The Electrification of the World

How the Dynamo, the Arc Lamp, the Incandescent Light Bulb, the First Grid, and the Battle of the Currents (DC vs AC) Made the Modern World

Part 1:

The Dynamo and the Arc Lamp - How the Electrification of the World Began

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INTRODUCTION

People relied on tallow candles and whale oil for light well into the 19th century. At the end of the 18th century, meantime, an enterprising engineer at Matthew Boulton and James Watt's steam engine works in Birmingham, England, had developed "a practical system to distill and distribute coal gas for illumination." The engineer, William Murdoch, continued to improve his extraction process in the early 1800s until his coal gas could be pumped from factory storage tanks into a maze of pipes buried beneath streets and "into home, church, theater, store, and office … where it was metered and finally piped to individual burners" [1]. In 1812, the world's first gas company was chartered in London. It was followed in 1816 by the first US municipal gas plant, in Baltimore, and that same year Germany's first gasworks was established in Freiburg. In 1820 Paris, known as the City of Lights since the reign of Louis XIV, adopted gas street lighting, and within a few years the inhabitants of cities worldwide grew accustomed to their streets, homes, and places of business being lit by gas. Despite the technology's noxious odors and flammability hazard, by the 1870s gas lighting had become a large and powerful industry.

The transition to cleaner, safer, and eventually more reliable, convenient, and less expensive electric lighting did not begin until the 1870s, with the development of the arc lamp. Though the arc lamp was soon eclipsed in private residences and businesses by the less powerful, gentler incandescent bulb, it retained its role in public spaces – streets, parks, train stations, docks, and large emporiums – well into the 20th century.

LIGHT, THE ETERNAL INSPIRATION

Electric lighting, envisaged by inventors and scientists since the start of the 19th century, had been stalled for decades for want of a sufficient, dependable power source. In the first decade of the 19th century, Faraday's mentor, Sir Humphry Davy, gave a public demonstration of what he termed "arch" (later, "arc") light at London's Royal Institution. Using two opposed charcoal stalks connected to a wire circuit powered by "a cumbersome array of 220 linked battery cells, the largest source of electrical power in the world" [2], Davy sent a powerful current into the stalks of charcoal, making a circuit, and then slowly separated them until a brilliant sparking "arch" of electricity formed across the gap, creating what Davy himself termed a light of "dazzling splendor." Davy's experiment showed that "electricity could produce high intensity lighting if the details could be worked out" [3].

The details took another seventy years to work out.

INVENTING THE DYNAMO

The most important detail was the creation of a reliable, steady source of power to replace Davy's massive acid-filled battery array. Within a year of Faraday's first demonstration of the principle of a dynamo in late 1831, a French instrument maker named Hippolyte Pixii was inspired to build the first practical dynamo. Faraday, who coined the term "dynamo," had demonstrated that if either a magnet or a wire coil (a solenoid) moves in relation one to the other, an electric current arises in the wire [4].

Beneath a bar of iron tightly wound with wire, Pixii placed a horseshoe magnet mounted on a shaft turned by a hand crank. In effect, the stationary wire-wound bar was the stator or stationary magnet in whose magnetic field the rotating magnet's poles induced a current whenever they passed beneath (see Fig. 1). But the rotating magnet's north and south poles induced pulses of current that travelled in opposite directions (as measured by a galvanometer). In effect, Pixii's machine operated as a magneto or primitive alternator, producing alternating current (AC). Alternating current, however, was a form of electric power both new and more complicated than the familiar direct current (DC) of the battery, a technology that had been used experimentally by scientists and inventors ever since Volta demonstrated it in 1800.

To solve the problem of alternating current, Pixii modified his magneto by inventing a commutator, a switching device he attached to the rotating shaft beneath the horseshoe rotor. Two spring-loaded contacts or "brushes" touched the commutator on its opposite sides and acted to reverse the current at each half turn, causing it to pulse in one direction instead of two, and thus produce unidirectional torque.

Within a year other inventors changed Pixii's stator into the rotor. The permanent magnet, formerly the rotor, was hereafter stationary, and the wire-wound iron bar, formerly the stator, became the spinning armature (or rotor) that cut the field force lines, or flux, of the stationary magnet, and induced a current. The modified Pixii dynamo was not used commercially until the 1840s, for electroplating. In the late 1850s, simple battery-charged magnetos were used to light arc lamps in lighthouses in Britain and France, and several countries in Europe began to make generators capable of powering telegraphs. But the spinning two-pole axial rotor coil developed by Pixii's successors still only produced a series of electric pulses, forming a relatively weak direct current useless for most industrial tasks.

