can be quite sporadic. The more users that can be connected together, the more everyone's spikes and swings in usage average out.

Making a gigantic, one-size-fits-all electrical grid work for every type of power user and producer is no simple feat. You can imagine the power grid as a freight train going up a hill, with generation representing the locomotives and freight representing electrical demands. All the engines must move in perfect synchrony to share the load. If one is slower or faster than the rest, it runs the risk of breaking the whole train. To make it even more challenging, the demands on the grid are continually changing over time like valleys and hills in the landscape. Power consumers turn on and off electrical devices at will, with no notification to the utilities. Demands peak during the day when people are using lots of electricity, particularly on scorching or freezing days when many are using air conditioners or heaters. To avoid *brownouts* and *blackouts*, generation must be continuously adjusted up or down to match electrical demands on the grid. This process is called *load following*, just like a locomotive adjusts its throttle to account for changes in grade along the way.

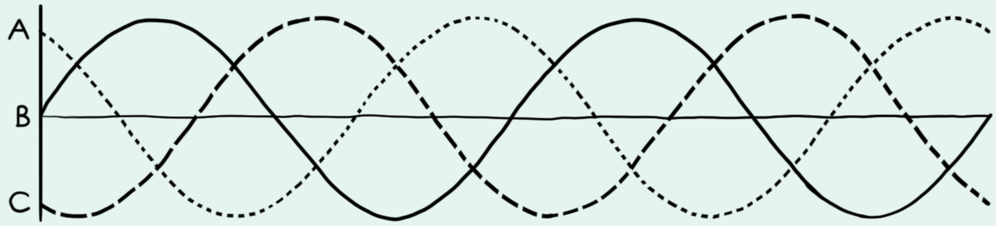
Electricity customers use power in different ways. COMMERCIAL AND INDUSTRIAL CUSTOMERS adjust their usage based on the fluctuating price of electricity, often running machines overnight to take advantage of the cheaper energy. RESIDENTIAL CUSTOMERS (who normally pay a fixed price) can be less attentive to the ebbs and swings of total grid demands, using electricity whenever it is most convenient.

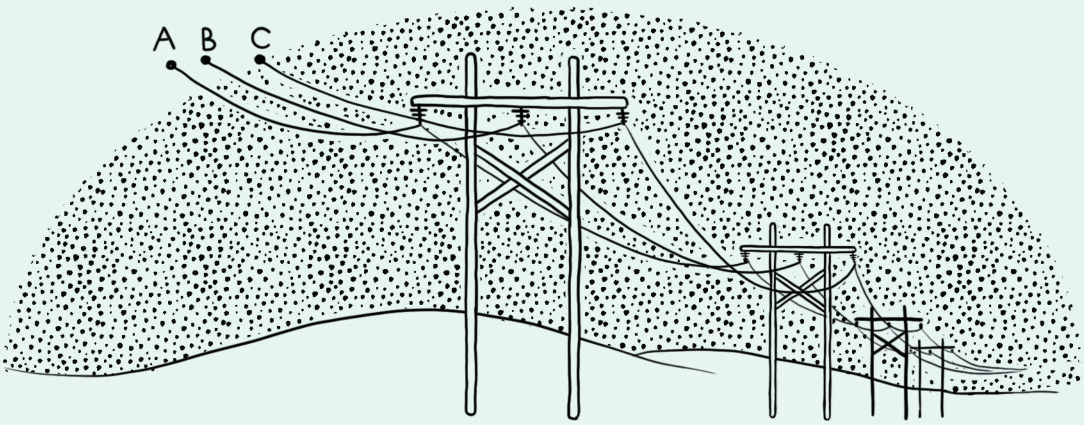
Similarly, different types of power plants are able to generate electricity in different ways. Solar farms generate lots of electricity when the sun is up, but none when the sun is down. WIND FARMS generate electricity depending on weather, with peak output during times when winds are strong and consistent. Nuclear plants generate consistent power with little ability to ramp up or down, while other THERMAL POWER STATIONS like coal or natural gas plants can adjust their output somewhat according to changing demands. Hydropower plants are the most responsive, often with the ability to start and stop generation within seconds or minutes.

Grid managers perform detailed forecasts of both generation and demand to make sure they can maintain balance between supply and demand. They have to consider when to schedule outages of power plants and TRANSMISSION LINES for maintenance and quickly adjust when facilities trip offline without notice due to damage or other issues. They hope for the best but plan for the worst, taking into account the abilities and limitations of the entire portfolio of power producers and users. If the worst comes, and there is not enough electricity to meet demands, grid managers will require that some customers be temporarily disconnected (called *load shedding*) to reduce demands and avoid a total collapse. Normally these disconnections happen on a rolling basis of 15 to 30 minutes to spread out the inconvenience of lost service, so they are often known as *rolling outages*.

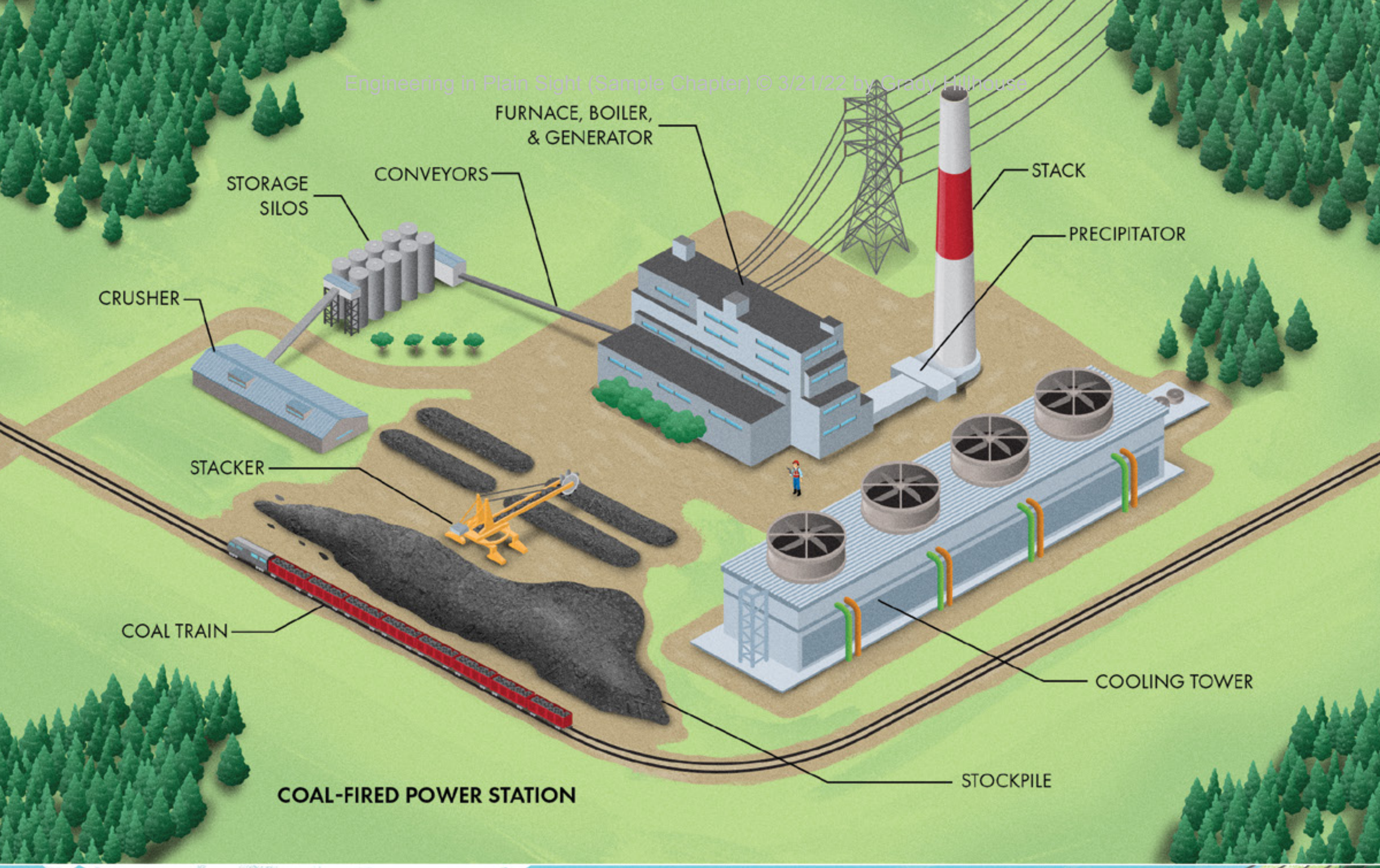
Many types of equipment are needed to generate, transmit, and deliver electricity over large areas. Remarkably, most of this infrastructure is out in the open for anyone to have a look. Many times, I've been accused of having my head in the clouds when I was just observing something at the top of a utility pole. You can examine and identify nearly every major piece of the electrical grid no matter where you are. The rest of this chapter provides a closer look at each part of the grid and more detail about the equipment and processes needed to keep the flow of electricity moving.

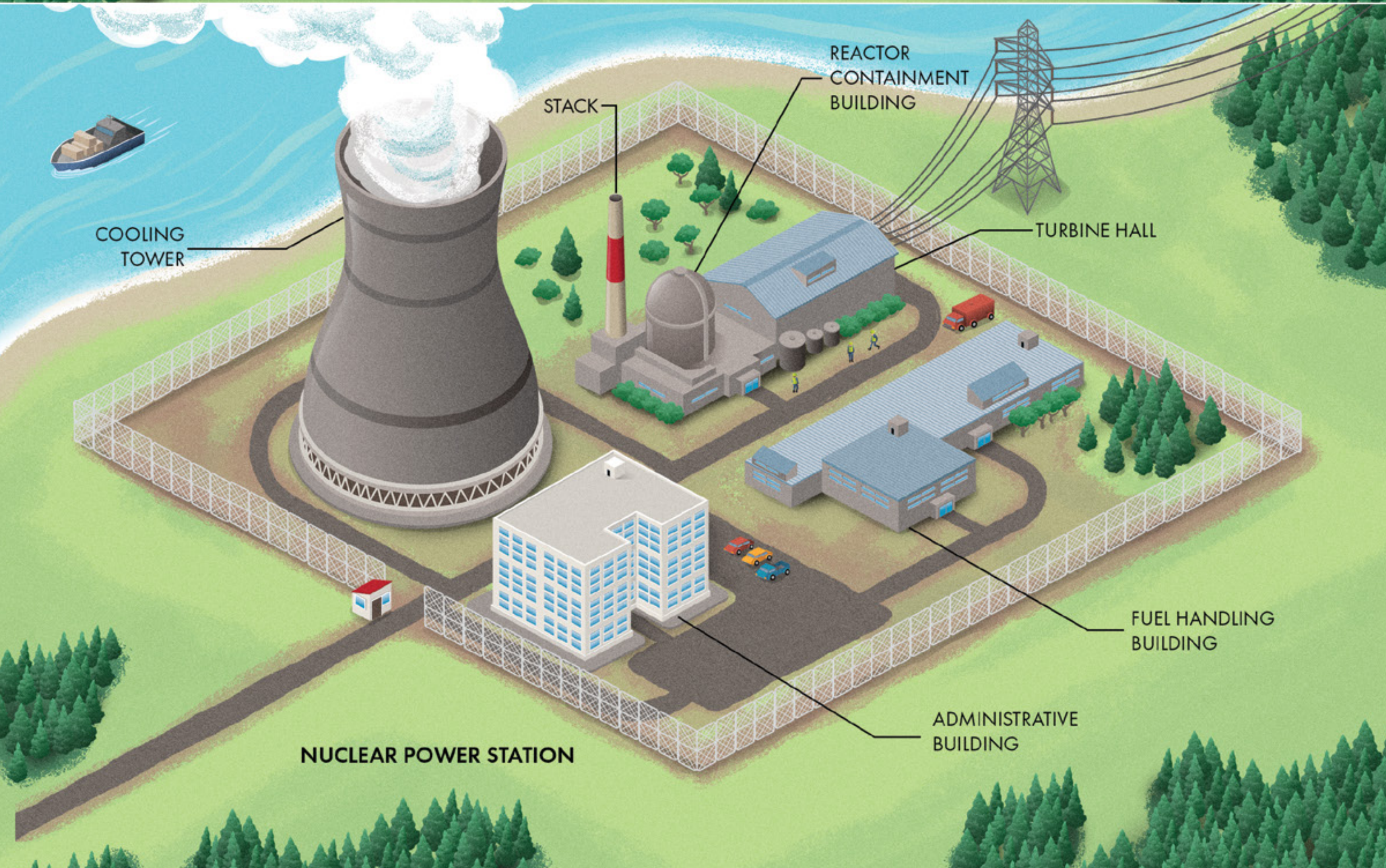
KEEP AN EYE OUT





Rather than a constant flow of current in a single direction (called *direct current* or *DC*), the vast majority of the power grid uses *alternating current* or *AC*, where the direction of voltage and current are continually switching. The benefit of having the current alternate is that its voltage can easily be stepped up or down using a transformer. In North America, this happens at 60 cycles per second, giving electrical infrastructure that familiar low hum. Power is usually generated and transmitted on three individual lines called *phases*, each of which has voltage offset from its neighbors. Creating electricity in three distinct phases provides a smooth supply that overlaps, so there is never a moment when all phases have zero voltage. A three-phase supply also uses fewer equivalent conductors than a single-phase supply to carry the same amount of power, making it more economical. You'll notice that almost all electrical infrastructure shows up in groups of three, with each conductor or piece of equipment handling an individual phase of the supply.