In the early 1860s, the Italian physicist Antonio Pacinotti developed the "ring armature," consisting of "symmetrically grouped coils" of wire wound around a metal ring. Pacinotti's armature enhanced the rotor's field-cutting efficiency. It was "connected to the bars of a commutator" and "delivered a practically continuous direct current" [5]. Independently of each other, in 1867 Werner von Siemens and Charles Wheatstone proposed replacing the permanent stator magnet with a self-powering electromagnet. This strengthened the dynamo's magnetic flux, and hence its potential to do work, and created the basis "for the modern technology of electric generators" [6]. Now, whenever the rotor's wire coils cut across the stationary electromagnet's field lines, they induced a powerful electric current.

In 1870 a Paris-based Belgian inventor, Zénobe Gramme, adopted Pacinotti's and Siemens' innovations and enlarged the stationary electromagnet. He also wrapped the rotating armature with multiple coils and used thick wire to increase amperage (current). The wire was wound in tight proximity all around the rotor armature or "ring." Three factors control a dynamo's output: the size of its magnetic field, the total length of the wire cutting its field, and the speed of its rotor's spin, or cutting motion. Crucially, Gramme also reduced the air spaces between the rotor and stator. The Gramme dynamo resulted in a "waveform" of electromagnetic energy that was "practically constant" and supplied a strong direct current capable of powering both arc lights and small industrial machines and motors [7].

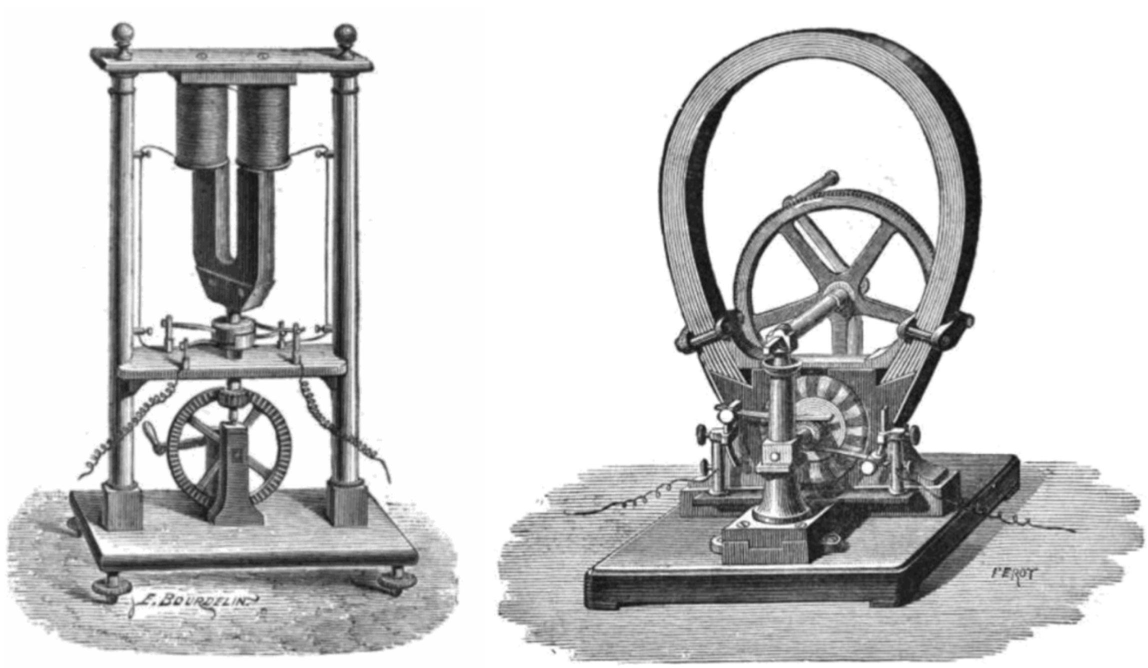

Figure 1: Pixii's prototype 1832 dynamo (left side) used a hand crank to rotate a permanent magnet whose poles passed beneath wire coils and induced an alternating current that Pixii converted to direct current by placing commutator "bars" at the base of the spinning magnet's axle. Gramme's prototype dynamo (ca 1870, right side) placed the rotating armature (rotor), with layers of copper wire wound tightly around its "ring," inside a much larger stationary magnet (the stator), using commutator bars that touched the rotating axle to produce a steady, direct current more powerful than any dynamo had ever produced. SOURCE:
https://upload.wikimedia.org/wikipedia/commons/3/30/Hippolyte_Pixii_dynamo.png
https://nationalmaglab.org/images/education/magnet_academy/history/museum/Gramme_dynamo.png