FURNACE, BOILER, & GENERATOR
STORAGE SILOS
CONVEYORS
STACK
PRECIPITATOR
CRUSHER
STACKER
COAL TRAIN
COOLING TOWER
STOCKPILE
COAL-FIRED POWER STATION


REACTOR CONTAINMENT BUILDING
STACK
COOLING TOWER
TURBINE HALL
FUEL HANDLING BUILDING
ADMINISTRATIVE BUILDING
NUCLEAR POWER STATION

Thermal Power Stations

Generation is the first step electricity takes on its journey through the power grid, a trip that may be hundreds or thousands of miles, but that happens almost instantly. Although most of us do not have a power plant in our backyard, we do have an immediate link to each one connected to the grid. There are many types of power plants, each with distinct advantages and disadvantages, but they all have one thing in common: they take some kind of energy that can be harvested from the natural environment and convert it into electrical energy for use on the grid. Many of the methods we use to generate power are just different ways of boiling water. Power stations that use this method are called *thermal power stations* because they rely on heat to create steam. The steam passes through a turbine, which is coupled to an AC GENERATOR connected to the power grid. The speed of the turbine must be carefully synchronized to the frequency of the rest of the grid.

Most power plants are sophisticated industrial facilities closed to visitors. In fact, be careful not to lurk suspiciously nearby because many plants are heavily guarded! However, you can still spot them regularly from highways or airplane windows by keeping an eye out for large congregations of high-voltage transmission lines and the recognizable tall stacks. Pay special attention to lakes outside large cities as well, because they sometimes serve as a source of cooling water for power plants. A detailed explanation of how thermal power plants work is beyond the scope of this book, but there is a lot of satisfaction in seeing and understanding the parts and pieces that you can observe from the outside.

A large amount of our electricity starts as fossil fuels (mainly coal or natural gas). COAL-FIRED POWER STATIONS are becoming less common as other fuels grow less expensive and, more important, are less polluting. However, coal still makes up a large proportion of overall electricity generation. You'll know immediately if you've spotted a coal power station, because most of the visible infrastructure will be related to handling the coal itself. These plants process and burn thousands of tons of fuel every day, so they need lots of equipment to offload, store, crush, and transport the coal to the FURNACE and BOILER.

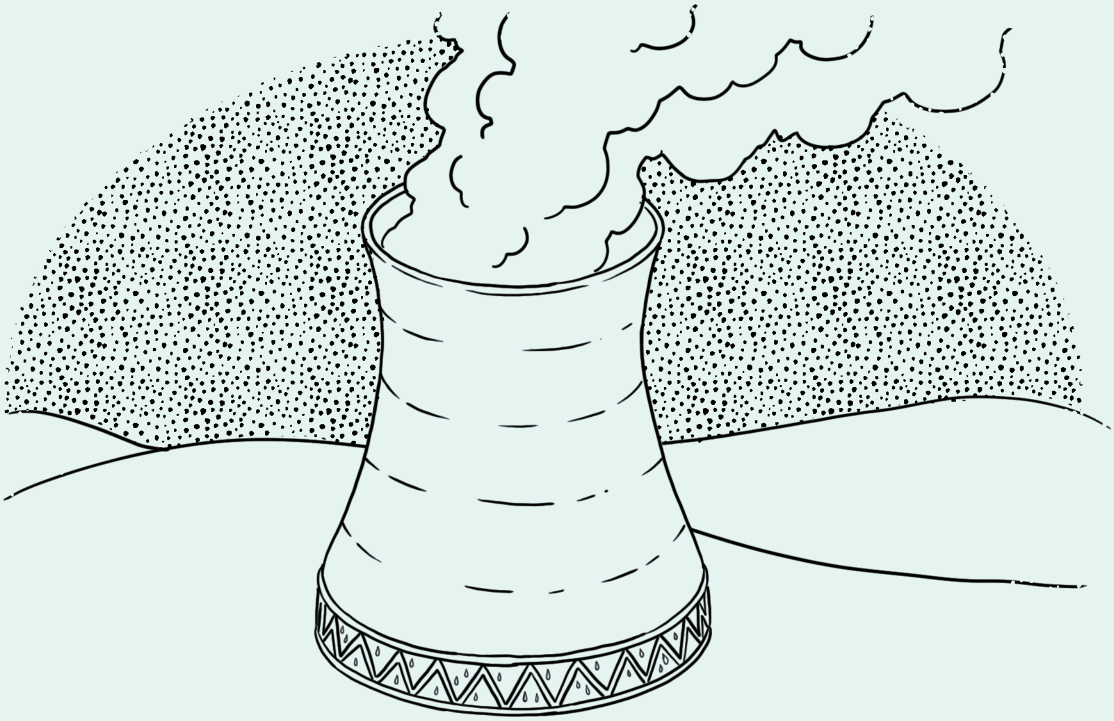
Unless the plant is situated next door to a coal mine, the primary way move this much fuel efficiently is by FREIGHT TRAIN. Complex systems of railways often surround these plants to allow for frequent and efficient delivery of fuel. Trucks and barges are sometimes used to deliver fuel when railways aren't feasible. COAL STACKERS are massive moveable conveyor belts for bulk handling of the fuel. They travel on tracks and use their booms to organize and create STOCKPILES of coal. Plants normally maintain several weeks' worth of fuel to make sure they can continue to operate if the supply is temporarily disrupted.

Unlike a charcoal grill in your backyard, most power plant furnaces burn a constant stream of fine coal powder. Coal is delivered in large chunks, so from the stockpiles, it must go into a CRUSHER to reduce its size for more efficient burning. Between each step of the fuel handling, large covered CONVEYOR BELTS transport the coal. STORAGE SILOS provide protection from the elements to the crushed coal. From there, it makes its final journey to the furnace and boiler.

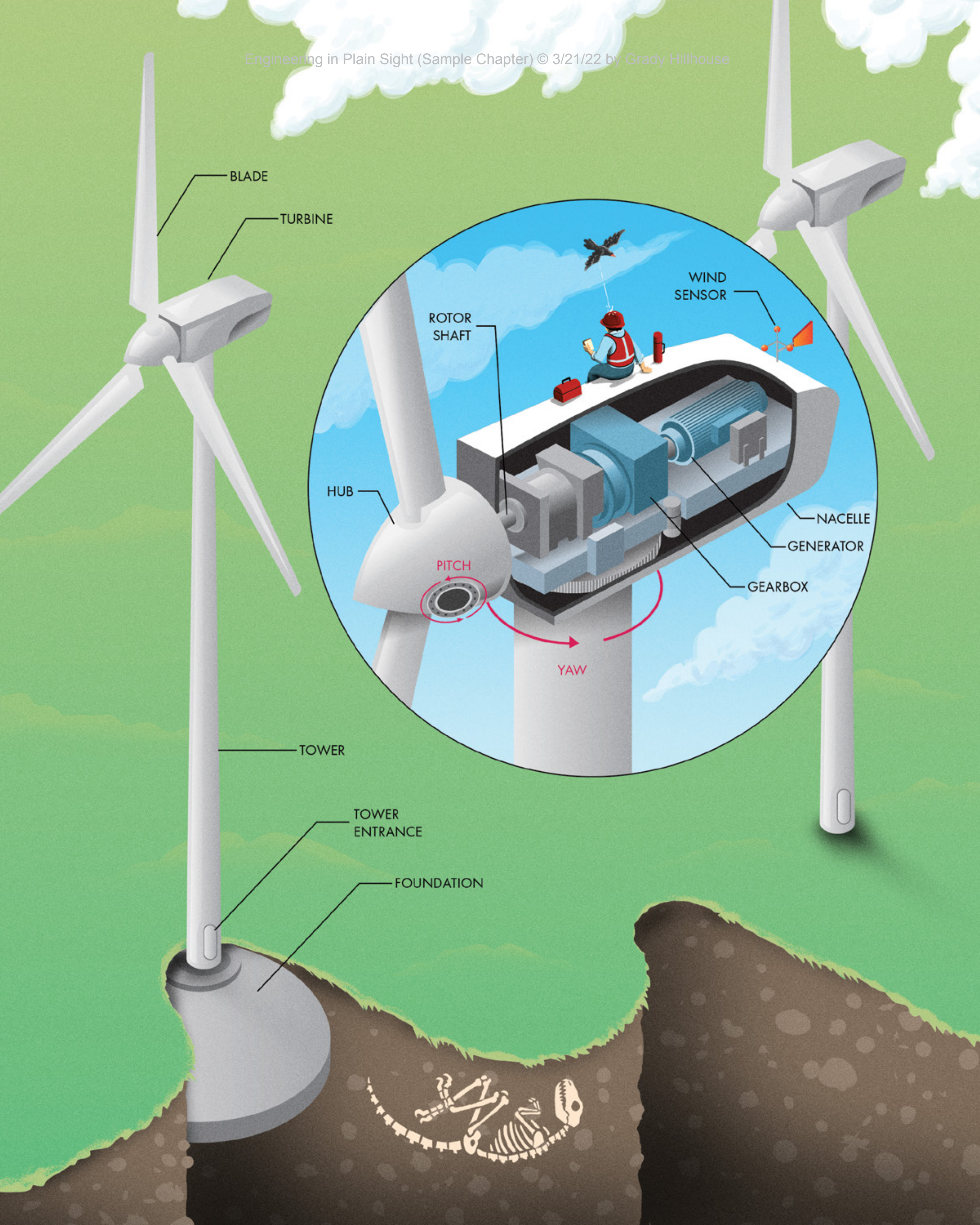
Natural gas-fired power stations (not shown here) can be identified by a lack of this coal-handling equipment. Gas pipelines that feed these plants are usually underground, hidden from view, which means gas plants usually appear much simpler and smaller from the outside. For both coal- and gas-fired plants, the air from the combustion of fossil fuels is called *flue gas*, and it can carry dangerous pollutants like ash and nitrous oxides. Environmental regulations require that flue gas be rid of the worst of these pollutants before it's released into the atmosphere since they can be harmful to humans and other animals. Many different facilities are used to clean flue gas: *baghouses* use fabric filters, electrostatic PRECIPITATORS capture particles through static cling, and *scrubbers* clean the air by spraying a fine mist that catches dust and ash. After passing through these facilities, the flue gas can be released through a STACK. Although these tall chimneys don't clean the flue gas directly, they do help manage pollution by releasing it high enough to be dispersed in the air (since dilution is the sometimes the solution to pollution).

One type of thermal plant does not rely on combustion of fuel. Instead, NUCLEAR POWER STATIONS rely on the carefully controlled *fission* of radioactive materials. This process happens in a nuclear REACTOR, often evident from the outside as a pressurized CONTAINMENT BUILDING with a domed roof. The reactor building usually has an outside armoring layer of thick concrete as a precaution against natural disasters or sabotage. A separate FUEL HANDLING BUILDING is generally used for receiving, inspection, and storage of nuclear fuel. Offices and controls are often located in an ADMINISTRATIVE BUILDING, away from the fuel and equipment. Nuclear plants sometimes also have a STACK, but it is not for releasing flue gas. In some reactors, the water used to drive the TURBINE comes into direct contact with radioactive fuel, which can create gases like hydrogen and oxygen that become mildly radioactive themselves. The tall, solitary stack seen at some nuclear plants allows for safe ventilation of those gases.

KEEP AN EYE OUT



The iconic symbol of a nuclear plant is the COOLING TOWER emitting unidentified plumes of gas. In reality, this gas is just water vapor. Nearly all thermal power stations use cooling towers. A separate stream of water is needed to condense the steam after it has passed through the turbine. After this water has absorbed so much heat, it can't be immediately released back into the environment because hot water is harmful to aquatic wildlife. Special structures are used to cool the water before it can be discharged or reused. The familiar wide concrete chimneys are open around the bottom to use natural drafts for cooling. Shorter, boxier units use fans. In both cases, you may be able to see the spray of water raining down along the bottom of the tower to help with evaporation.


BLADE
TURBINE
WIND SENSOR
ROTOR SHAFT
HUB
NACELLE
GENERATOR
PITCH
GEARBOX
YAW
TOWER
TOWER ENTRANCE
FOUNDATION

Wind Farms

Wind farms consist of multiple turbines that capture wind energy and convert it into electricity. In a way, they harvest solar energy, because wind currents are driven by the heating and cooling of the atmosphere by the sun. Since we can't choose when the wind will blow, wind farms are less reliable than thermal power plants. Grid operators in areas with lots of wind turbines must rely on weather forecasts not only to predict electrical usage, but also to predict electricity production. However, unlike coal, natural gas, and uranium, wind is free and it's going to blow whether we have turbines to harvest its power or not. Taking advantage of such a resource only makes sense, and modern wind farms offer a relatively low-cost and low-pollution alternative to traditional power stations.

Wind turbines come in a wide variety of shapes and sizes, but modern variants around the world have converged to a consistent, instantly recognizable style. This design features a horizontal axis TURBINE atop a tall steel TOWER with three slender composite BLADES, all usually colored in pure white for visibility. If you didn't know better, you might assume they were modern art pieces dotting the landscape, somehow appearing both sleek and ungainly at once. Towers are usually attached to a massive concrete FOUNDATION buried below the ground and are almost always hollow with an ENTRANCE at the bottom for maintenance workers and a ladder up to the turbine. The foundation is designed to prevent the tower from toppling, even under the most extreme wind conditions.