Gramme and his partner Hippolyte Fontaine began to produce his dynamo in 1871 and started up the world's first central power station in Paris to light factories, streets, and public forums (but not residences). The Gramme machine had already begun to dominate the nascent dynamo market when the two partners were preparing for the 1973 Vienna Exposition. Fontaine used “a copper cable to connect Gramme’s machine to another dynamo located 500 metres away. Unexpectedly, the shaft of the second dynamo began to spin, which in turn” powered a water pump to which it was attached, thus “turning Gramme’s [second] dynamo into the first electric motor with enough power” to run industrial machinery. “[I]t also allowed energy to be used at a different location from where it was generated” [8].

In effect, Fontaine and Graham reconfirmed Lenz’s 1833 “law of reciprocity,” which stated generators could function as motors, and motors, as generators. After Gramme and Fontaine’s 1873 demonstration, dynamos were used as DC electric motors for various industrial tasks.

THE FIRST ELECTRIC LIGHT: THE ARC LAMP

“Lighting,” meantime, not the electric motor, “was the ‘killer app’ of the early electrical industry – the one application that was so valuable that it would drive the development of the technology and investment” needed to build an entirely new, revolutionary industry [9]. Lighting could be powered directly by a DC dynamo or by an AC alternator or generator. Neither an arc lamp nor an incandescent bulb depended on an intermediary electric motor to power it, only the current-generating dynamo.

Two years after the Vienna Exposition, a telegraph technician named Pavel Yablochkov, a Russian émigré, arrived in Paris. In 1875 the carbon electrodes of the arc lamps being deployed in French factories and public buildings, such as the Gare du Nord train station, burned unevenly and had severe operational problems, requiring constant repair and maintenance. Yablochkov placed the electrodes side by side in parallel instead of having each tip opposed to the other, one on top, the other below, as was customary. He then “devised a startlingly simple solution” to the problem of uneven burning of the carbon rods that DC current caused. He switched to “alternating current so that both carbons would be consumed at the same rate.” To prevent the adjacent electrodes from shorting out, he separated them with a thin sheet of plaster so that “the arc moved downward in tandem, similar to the burning of a candle,” giving rise to the term Yablochkov “candle” [10]. (See Fig. 4.)

To supply the necessary power for Yablochkov’s candle, in 1878 “Gramme developed an efficient alternator … whose alternating current ensured the equal consumption of the two carbon electrodes” [11] and catalyzed the investigation and improvement of AC generators in Europe (which would eventually overshadow DC dynamos during the last decade of the century).

As noted, various types of arc lamps powered by Gramme dynamos were already in use to light French factories and public buildings when Yablochkov’s new arc lamps lit up the Grands Magasins du Louvre, the Avenue de l’Opéra, and the Place de la Opéra for the occasion of the 1878 Paris Exposition. The German inventor and industrialist Werner von Siemens was so impressed with Yablochkov’s arc lamp that he acquired the rights to distribute it in Germany. That same year the Ganz company in Budapest began producing AC generators. Within two years Yablochkov “candles” lit streets, train stations, factories, museums, theaters, and emporiums throughout Europe, as well as in Mexico City, Rio de Janeiro, New Delhi, and Calcutta.

Figure 2: The Avenue de l'Opéra lit up by Yablochkov "candles" or arc lamps in 1878 during the Exposition Universelle, France's third "World's Fair." SOURCE: https://commons.wikimedia.org/wiki/File:L%27avenue_de_l%27op%C3%A9ra_eclairee_par_les_lampes_Jablochkoff.jpg

After the 1878 Paris Exposition, "[r]eports filtered back to America about 'this grand fire', one that made gaslights look 'yellow, muddy, and petty by comparison'" [12]. One American inventor was already inspired to set America ablaze with the "grand fire" of electric light. Charles Brush had been fascinated since childhood by Davy's arc-light experiments. Brush grew up on a farm outside Cleveland, Ohio, possessed by a "vision to light America on a grand scale." He "realized that the dynamo was the key to a successful lighting system" [13]. Two years before the 1878 Paris Expo he had been working on improving Gramme's dynamo design.

Brush saw that Gramme's armature coils were formed to fit around a cylindrical edge so that "only the outside portion of the coils would cut through the strong magnetic field" of the stator [14]. The wire windings on the inside and sides of Gramme's rotor were wasted as they did not "cut" the magnetic "lines of force," or magnetic flux. Brush replaced the cylinder shape of Gramme's dynamo with a disc whose relatively flat sides permitted most of its windings to face and almost touch the two opposed stator electromagnets, optimizing the rotor's capacity to cut more of the magnetic field and thus create a stronger current.

The other problem posed by Gramme's dynamo was its tendency to retain heat because the armature's continuous wire winding "acted as an insulating layer that retarded cooling of the armature core." Since heat reduces the efficiency of electric current generation, Brush spaced the wire coils on his armature disk, limiting them to four electromagnets, one pair "with north pole shoes" and the other "with south pole shoes," so that the "like poles opposed each other, one on each side of the disc armature. With this arrangement Brush was able to bring a major portion of each loop of wire on the armature very close to the field magnets [the stator], thus increasing the efficiency of the machine" [15].

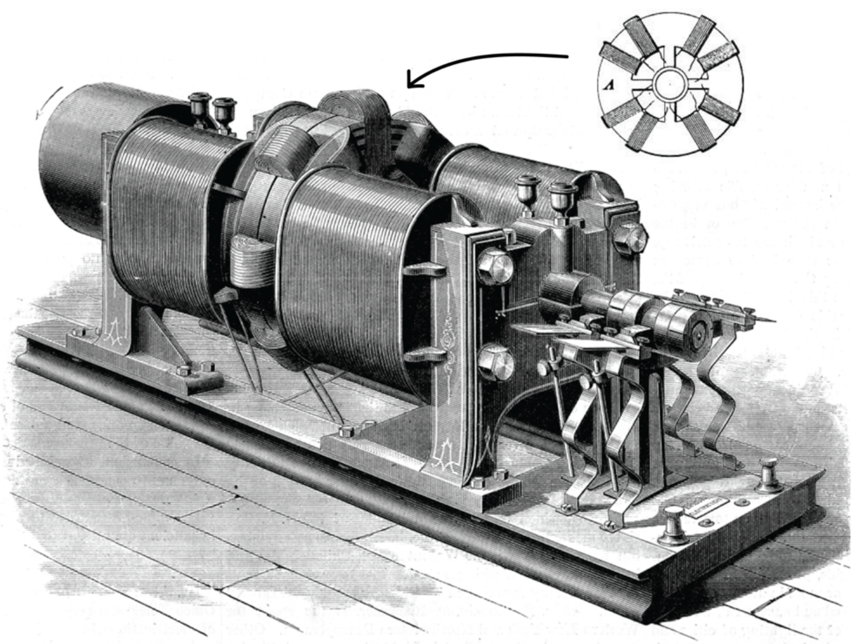

Figure 3: An early Brush dynamo, with inset drawing of his four opposed electromagnets (designated by the letter A for armature). The armature spun between the stator's poles, cutting its magnetic field or flux. Most of the area comprised by the copper wire windings – deliberately spaced to permit the armature's core to cool – cut the flux and thereby enhanced the dynamo's power output. SOURCE: https://hiddencityphila.org/wp-content/uploads/2012/05/Brush-Dynamo-Electric-Machine-from-Scientific-American-1881.jpg

A patent for Brush's "open-coil" dynamo was awarded in April 1877. By then he was already at work improving the arc lamp for use with his new dynamo – without recourse to making the electrodes parallel or using alternating current as Yablochkov had done. Within a year Brush improved the complicated electromagnetic "regulators" that other inventors had devised and used with limited success to maintain the critical arc gap between the two carbon electrodes positioned one above the other, with each tip nearly touching (see Fig. 4). Since each rod burned from the tip down, Brush's regulators had to somehow adjust their positions to maintain the critical dielectric air gap.

Brush developed a combination of electromagnetic and mechanical devices that included a solenoid (coil) which held inside it an electromagnetically controlled iron carbon rod (electrode), so it could move up and down, as well as a ring clutch and limit screw to stop or start the electrodes' movement to maintain the critical dielectric air gap as the rods slowly burned down. Brush's regulator "represented a breakthrough in arc lamp technology" and he "now had a product that could replace the gas lamps used in many cities in America and throughout the world" [16].