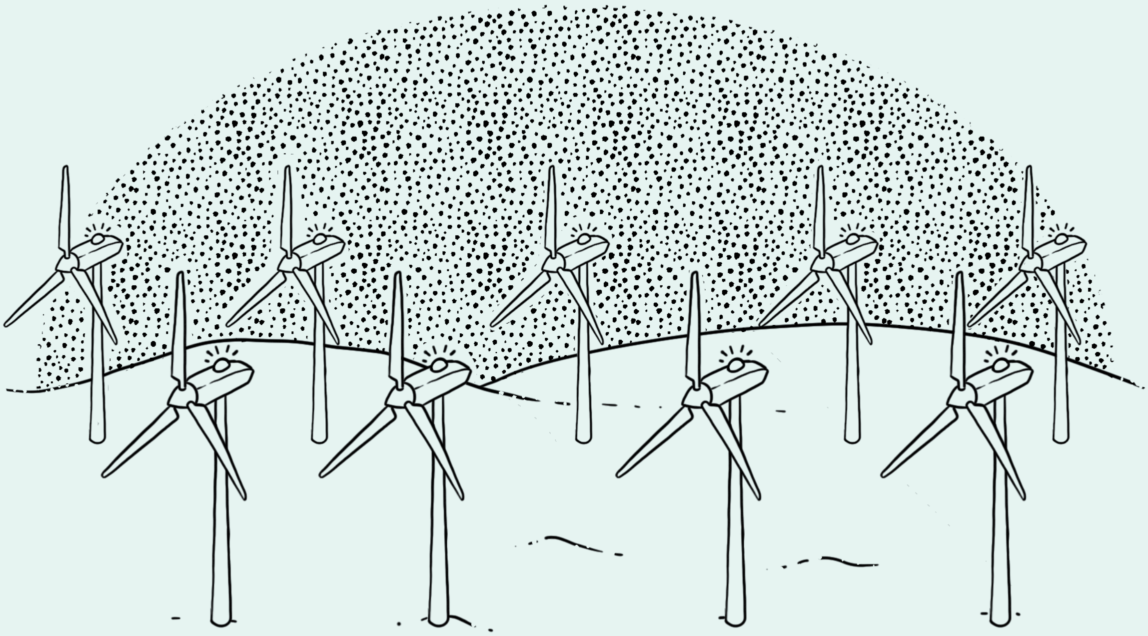
Utility-scale turbines are usually rated around 1–2 megawatt each, but units as large as 10 megawatts have been installed. That's enough to power about 5,000 households with a single turbine! From the outside, you can see the HUB with attached blades and the NACELLE, the outer housing for the rest of the turbine's equipment. Inside the nacelle are the ROTOR SHAFT, GEARBOX, GENERATOR, and other equipment.

Every aspect of a turbine is intended to capture as much of the energy from the wind as possible. An important part of a turbine's efficiency is how fast the blades rotate. If they go too slowly, wind will pass through the gaps in the blades without providing any power. If they spin too quickly, the blades will act as a block to wind, reducing the amount of power that can be harvested. I remember taking a tour of a wind farm as a kid and trying to race the shadow of the blades on the ground. I would move toward the hub's shadow little by little until I could keep up with the rate of rotation. It turns out that a turbine is most efficient when the tip of the blades is moving around four to seven times the speed of the wind. Since larger turbines have longer blades, they rotate slower to keep the tip speed near this ideal range. Even though these blades seemed quite fast to me as a child, electrical generators need to spin much faster to operate efficiently and keep up with the alternating frequency of the grid. Most turbines use a gearbox to convert the slow pace of the blades to a speed more suitable for the generator.

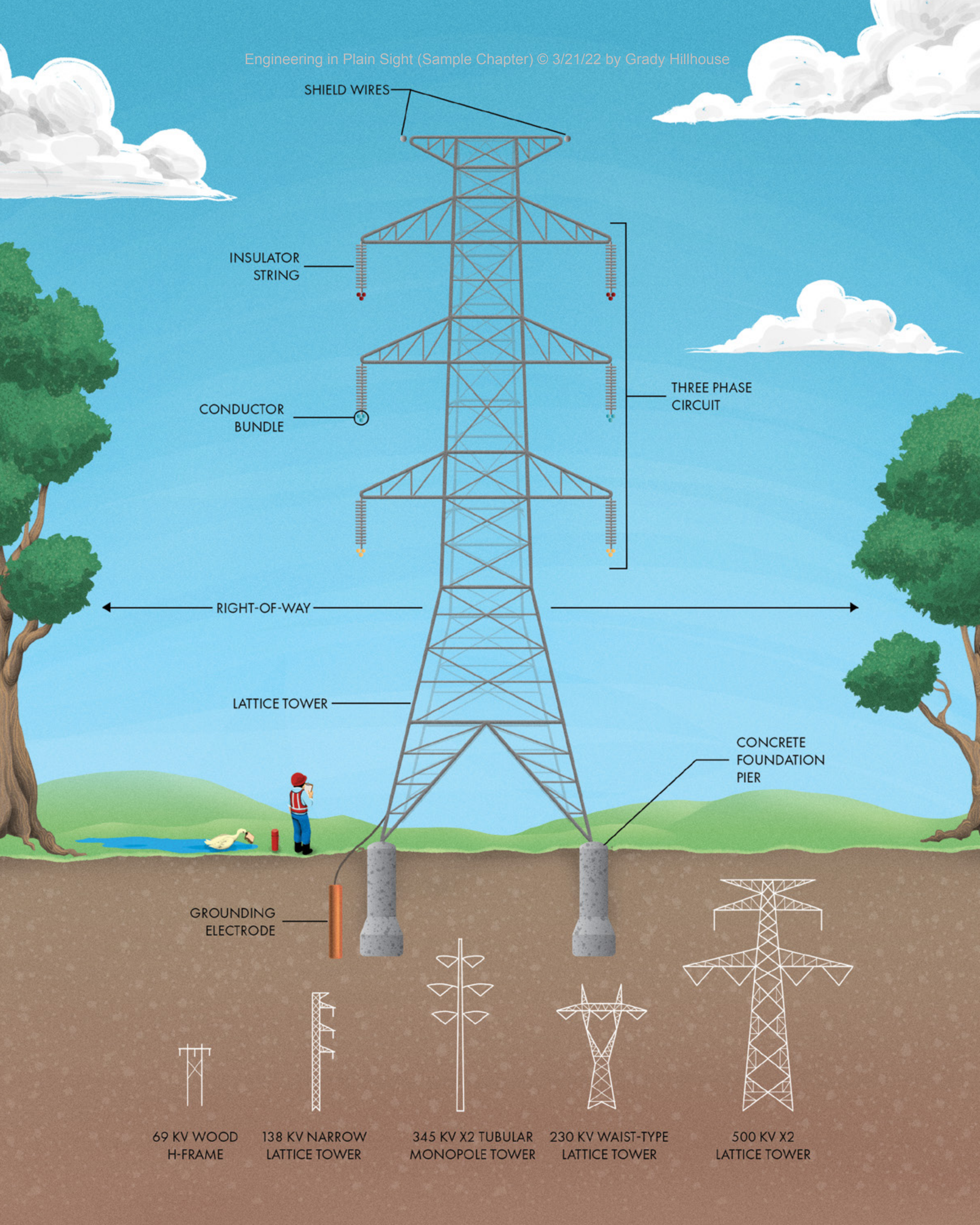
Turbines operate at their best when facing directly into the wind. Older windmills used a large tail to keep this proper orientation, called YAW. Modern turbines use a WIND SENSOR atop the nacelle to measure both the speed and direction of the wind. If the wind vane senses a change in direction, it directs motors to adjust the yaw of the turbine back into the wind. Most turbines also include a way to adjust the angle, or PITCH, of each blade. When the wind is too fast for the turbine to operate efficiently, the blades are furled (that is, tilted so only the edge of the blade faces into the wind) to reduce the forces on the turbine. You may wonder why, during a very windy day or a storm, all the turbines in a wind farm have stopped turning. In extreme winds or emergencies, operators apply a mechanical brake to stop the rotation and prevent damage to the turbine.

Another aspect of a wind turbine's efficiency is the narrow shape of the blades. You might think that a wider the blade would allow more wind energy to be harvested, but consider this: if 100 percent of the power could be extracted from the wind, the air would have no velocity left to exit behind the blades. This would cause air to "pile up" and block any new wind from driving the turbine. Some wind movement is required to keep fresh air supplying the turbine, which means it's never possible to harvest all the energy from the wind. The theoretical maximum efficiency that can be extracted (called the *Betz limit*) is about 60 percent. The slender blades of the turbine are carefully designed to capture as much energy as possible without slowing the air stream too much.

KEEP AN EYE OUT



If you drive past or fly over a wind farm at night, you'll notice the red lights on top of the towers. Like on all tall towers and buildings, these lights are a warning to aircraft to help avoid collisions. On most wind farms, all these warning lights flash in perfect synchrony to help aircraft pilots judge the shape and extent of the entire wind farm. If all the lights blinked randomly, it would be too disorienting. Maintaining this synchronicity between all the turbines in a wind farm is a totally separate challenge. You might think that all the lights would need to be wired together, but the complexity of such a system would be unreliable and costly. Instead, each light is outfitted with a GPS receiver that gets a highly accurate clock signal from satellites overhead. If each light has its clock synchronized, the flashes will be synchronized as well.


SHIELD WIRES
INSULATOR STRING
CONDUCTOR BUNDLE
THREE PHASE CIRCUIT
RIGHT-OF-WAY
LATTICE TOWER
CONCRETE FOUNDATION PIER
GROUNDING ELECTRODE
69 KV WOOD H-FRAME
138 KV NARROW LATTICE TOWER
345 KV X2 TUBULAR MONOPOLE TOWER
230 KV WAIST-TYPE LATTICE TOWER
500 KV X2 LATTICE TOWER

Transmission Towers

Power plants are almost always located far away from populated regions. The land is cheaper in rural areas, and most people don't like to live near huge industrial facilities. It just makes sense to keep some distance between our power plants and cities. However, creating all the electricity far from where it's needed presents a transportation challenge. You can't load electricity onto trucks and deliver it to customers. Instead, it travels instantaneously from producers to users on wires we call transmission lines. You may be familiar enough with this concept if you've ever used extension cords to bring power to lights or devices that can't reach an electrical outlet. Scaling up this operation for the bulk transmission of electricity from power plants, however, creates some interesting challenges.

Wires used for the transmission of electricity are called CONDUCTORS, and no conductor is perfect. You can put electricity in on one side, but you never get 100 percent of it out at the end. That's because all conductors have some *resistance* to the flow of electricity. This resistance converts some of the electricity to heat, wasting its power along the way. Generating electricity is a costly and complex process, so if we're going to go to all that trouble, we want to make sure that as much of it as possible actually reaches the customers for whom it's intended. Luckily, there's a trick to reducing the amount of energy that gets wasted from the resistance of transmission lines, but it requires understanding a little bit about electrical circuits.

Electricity flowing in a circuit has two important properties: *voltage* is the amount of electric potential (somewhat equivalent to the pressure of a fluid in a pipe), and *current* is the flow rate of electric charge (like the flow rate of a fluid in a pipe). These two properties are related to the total amount of power traveling through a line. The amount of wasted power from resistance is related to the current in the line, so more current means more wastage. If you increase the voltage of the electricity, you need less current to deliver the same amount of power, so that's exactly what we do. Transformers at power plants boost the voltage before sending electricity on its way over transmission lines, which reduces the current in the lines, minimizes energy wasted due to resistance of the conductors, and ensures that as much power as possible reaches the customers at the other end.

These high voltages make electrical transmission much more efficient, but they create a new set of challenges. High voltage is extremely dangerous, so conductors need to be kept far away from human activity on the ground. Running high-voltage transmission lines underground is quite expensive, so they're typically strung overhead on TOWERS (also called *pylons*) except in the most densely populated areas.

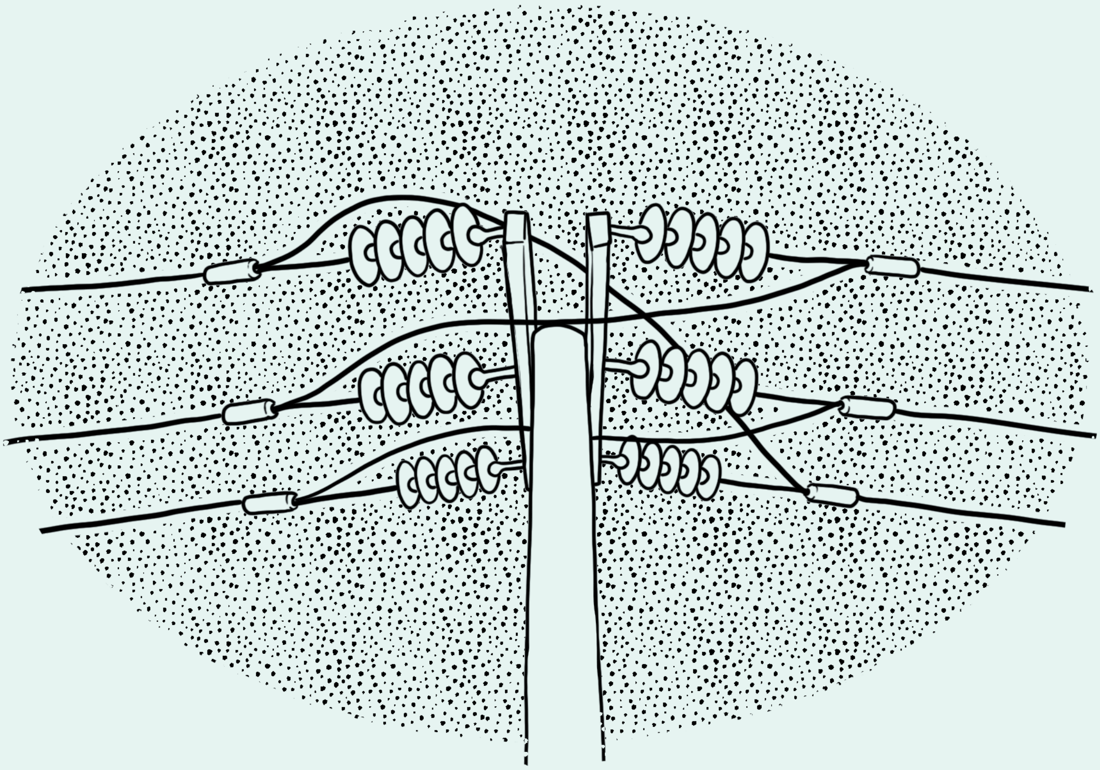
There are many factors to consider in the design of an electrical transmission line, leading to a massive variety of shapes, sizes, and materials used for these towers. One of the most fundamental of those is the voltage of the line. The higher the voltage, the more distance required between each PHASE and above the ground. Many transmission lines carry multiple CIRCUITS to save cost, so instead of three phases, you may see six or even nine. The illustration shows only a few examples of the unique shapes and sizes of towers that can be built.