Brush's DC-powered arc lamp was notable for its reliability, relative simplicity, and easy maintenance. It also "featured other improvements including copper plated electrodes" that enabled the inventor to increase their length and burn time, and, following Yablochkov's lead, Brush also placed double sets of electrodes inside each lamp, so that when one set burned down the other started up, extending the lamp's burn time [17].

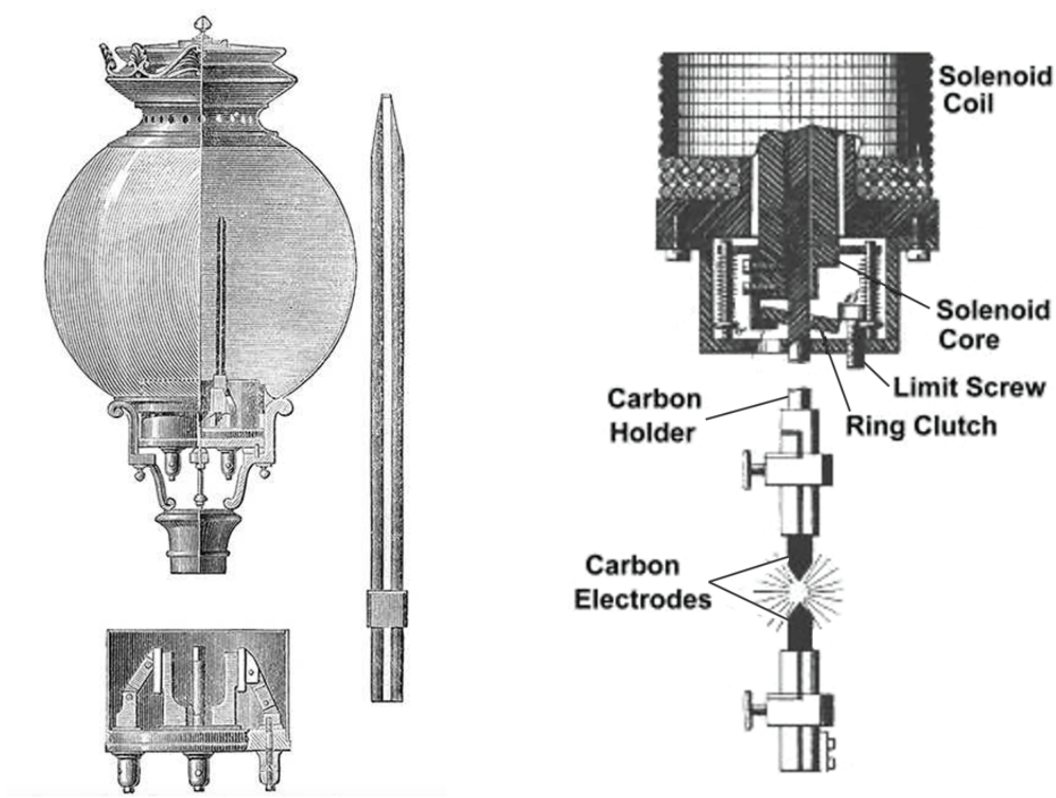

Figure 4: A Yablochkov arc lamp (left side), with an enlarged electrode pair shown separately. Inside the lamp only the right-side pair of electrodes is shown (the left side pair being hidden behind the lamp glass). In between each electrode pair Yablochkov placed a thin sheet of plaster, not shown, to keep both electrodes burning evenly. The right-side illustration shows the most

significant components of Brush's arc lamp, including the ring clutch and limit screw that mechanically controlled the carbon electrode in synch with the electromagnetically controlled solenoid coil and solenoid core in which the carbon holder moved, releasing the carbon electrode on signal. SOURCES: Left image: https://stock.adobe.com/images/yablochkov-candle/148487859; Right image: http://www.lafavre.us/brush/lamparc.htm.

By June 1878, when Brush had also perfected his arc light, Philadelphia's prestigious Franklin Institute formally acknowledged Brush's dynamo was "capable of producing stronger currents at a wide range of voltages," and "had a simple … easier to maintain" design than the Gramme dynamo [18]. The Institute then purchased Brush's dynamo, giving it a publicity boost. Soon Philadelphia's pioneering merchant Jon Wanamaker "installed a set of Brush's powerful arc lights" in his huge flagship emporium, and the public flocked in. "Brush's system allowed Wanamaker to create acres of dazzling retail space under one roof" so that the public could "take in the spectacle … particularly 'beautiful and stirring' at night." Wanamaker's investment in Brush's arc lamps were soon copied by large stores all over America [19].