The width of the RIGHT-OF-WAY is also important. In urban areas, land is more expensive, so the available width to run transmission lines may be much smaller than for lines run across rural areas. A narrower path means arranging conductors vertically rather than horizontally, increasing the height (and cost) of the towers. Finally, there are aesthetic considerations. I find transmission towers to be interesting and beautiful. However, many people believe these towers create an imposition on the landscape, and they are sometimes considered a type of visual pollution. People generally tend to prefer the look of MONOPOLE structures compared to their LATTICE equivalents. Even though monopoles are usually more expensive, they are more common in populated areas where more people will have to look at them.

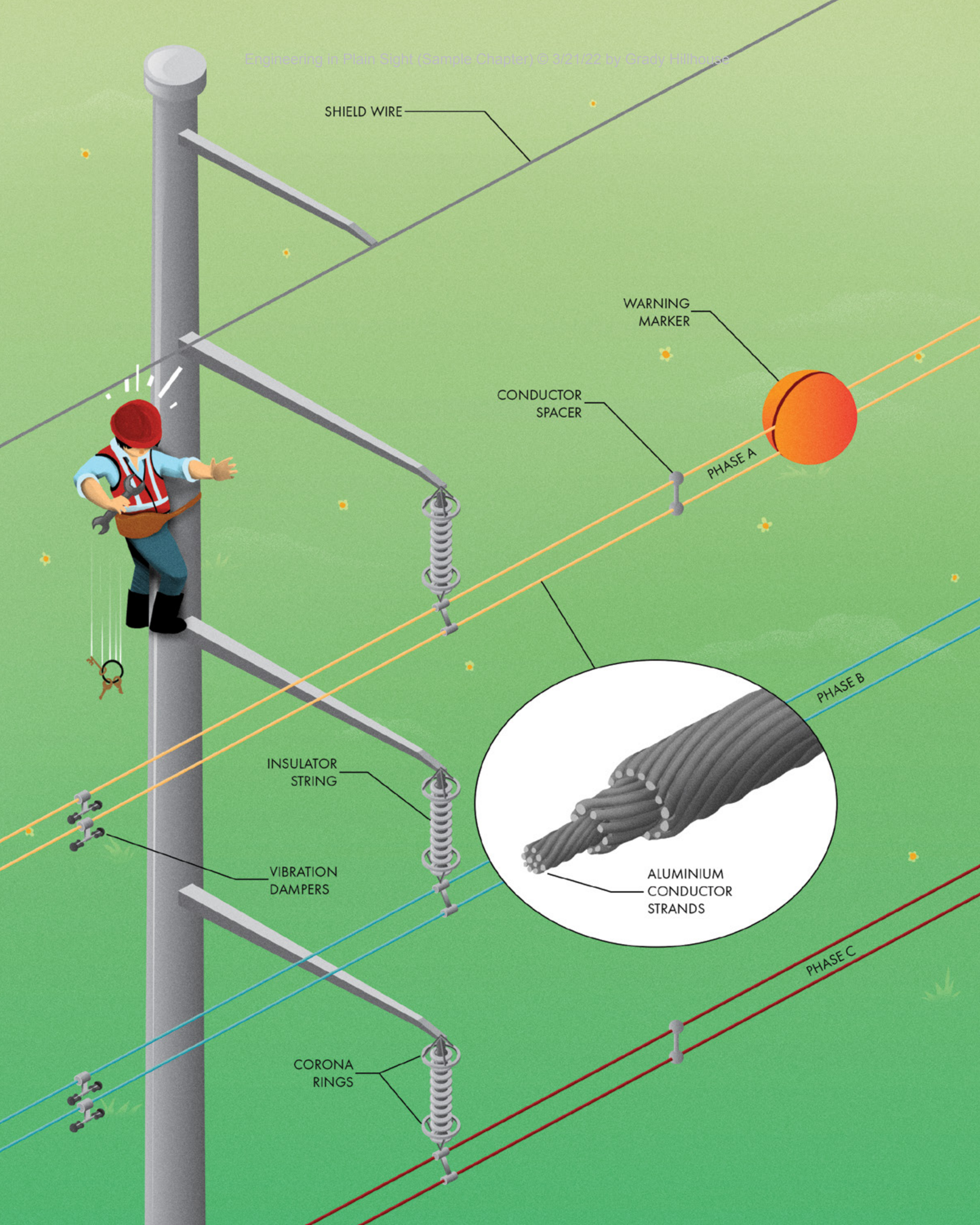
Transmission towers must resist significant loads from wind and the tension of the lines. Their foundations usually consist of drilled CONCRETE PIERS deep into the earth. Most towers are designed as suspension structures where the conductors simply hang vertically from the INSULATORS. Suspension towers can't withstand much unbalanced force from the conductors. Stronger towers, called *dead-ends*, *tangents*, or *anchors*, are placed at locations where the line changes direction, crosses a large gap like a river, or serves as a block to a cascading collapse that could occur if the conductors were to break. Differentiating between suspension and dead-end towers is simple: just look at the orientation of the insulators. On suspension towers, they'll be mostly vertical. Any other direction means unbalanced tension in the conductors, requiring a stronger tower.

Lightning represents a major vulnerability for overhead electric lines. A lightning strike can send a massive surge of high voltage down the wires, leading to arcs (also called *flashovers*) and damaged equipment. Overhead transmission lines typically include at least one non-energized line running along the tops of the pylons. These are called SHIELD WIRES and are intended to capture lightning strikes so that the main conductors are not affected. Stray voltages are harmlessly routed to ground at each pylon. If you look closely, you can often see copper conductors at the bottom of the tower, which are connected to either separate GROUNDING ELECTRODES or the steel reinforcement within the concrete foundation piers. Utilities occasionally include fiber optic cables within the core of the shield wires. They can be used for the utility's own communications or leased to another utility.

KEEP AN EYE OUT



Magnetic fields created by each high-voltage transmission line and the environment can distort the current flowing in parallel conductors. The arrangement of the phases to each other and to the ground means that the flow of electricity in each conductor will be warped in a slightly different way. To balance out the distortion between each of the three phases, long transmission lines need to be "twisted" at regular intervals along the way. Look for special towers called *transposition towers* that allow conductor phases to swap locations before continuing onward.


SHIELD WIRE
WARNING MARKER
CONDUCTOR SPACER
PHASE A
PHASE B
PHASE C
INSULATOR STRING
VIBRATION DAMPERS
CORONA RINGS
ALUMINIUM CONDUCTOR STRANDS

Transmission Line Components

Unlike a typical household extension cord, transmission lines are more than just a group of wires. Their enormous scale and high voltages create many engineering challenges to overcome. A variety of equipment and components arise from the need to make transmission lines efficient, cost-effective, and safe (both for the workers who maintain them and the public).

Of course, the most important components are the lines themselves. Conductors are almost always made from many individual STRANDS of aluminum. Aluminum is a great choice because it's lightweight, doesn't easily corrode, and offers low resistance to electrical current. But, if you've ever crushed a soda can, you know that aluminum is not particularly strong compared to other materials. Transmission conductors not only need to carry the electricity, but they must also span great distances between each pylon and withstand the forces of wind and weather. They can also become hot when moving a great deal of electrical current. This heat causes the lines to sag as the metal conductors expand. If they sag too far, conductors can come into contact with tree branches or other obstacles, creating a dangerous short circuit or even starting a fire. For these reasons, aluminum cables are often reinforced with steel or carbon fibers for extra strength.

Another difference compared to a household extension cord is that the conductors of high-voltage transmission lines are bare. They have no outer jacket of insulation. The amount of rubber or plastic that would be required to prevent electrical arcs would add too much weight and cost to the wires. Instead, most of the insulation for high-voltage lines comes from air gaps, simply maintaining large amounts of space between the energized lines and anything that might serve as a path to ground. You might see the challenge here. The conductors can't float in the air without support, but anything they touch becomes dangerously energized. If they were connected directly to the towers, it would create a severe hazard to anyone or anything on the ground (not to mention a short circuit between each phase). So, conductors are instead connected to each tower through long INSULATOR STRINGS.

The design and construction of these insulators are critical because they are the only connection between conductors and towers. Traditionally, insulators have been made from a string of ceramic discs (usually glass or porcelain). The discs lengthen the flow path of electricity leakage if the insulator gets wet or dirty, reducing how much power can escape. These discs are also somewhat standardized in size, so counting them provides an easy way to roughly guess a line's voltage: multiply the number of discs by 15 kilovolts (kV). Nonceramic insulators are becoming more popular, including those made using silicone rubber and reinforced polymers. Unfortunately, the

15 kV per disc rule of thumb doesn't apply for the newer nonceramic insulators, so you'll have to use other clues to guess the voltage of the line.

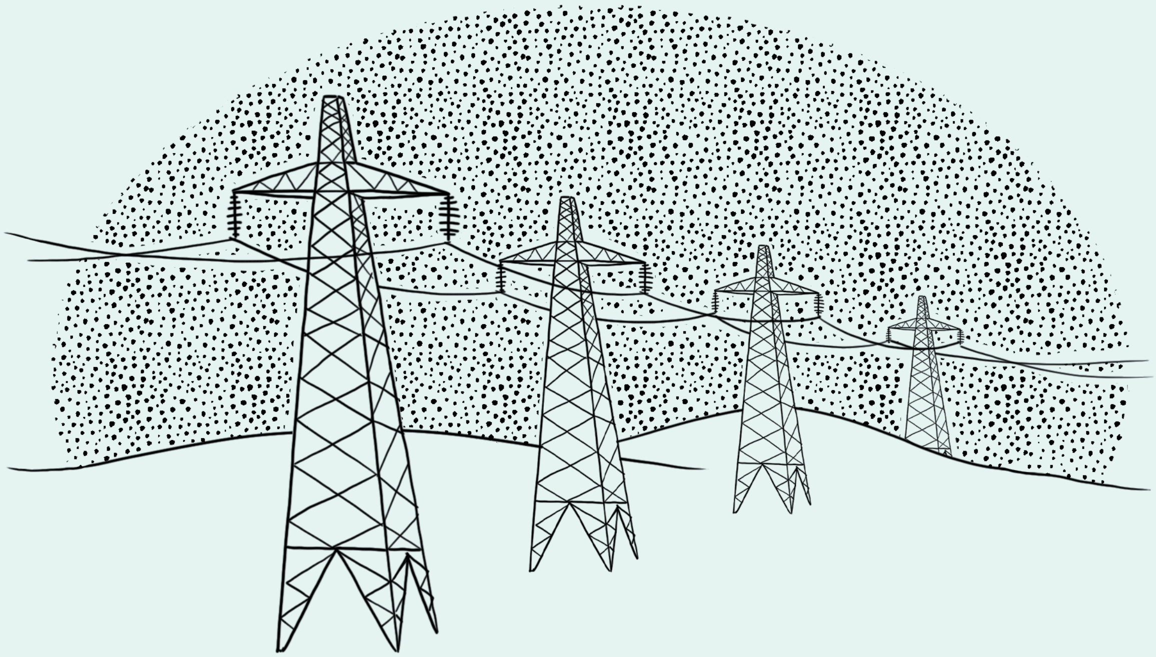
The high voltages used in transmission lines can lead to some interesting phenomena. For one, the alternating current creates a *skin effect* where most of the current travels around the surface of the conductor rather than evenly through the full area. That means increasing the diameter of a conductor doesn't always create a corresponding increase in its ability to carry electricity. Also, power on the lines can be lost to *corona discharge*, an effect created from ionization of the air surrounding the conductors. Listen closely and you can occasionally hear the corona discharge as a sizzling sound, particularly on dewy mornings, during stormy weather, or in high altitudes where atmospheric pressure is low.

Because of these two phenomena, each phase of a high-voltage transmission circuit is sometimes run as a *bundle* of smaller conductors separated by SPACERS rather than a single large one. The smaller diameter conductors are more efficient at transmitting alternating current since they have more area on the surface where the electricity prefers to travel, and the large overall diameter of the bundle reduces corona discharge. One way to estimate the voltage of a transmission line is to count the number of bundled conductors for each phase. Lines below 220 kV commonly use only one or two conductors, and lines above 500 kV often have three or more. Corona discharge is most prevalent at sharp corners and edges of metal surfaces, such as connections to the insulator strings. On transmission lines with very high voltage or in areas that receive a lot of rainfall, you may see CORONA RINGS attached to insulators. These rings distribute the electric field over a larger area, eliminating sharp corners and edges to reduce corona discharge even further.

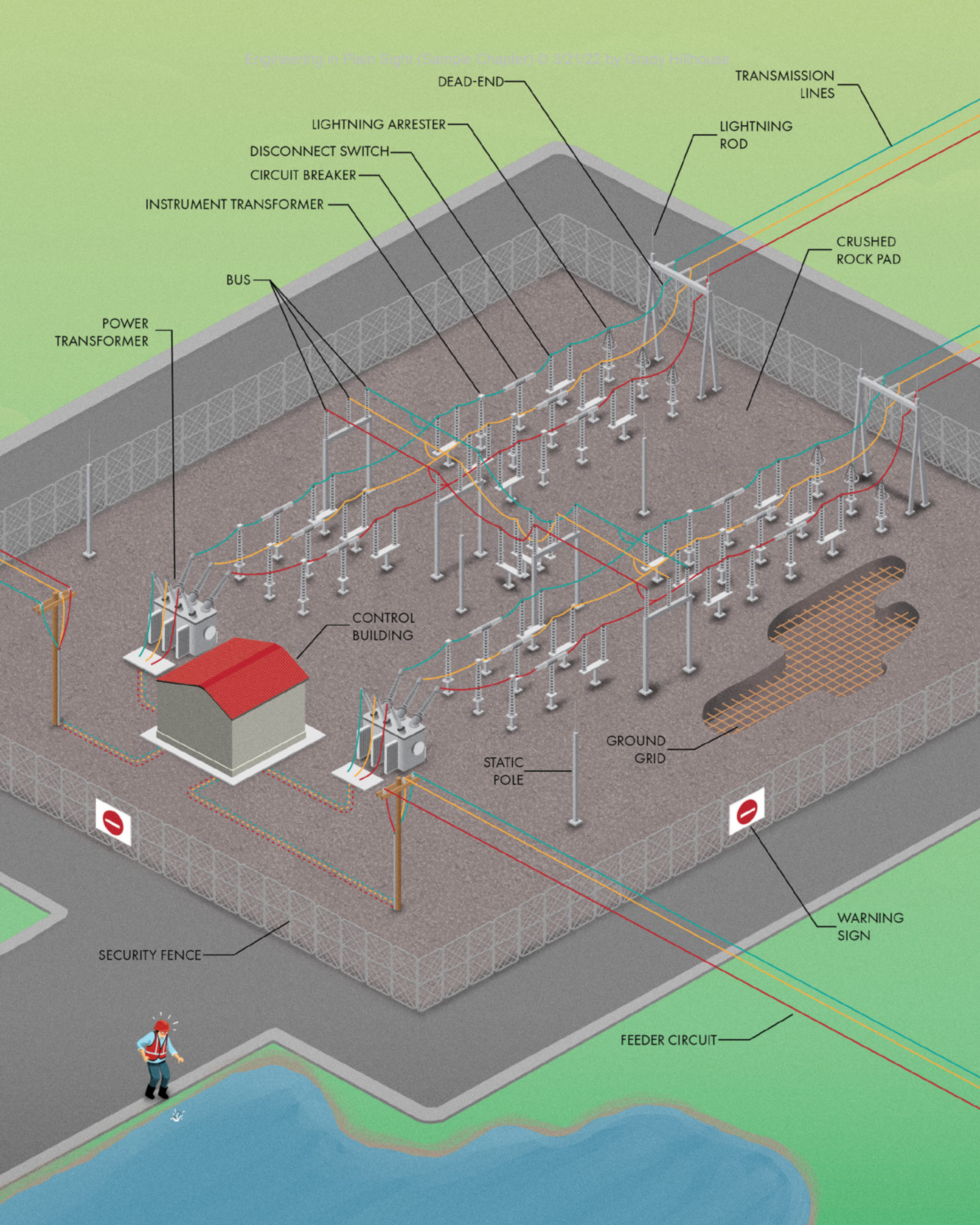
Wind can affect the conductors, causing oscillations that lead to damage or failure of the material. Over time, this vibration can fatigue the conductor material or cause abrasion at connections, reducing its lifespan. Replacing conductors is a big, expensive job, so utilities want them to last as long as possible. DAMPERS are often installed to absorb wind energy and reduce long-term damage to the wires. Spiral dampers are used for smaller conductors, and larger lines use suspension dampers, also called *Stockbridge dampers*. Not all wind is unwelcome, though. It also provides a beneficial effect by cooling off the wires. Conductors are often reinforced where they attach to insulators to give this critical element extra strength.

Finally, not all human activities occur on the ground well below these dangerous lines. Spheres called WARNING MARKERS are sometimes attached to lines to make them more visible to people who may be operating tall equipment or up in the air themselves. You'll notice them most often near airports and over waterways.

KEEP AN EYE OUT



Above a specific voltage and a certain distance, it becomes economical to use direct current instead of alternating current for electrical transmission lines. Although the equipment to convert from AC to DC and vice versa is quite expensive, *high-voltage DC (HVDC)* lines have many benefits over AC. AC power must “charge up” the line each time the current changes direction, which requires a lot of extra power. HVDC lines aren’t affected by this effect (called *capacitance*) and thus can be more efficient. HVDC lines are also used as connections between separate power grids where the alternating currents may not be synchronized. HVDC transmission lines use incredible voltages (up to 1100 kV), but they are rare, especially in North America. They are instantly recognizable because they use only two conductors—positive and negative, just like a battery—rather than the three phases of typical AC lines.


DEAD-END
TRANSMISSION LINES
LIGHTNING ARRESTER
LIGHTNING ROD
DISCONNECT SWITCH
CIRCUIT BREAKER
INSTRUMENT TRANSFORMER
CRUSHED ROCK PAD
BUS
POWER TRANSFORMER
CONTROL BUILDING
GROUND GRID
STATIC POLE
WARNING SIGN
SECURITY FENCE
FEEDER CIRCUIT

Substations

If you consider the power grid a gigantic machine, substations are the links that connect the various components together. Originally named for smaller power plants, *substation* has become a general term for a facility that can serve a wide variety of critical roles on the power grid. These roles include monitoring the grid's performance to make sure nothing is awry, changing between different voltage levels, and providing protection against faults. The most commonly seen substation around cities are *step-down* facilities that convert high-voltage transmission to a lower, safer voltage for distribution within populated areas.

At first glance (and sometimes even after a good long stare), substations are a complex assemblage of wires and equipment. When I was a kid, I thought they were playgrounds (to the delight and horror of my parents). For a power-grid greenhorn, mentally untangling these mazes of modern electrical engineering can be challenging, especially because the scaffolding and support structures look so similar to the conductors and bus work. The simplest way to identify energized lines and equipment is to look for which parts are held by insulators. Eventually, you'll be able to follow the current's path as it makes its way through. Each phase of the conductors is highlighted in the illustration to help you trace the paths of flow. (The next section describes specific pieces of equipment in a substation and their functions in further detail.)

Substations often serve as the termination points of many TRANSMISSION LINES. High-voltage lines enter the substation through a support structure called a DEAD-END that provides support and spacing. These are the only locations where very high-voltage lines drop from their safe heights down to ground level, so extra precaution is required to keep the lines contained.

The heart of a substation and the primary connection between all the various devices and equipment in a substation is the BUS, a set of three parallel conductors (one for each phase). The bus is usually made from rigid overhead tubes running along the entire substation. The substation's overall reliability depends on the arrangement of the bus because different schemes offer different amounts of redundancy. In the event of an equipment failure or regularly scheduled maintenance, utilities don't want to shut down the entire facility, so the bus is designed to reroute the power around equipment that's out of service when necessary.

Substations have a high-voltage side and a low-voltage side, separated by the POWER TRANSFORMERS (discussed in the next section). At step-down facilities, power leaves the substation as individual circuits called FEEDERS. Each feeder has its own circuit breaker, allowing smaller groups of customers to be isolated from the grid in the event of a fault. Many feeders leave the substation underground and resurface at a nearby utility pole for distribution to customers.

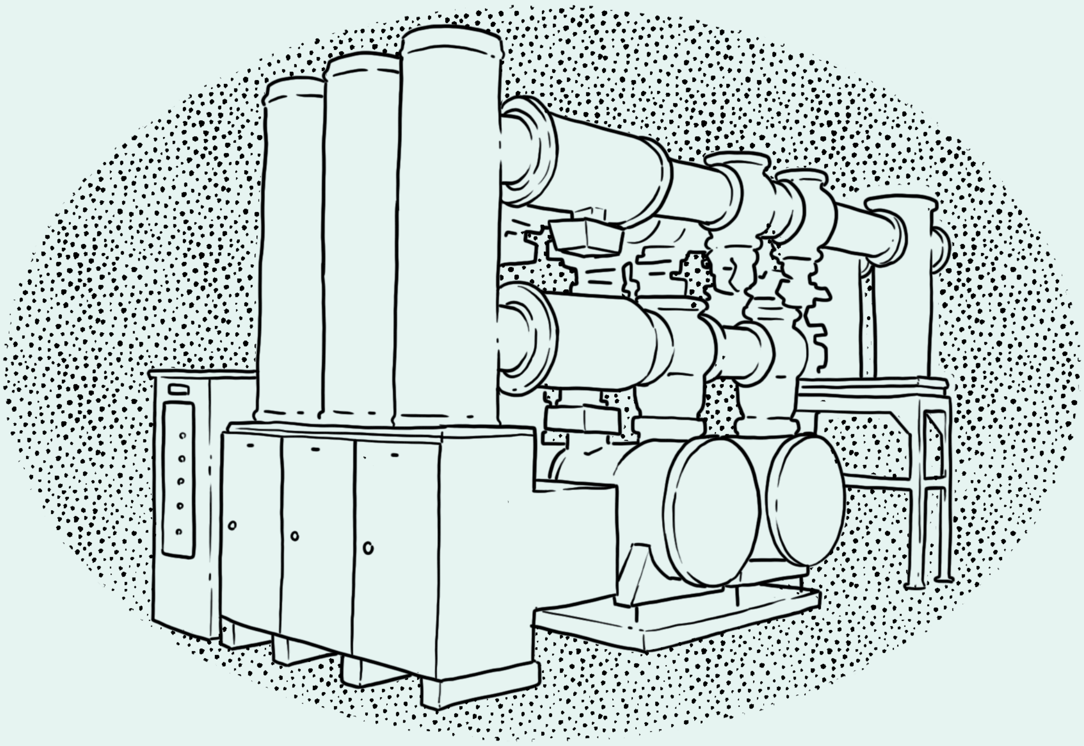
Most substation equipment is located outdoors in the open air. However, certain components are more vulnerable to weather and changes in temperature, including relays, operating equipment, and some CIRCUIT BREAKERS. These more sensitive pieces of equipment are often located within a CONTROL BUILDING at the substation. As with transmission lines, lightning poses a severe threat to substations. STATIC POLES and LIGHTNING RODS poke into the air to capture strikes and shunt them directly to ground, protecting costly equipment from surges. ARRESTERS also help deal with the damaging effects of lightning. These devices are connected to energized lines, but they don't normally conduct any current. Only if they sense a large spike in voltage, the arresters instantly become conductors, safely diverting excess electricity into the earth.

Many substation features observable from the outside are related to safety of the workers who operate and maintain the equipment. One of the most critical factors in protecting equipment and workers in a substation is ensuring that stray electricity has somewhere to go. All substations are built with a GROUNDING GRID, a series of interconnected copper wires buried below the surface. In the event of a fault or short circuit, the substation needs to be able to sink lots of current into the ground through this grid to trip the breakers as quickly as possible. This grounding grid also makes sure that the entire substation and all its equipment are kept at the same voltage level, called an *equipotential*. Electricity flows only between points of different voltage potential, so keeping everything at the same level ensures that touching any piece of equipment doesn't create a flow of electricity through a person. The cases and support structures of every piece of equipment are bonded together via the grounding grid.

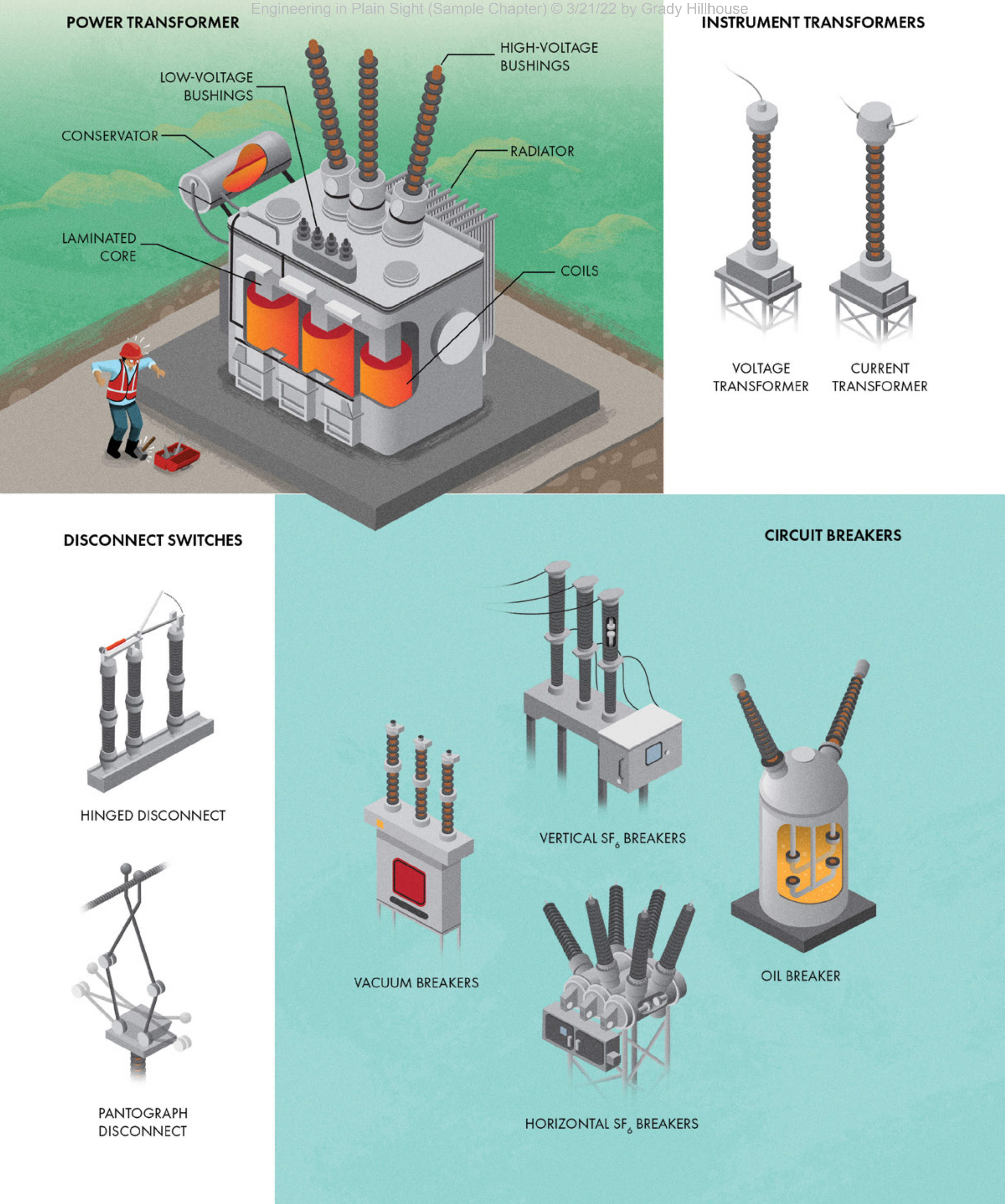
You might notice that most substations have a layer of CRUSHED ROCK as a floor. This isn't just because linesmen don't like to mow the grass! Crushed rock is freely draining and doesn't hold moisture, so it provides a layer of insulation above the soil and prevents formation of puddles from rain.

Keeping away from high-voltage facilities is common sense for most people, but as crazy as it sounds, substations are common targets for thieves wanting to steal copper wire. Substations are surrounded by FENCES and WARNING SIGNS to make sure that any wayward citizens know to stay out. If you look closely, you'll notice that even the fences have wires connecting them to the subsurface grounding grid ensuring the equipotential extends not only to workers inside the fence, but also to anyone on the outside.

KEEP AN EYE OUT



The equipment used in most outdoor substations is called *air insulated switchgear* because it uses ambient air and spacing to prevent high-voltage arcs from forming between energized components. Another type of equipment called *gas insulated switchgear* involves encapsulated equipment in metal enclosures filled with a dense gas called *sulphur hexafluoride*, which allows installation of high-voltage components in locations where space is limited. You'll have to be lucky to see a substation consisting entirely of gas insulated switchgear because they are much costlier and, thus, rare. Gas insulated switchgear is also more likely to be hidden inside a building and protected from weather, rather than exposed to the open air. You'll know you've spotted one from the characteristic tight clusters of metal piping, lots of bolted flanges, and many components in groups of three to handle each phase of power.


POWER TRANSFORMER
HIGH-VOLTAGE BUSHINGS
LOW-VOLTAGE BUSHINGS
CONSERVATOR
RADIATOR
LAMINATED CORE
COILS
INSTRUMENT TRANSFORMERS
VOLTAGE TRANSFORMER
CURRENT TRANSFORMER
DISCONNECT SWITCHES
HINGED DISCONNECT
PANTOGRAPH DISCONNECT
CIRCUIT BREAKERS
VERTICAL SF_6 BREAKERS
VACUUM BREAKERS
OIL BREAKER
HORIZONTAL SF_6 BREAKERS

Substation Equipment

Understanding the layout and flow of electricity in a substation is only half the story. Substations are made up of many different individual pieces of equipment, each of which serves an important role. The joy of substation spotting is made much greater by being able to identify those pieces of equipment and understanding how they work.

Stepping up or down voltage is one of the most important jobs at a substation, converting between the more efficient (but more dangerous) high voltage from transmission lines and the lower (and easier to insulate, although still quite dangerous) voltage for the smaller lines within urban areas. This conversion is done using a POWER TRANSFORMER, a device that relies on the alternating current of the grid to function with no moving parts by taking advantage of *electromagnetism*. A transformer mainly consists of two adjacent COILS of wire. The alternating current of the input electricity generates magnetic fields that are focused and directed by a LAMINATED CORE consisting of many thin sheets of iron. These magnetic fields couple to the adjacent coil, inducing a voltage in the output wires. The voltage out of the transformer is proportional to the number of loops in each coil. Transformers are usually the largest and most expensive pieces of equipment in the entire substation, so they are easy to identify.

The insulators guiding conductors into and out of the transformer are called BUSHINGS. They support the energized lines as they pass through the metal case into the transformer, protecting against short circuits. You can easily tell which lines are higher- and lower-voltage by the difference in the size of the bushings. The higher the voltage, the larger the bushings need to be to maintain enough distance to prevent arcs.

Although grid-scale transformers are very efficient, they still lose some power to noise and heat. If you get close enough to a power transformer, you'll definitely notice the low-pitched hum that occurs because the constantly changing magnetic fields cause vibrations to the components inside the transformer. The heat is generated from the resistance in the copper coils and can eventually damage the transformer. Transformers are usually filled with oil to help with cooling. RADIATORS consisting of fans and heatsinks can be seen on the outer metal case to dissipate heat and help keep the oil and components cool. You may even see a smaller tank (called a CONSERVATOR) on top of a transformer case to hold extra oil and allow the fluid to expand and contract.

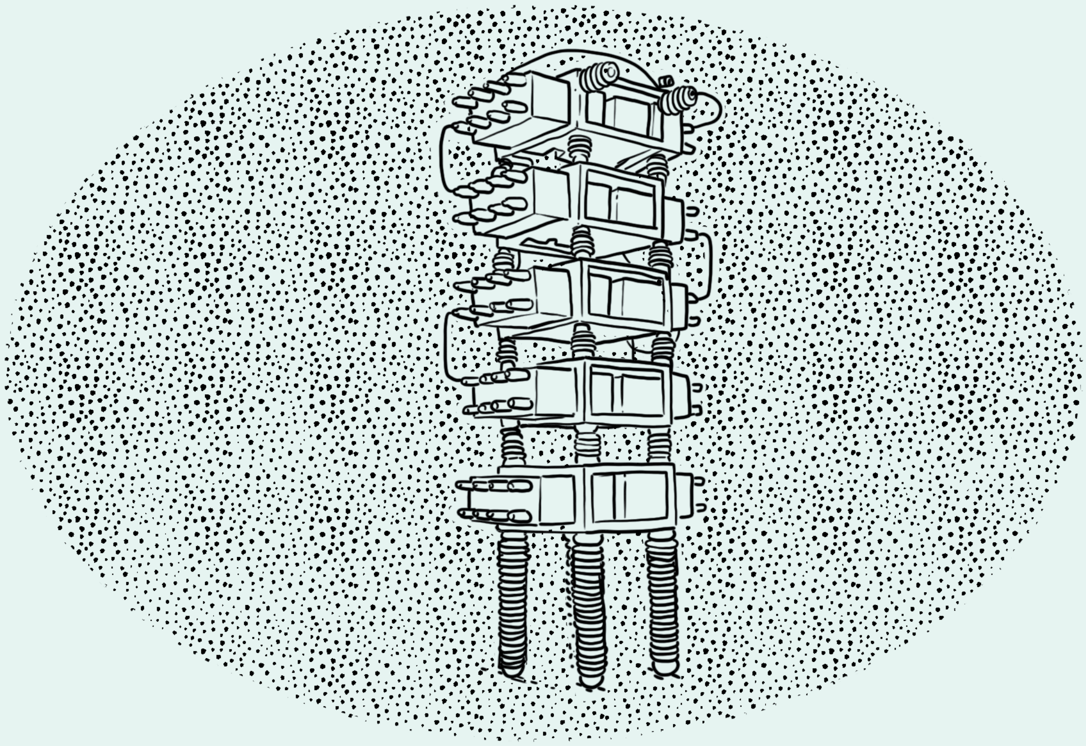
Nearly every line and piece of equipment in a substation needs to be isolated completely from the rest of the energized system during maintenance or repairs. DISCONNECT SWITCHES are usually installed on each side of the equipment for this reason. They can't interrupt large currents through the system and are used strictly for isolating equipment to keep workers safe. The most common disconnect switches are motor-operated and consist of a HINGED blade and a stationary contact, both of which are mounted on insulators. PANTOGRAPH disconnect switches raise and lower with a scissor action to connect to bus bars.

On occasion, it is necessary to interrupt the flow of electricity on some part of the power grid. Most commonly, interruption is needed due to a fault, which can cause significant damage to costly and vital equipment. CIRCUIT BREAKERS provide the means to stop the flow of electricity, allowing faults to be isolated from the rest of the system. They not only protect the other equipment on the grid, but also make problems easy to find and repair quickly. Interrupting current on energized lines isn't as simple as it sounds, though. Just about anything can conduct electricity if the voltage is high enough, and that includes air. Even if you create a break in the line to disconnect it, electricity can continue flowing through the air in a phenomenon known as an *arc*. Arcs need to be extinguished as quickly as possible to prevent damage to the breaker or unsafe conditions for workers, which means all circuit breakers for high-voltage equipment need to include some type of arc suppression.

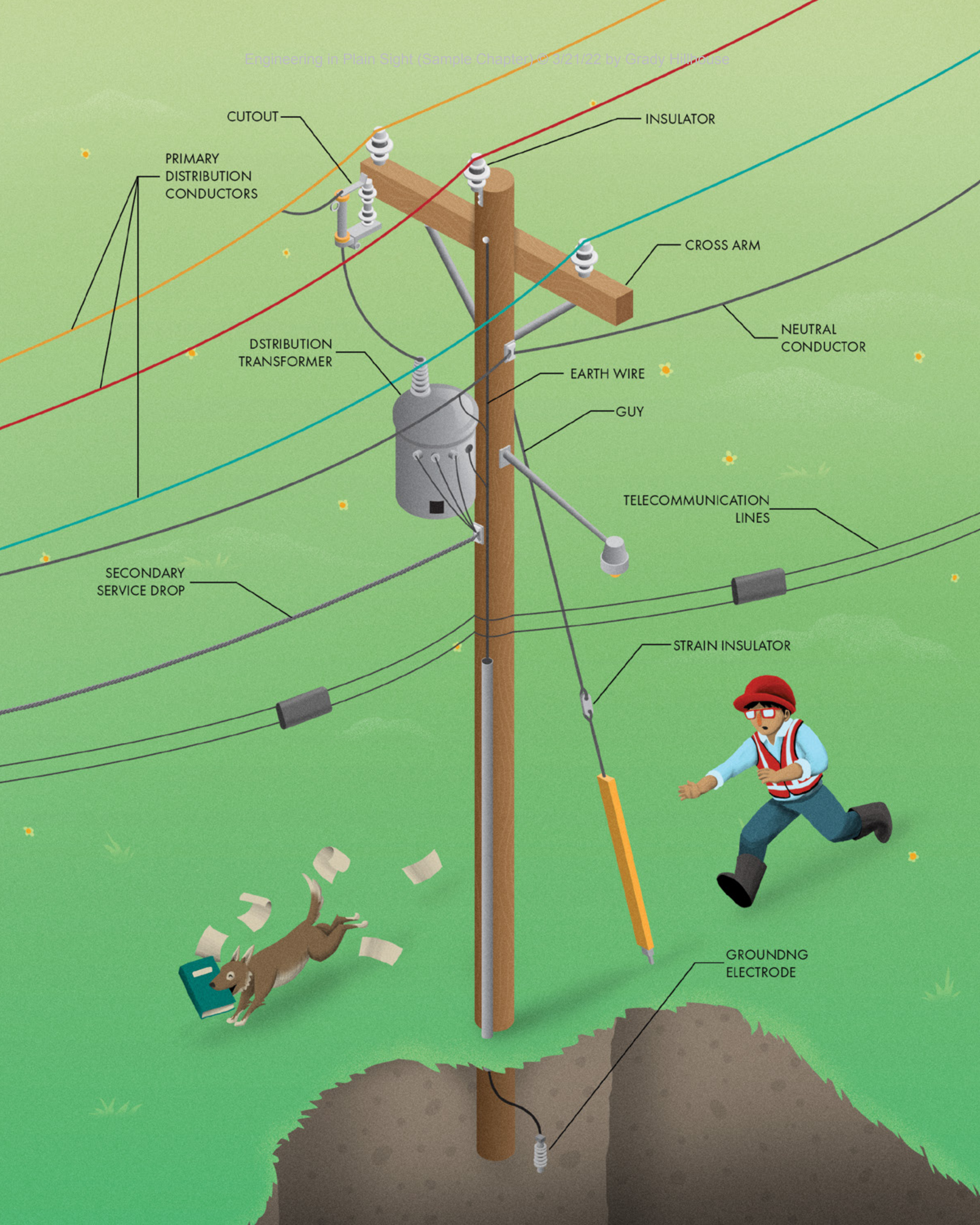
For lower voltages, the circuit breakers are located in a sealed container under VACUUM to avoid electricity conducting in the air between the contacts. For higher voltage, breakers are often submerged in tanks filled with non-conductive OIL or dense gas called SULFUR HEXAFLUORIDE (SF_6). Another option is to use a massive blast of air to blow out the arc. All breakers are connected to devices called *relays* that can automatically trigger during a fault condition. Breakers can also be manually operated to remove a circuit from service as needed for maintenance or to shed load during period of extreme electrical demand. Because many faults are temporary (for example, lightning strikes), some breakers, called *reclosers*, automatically re-energize the circuit if the fault has cleared.

Relays monitor the voltage, current, frequency, and other parameters on the grid to identify problems and trigger the breakers, but we can't just feed high voltage into sensitive operating equipment. Instead, special transformers called INSTRUMENT TRANSFORMERS convert the high voltages and currents on the conductors to smaller, safer levels that can be sent to the relays. Instrument transformers are the eyes of the power grid, monitoring conditions to make sure everything is working properly. Although they look similar, there's an easy way to tell them apart: the primary coil for VOLTAGE TRANSFORMERS is usually connected between one phase and ground, so you'll only see one high-voltage terminal. The primary coil for a CURRENT TRANSFORMER is connected inline (that is, in series) with the conductor, so there will be two high voltage terminals.

KEEP AN EYE OUT



One challenge with alternating current is that the voltage and current can lose synchronization. Certain kinds of electrical loads are reactive, meaning they momentarily store power before returning it to the grid. This causes the current to lag or get ahead of the voltage, reducing its ability to perform work. It also reduces the efficiency of all the conductors and equipment powering the grid because more electricity has to be supplied than is actually being used. The measure of this reduction is called the *power factor.* Some substations include banks of capacitors to bring the current and voltage back into sync and help improve the power factor in the lines. The capacitors absorb some or all of the mismatch in voltage and current, allowing more efficient use of conductors, transformers, and other equipment and helping stabilize the voltage on the grid. Look for arrays of small boxes on steel racks.


CUTOUT
INSULATOR
PRIMARY DISTRIBUTION CONDUCTORS
CROSS ARM
NEUTRAL CONDUCTOR
DSTRIBUTION TRANSFORMER
EARTH WIRE
GUY
TELECOMMUNICATION LINES
SECONDARY SERVICE DROP
STRAIN INSULATOR
GROUNDNG ELECTRODE

Typical Utility Pole

Almost nothing is more ubiquitous in the constructed world than the UTILITY POLE, which serves a critical role in the distribution of electricity on the grid. *Distribution* describes the portion of the power grid that brings electricity to all the individual consumers. If transmission lines are electrical highways, distribution lines are the residential streets. They usually start at a substation where individual power lines (feeders) fan out to connect to residential, commercial, and industrial customers. In some ways, distribution is nearly identical to high-voltage transmission. Wires are wires, after all. But, in other ways, it is surprisingly different. The most obvious difference is that the voltages come down to levels that are easier to insulate, so the heights of the poles and conductors get lower as well.

In most parts of North America, wood is a relatively abundant resource, so it is the material that makes up the vast majority of utility poles. *Preservatives* are used to treat the wood and slow down deterioration from weather and insects. Standards vary regionally, but poles of normal height are usually buried between two and three meters (six and nine feet) into the earth. Most utility poles have their own EARTH WIRE running down the pole attached to an ELECTRODE driven into the ground. This wire provides a safe path for any stray currents instead of allowing them to travel through the pole itself, which could lead to shocks or fires.

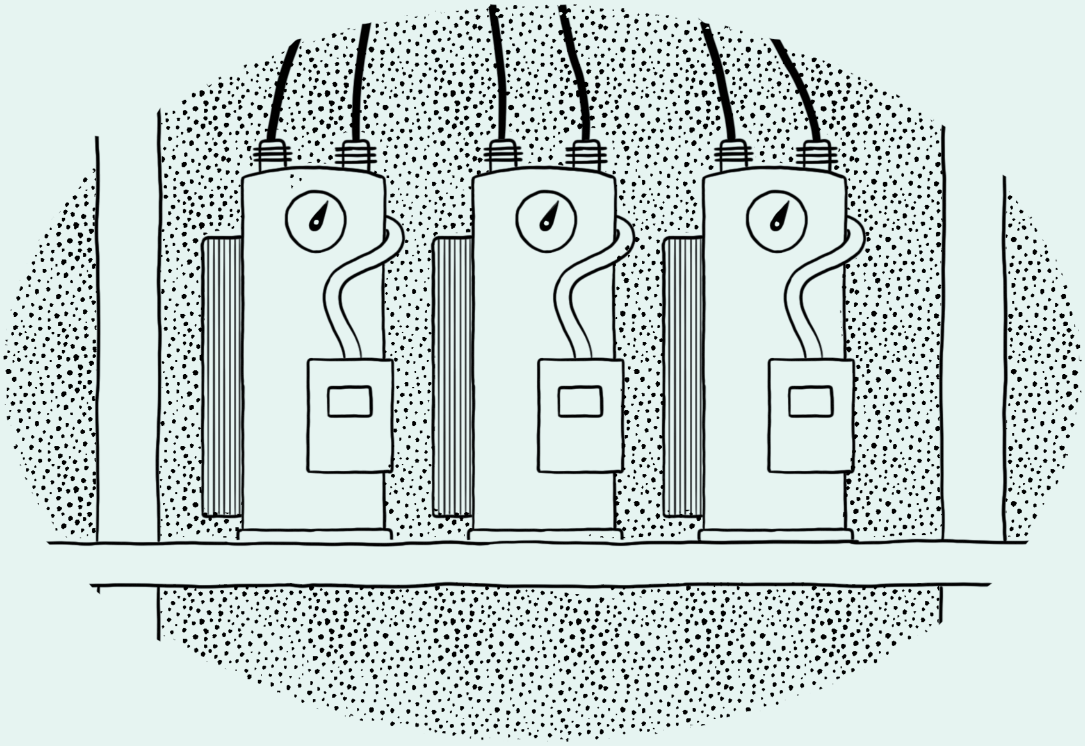
Poles in a straight line need to support only the vertical weight of the wires atop, but if a pole serves as a corner or dead-end, it experiences a pull to one side. Even if this tension isn't substantial, the long pole acts like a lever, magnifying the force into the ground and potentially toppling it altogether. Whenever the horizontal forces on a pole aren't balanced, GUYS are used for additional support. Each guy is equipped with a STRAIN INSULATOR to make sure that, in the event of an accident, dangerous voltages can't reach the lower section of the cable.

The PRIMARY DISTRIBUTION CONDUCTORS (or lines) you see at the top of utility poles are considered medium voltage and usually range from 4 kV to 25 kV. Energized lines are easy to identify because they are supported by INSULATORS. Even though they are at a much lower voltage than transmission lines, the voltage of primary distribution lines is still too hazardous for use in homes and businesses. DISTRIBUTION TRANSFORMERS (described more in the next section) reduce the voltage to its final level—often called *mains* or *secondary voltage*—for use by regular customers. For the safety of workers, the energized lines are always at the top of the poles with space to work between them and other COMMUNICATION LINES (such as cable, telephone, and fiber optics). See Chapter 2 for more information on communications infrastructure, which often runs parallel to distribution lines on utility poles.

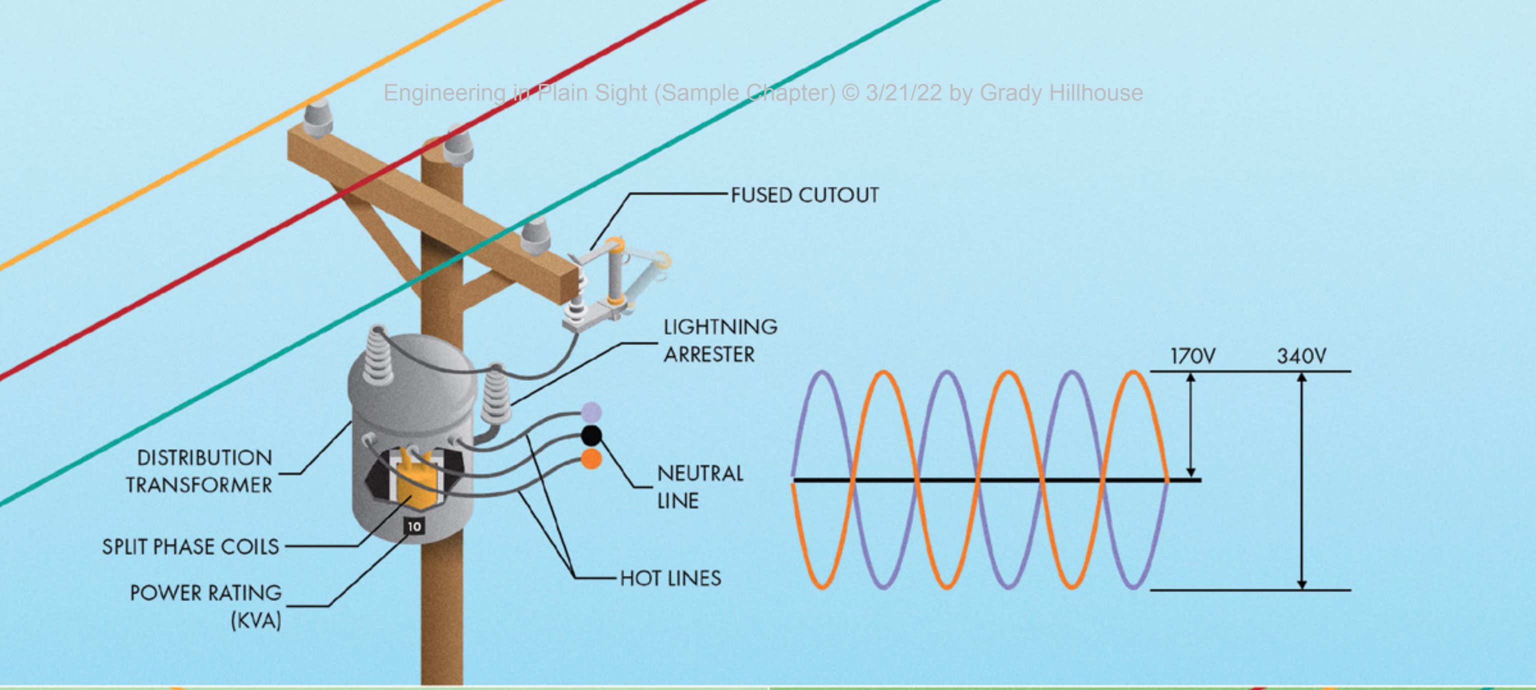
One major difference from transmission lines is that the number of conductors on the distribution grid increases from three to four. This is due to how electrical demands are distributed between each of the grid's three phases. All electrical circuits are loops, so they require two lines: one to supply the current and one to return it to the source. On high-voltage transmission lines, the electricity usage between each of the three phases is perfectly balanced, eliminating the need for a separate return path for electricity. Each pair of phases serves as a source and a return path at the same time. However, on the distribution side, it's not always so simple. Many electrical consumers (including most residential customers) make use of only a single phase. In fact, on the distribution grid, each of the three phases is often split from one another to service different areas entirely. Look around some residential neighborhoods and you may see many poles with only a single primary conductor and no CROSS ARM. Grid operators try to arrange distribution lines to make sure that all the loads on each phase will be roughly equal, but they are never perfectly in sync. These imbalances between phases necessitates a NEUTRAL CONDUCTOR to act as a return path for stray current.

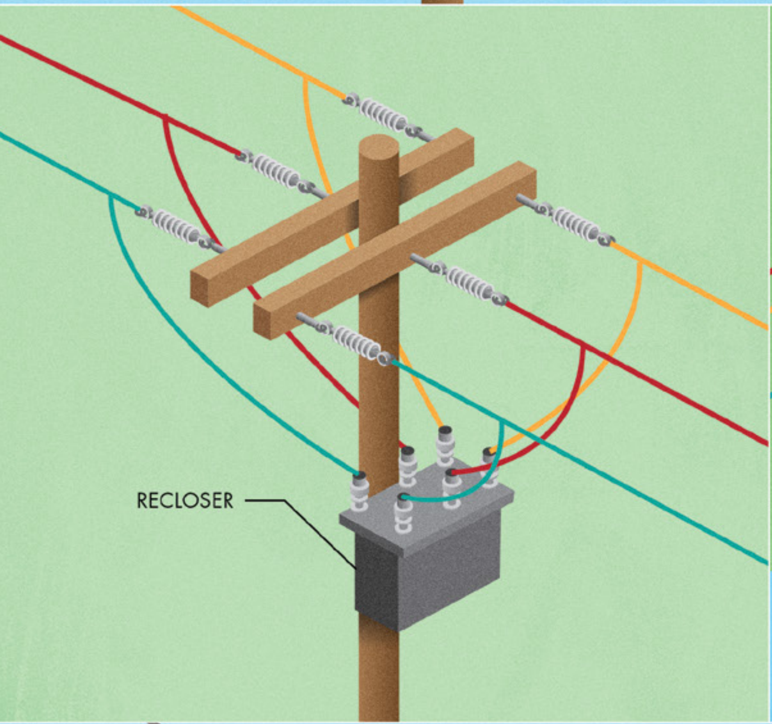
Much of the complexity of power grid is due to how we protect it when things go wrong. The grid got its name for a reason. It's an interconnected system, which means that, if we're not careful, small problems can sometimes ripple out and impact much larger areas. Engineers establish zones of protection around each major piece of the power grid using fuses and circuit breakers to isolate faults and make them easy to find and repair. These devices create "managed failures" where you have some loss of service at the cost of protecting the rest of the system (just like the breakers in your house). The goal is that isolating equipment when things go wrong speeds up the process and reduces the cost of making repairs to get customers back online. When your power goes out, it's easy to be frustrated at the inconvenience, but consider also being thankful that it probably means things are working as designed to protect the grid as a whole and ensure a speedy and cost-effective repair to the fault.

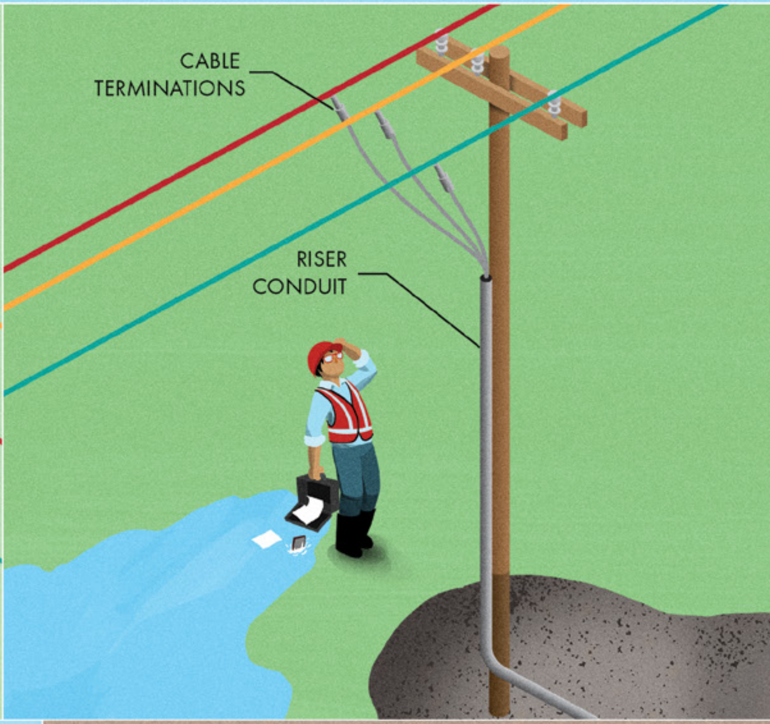
KEEP AN EYE OUT

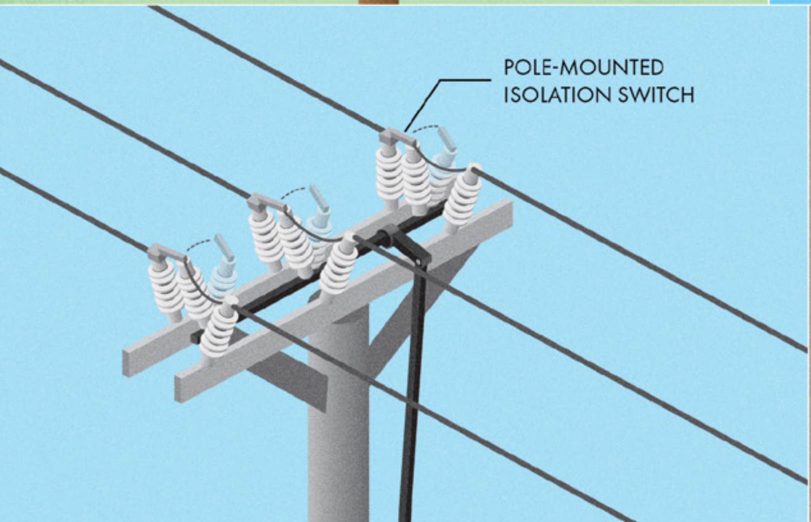


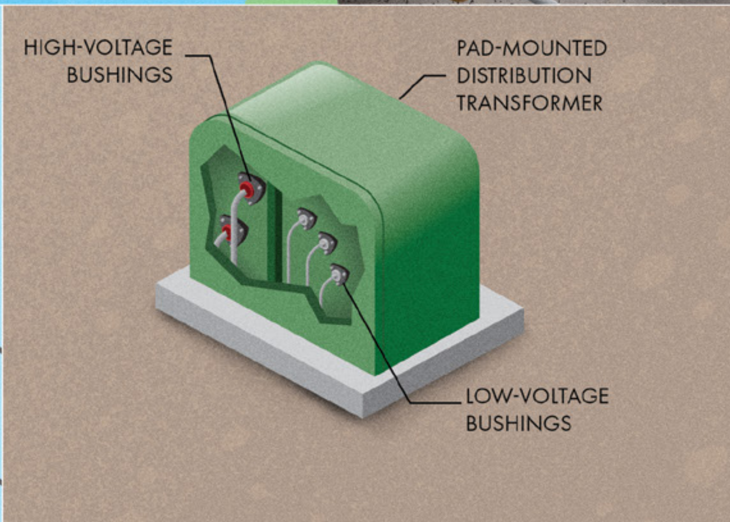
Rural areas often have long runs of primary distribution lines. These long distances create extra resistance and make maintaining a steady voltage level difficult. Another challenge is the increasing popularity of grid-connected solar panel installations. Clouds temporarily casting shadows on the panels can create instability in the distribution voltage for areas with lots of connected panels. *Voltage regulators* are devices with multiple taps that can make small adjustments to the distribution voltage. They work similarly to transformers but make only minor adjustments to voltage, usually plus or minus 10 percent. Regulators monitor voltage on the line directly or perform automatic calculations of voltage drop based on the measured current to adjust their taps up or down. They also look like distribution transformers with cylindrical casings (one per phase). However, they have a few recognizable differences. Both the input and output of a regulator is attached to the primary distribution line, and both bushings are the same size. Also, look for the dial at the top of the canister, which indicates the regulator's tap position. If you're lucky, you might catch it automatically switching positions to maintain the correct voltage on the line.


FUSED CUTOUT
LIGHTNING ARRESTER
DISTRIBUTION TRANSFORMER
SPLIT PHASE COILS
POWER RATING (KVA)
10
NEUTRAL LINE
HOT LINES
170V
340V


RECLOSER


CABLE TERMINATIONS
RISER CONDUIT


POLE-MOUNTED ISOLATION SWITCH


HIGH-VOLTAGE BUSHINGS
PAD-MOUNTED DISTRIBUTION TRANSFORMER
LOW-VOLTAGE BUSHINGS

Electrical Distribution Equipment

Like all the other parts of the grid, distribution of electricity requires various pieces of equipment to help with reliability and safety. Just like in a substation, one of the most important pieces of equipment on the distribution grid serves to change the voltage. Although significantly lower than transmission voltages, primary distribution circuits are operated at many thousands of volts, still much higher than can be safely used in most houses and businesses. In most cases, another transformer (called a DISTRIBUTION TRANSFORMER) is needed to step down the voltage to the level generally used in buildings by lights, appliances, and other devices. These transformers often appear as gray canisters just below the conductors on utility poles. They are filled with oil, just like the transformers at substations, and work in almost the same way.

One interesting difference is that the output of distribution transformer coils use a SPLIT-PHASE design. In this configuration, two energized (or HOT) lines are supplied to the customer with one NEUTRAL conductor connected to ground. One of the energized lines is inverted from the other. In this way, smaller appliances can use the line-to-neutral voltage, about 120 V nominal (170 V peak-to-peak) in most of North America. Devices requiring more power (such as heaters, air conditioners, clothes dryers, and so on) can be connected between the two energized lines, receiving double the voltage. In residential settings, a single distribution transformer can often supply multiple homes. Take a look outside your house and you may notice you share a transformer with a few of your neighbors. Customers with bigger equipment (for example, large air conditioning units) can take advantage of all three phases on the grid. In this case, you may see three single-phase transformers grouped together on the same pole. Look for the POWER RATING on the side of the transformer in *kilo-Volt-Amperes* (*kVA*, roughly equivalent to *kilowatts*).

Just like transmission lines and substation equipment, the distribution grid needs protection from faults and lightning strikes. Much of the hardware you see on pole tops is for when things go wrong. One common protective device is the FUSED CUTOUT, which serves as both a circuit breaker and an isolation switch. The fuse automatically protects a service transformer from short circuits and voltage surges. If the current in the fuse gets too high, the element inside melts, breaking the circuit and disengaging a latch, allowing the fuse door to swing down. These fuses often include an explosive liner to help extinguish the arc that forms inside, so you might hear a loud pop if one trips nearby. It is often so loud that many people assume the transformer has exploded, when really it was protected from damage by the fuse.

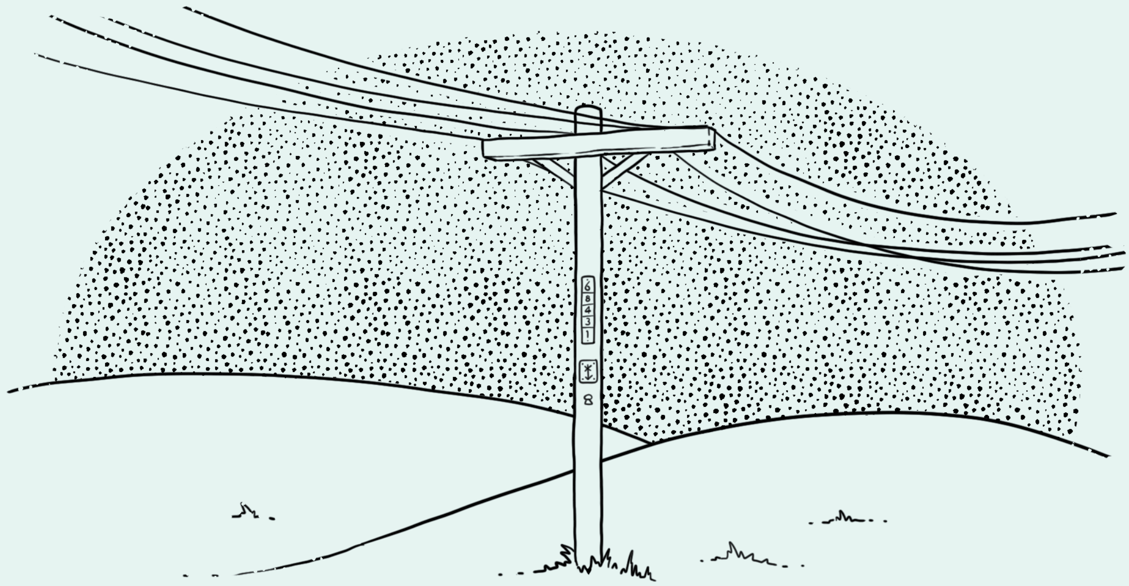
Even if the fuse in a cutout hasn't blown, linemen can disengage it to isolate the line for maintenance or repair. However, fuses are the simplest protective devices. More sophisticated circuit breakers can occasionally be seen, including RECLOSERS, which are usually housed in small gray cylindrical or rectangular canisters. Reclosers open when a fault is detected, then close again to test whether the fault has cleared. Most faults on the grid are temporary, such as lightning or small tree limbs making contact with energized lines. Reclosers protect transformers without requiring a worker to come replace a fuse for minor issues. They usually trip and reclose a few times before deciding that a fault is permanent and locking out. If you ever lose and regain electricity in a short period of time, a recloser is probably why. Other types of ISOLATION SWITCHES atop utility poles help linesmen perform maintenance or make repairs. Many use a mechanism to disconnect all three phases at once. Finally, like other parts of the grid, distribution lines use ARRESTERS to redirect surges in voltage from lightning strikes safely to ground.

Not all distribution of grid power happens overhead. In the urban core of many cities, you'll hardly see any overhead lines at all. Instead, power is run in ducts below the ground. Also, newer residential and commercial developments often elect to bury distribution lines to avoid the untidy and cluttered appearance of overhead wires. Using underground distribution lines is not a trivial choice, since they are far more expensive to install and often require more time to repair when damaged. However, these lines are better protected from weather and don't impose on the aesthetics of the urban landscape. Even if not run continuously underground, it is not uncommon for a distribution line to dive below ground and come back up shortly after to avoid an overhead hazard or even to keep a sign from being obstructed.

Although you can't see underground distribution lines, you can often see where they start and stop. Look for a utility pole with large CONDUIT RISERS attached. Underground power lines must have an insulating jacket to protect them from moisture and short circuits. Insulation around conductors can't just start and stop wherever because moisture could get inside from the ends. CABLE TERMINATIONS (colloquially called *potheads*) are used to seal the transition between insulated and bare cables.

Another location where underground wires come up to the surface is at a transformer. Although less visually intrusive than its overhead equivalent, the PAD-MOUNTED DISTRIBUTION TRANSFORMER serves as a reminder that the power grid still exists in areas without overhead lines. You may be curious what's inside those green cabinets. It's the exact same device as the ones mounted overhead. The cabinet door provides access to the high- and low-voltage BUSHINGS just like you see on a pole-mounted transformer.

KEEP AN EYE OUT



Utility poles are often adorned with cryptic markings and metal tags. Sometimes they are simply identifiers for the utility or a manufacturer's mark, but not always. Red tags with arrows are warnings to linesman that the pole is damaged and to be careful or avoid climbing the pole altogether. Pole tags can also indicate the last time the pole was inspected and what type of treatments have been applied to protect it from bugs and rot. Finally, stamps in the wood offer clues about where the pole was manufactured, the wood species used, and even the length of the pole. Keep an eye out for different kinds of markers and see if you can decipher their meaning.