In April 1879, Brush persuaded Cleveland's city fathers to allow him to demonstrate his arc lamp system in the city's downtown Monument Park. "When Brush flipped the switch on twelve arc lights, filling the square with instantaneous illumination, a crowd of ten thousand roared its approval, while ships moored in Lake Erie fired canon volleys and a band let loose 'with brassy strains of triumph'." Reporters compared "this new, unearthly light … to 'the brightest moonlight'" and, most wondrously, "'reading was a matter of perfect ease'" beneath its powerful glare. Brush received a contract to light Monument Square for a year, striking "the first blow in what would become a decades-long struggle between gas and electric companies for control of the streets" [20].

After Cleveland's arc-lamp debut, Brush dazzled tourists by lighting up Niagara Falls with 16 arc lamps on July 4th. Later in 1879 the California Electric Company in San Francisco bought two Brush dynamos to supply arc-lamp lighting via its own transmission lines to multiple customers, becoming the first US electric power station (utility) to do so. The following year the Grand Rapids Electric Light & Power Company in Michigan became the world's first commercial hydroelectric plant, relying on a nearby furniture company's water turbine to run their Brush dynamos.

In spring 1880 Wabash, Indiana, became the first town to fully light its streets with arc lamps, using a single cluster of eight lamps mounted atop the town hall to do the job. For weeks afterward thousands of visitors arrived on special excursion trains and "pressed together in the dark streets as Brush started his dynamo, filling the town with … a 'strange weird light, exceeded in power only by the sun, yet mild as moonlight'." The people, "'almost with bated breath, stood overwhelmed with awe, as if in the presence of the supernatural'" [21].

Compared to the gas lamp's 12 to 16 candlepower, arc lamps shed light of 2,000 to 6,000 candlepower, and were far more efficient, less expensive, and despite the 2,000 to 3,000 volts required to power them, safer. Although a few towns and cities pioneered the new lighting system for city streets and parks, it was factory owners who "usually led the way, since they were willing to pay extra for a light that produced more efficient workers." Large retailers, who used “the technology to lure curious customers” were also early investors. Because these early adopters typically acquired more lamps than they could use, “they often rented their surplus lamps to adjoining stores, or to the city … enough to light an adjoining street or two. In this way many towns and cities eased their way into the electrical future” [22].

As evening approached on the December solstice, 1880, the generators inside the Brush Electric Company’s central station on New York’s West 25th Street “roared to life and illuminated seventeen powerful new arc lights, lighting up Broadway for the three-quarters of a mile from Union Square up to Delmonico’s Restaurant at 26th Street” [23]. America’s “First Great White Way,” as it was later called, soon became the “greatest American showcase for electric street lighting.” Although “the city always turned off its gaslights around midnight,” from that December night onward “the carbon arcs flamed on until sunrise, ‘lighting up the deserted streets with unwonted splendor’” [24].

Bureaucrats and politicians from cities nationwide visited New York to see first-hand the city’s public lighting miracle, and “because Americans embraced the idea that their town’s standing on the great ladder of civilization could be measured by its ability to provide residents with the latest technological conveniences … neighboring municipalities soon felt the sting of inferiority” and climbed aboard the arc-lamp bandwagon [25].

“Soon cities across America would place orders for the Brush arc lights,” and before the end of 1881, “Brush arc light systems were illuminating the streets of New York, Boston, Philadelphia, Baltimore, Montreal, Buffalo, San Francisco, and other cities,” all served by central stations that housed the dynamos that powered the lamps [26]. Brush’s lamps soon commanded 80 percent of the world market as “the US quickly became the leader of electric arc lighting,” growing from 90,000 lamps in 1884 to 235,000 by 1890, “when virtually every US city was using arc lighting” [27].

While Europeans placed their arc lamps on posts, “Americans had the idea of lighting entire cities and villages by means of grid towers” that stood as high as 300 feet and were “equipped with 4 to 6 arc lights of 2,000 to 6,000 candlepower each.” They “burnt all night and all year (except at full moon)” [28]. The first of these “moonlight” or “moon towers,” as they came to be called, was built by the city of San Jose in California in December 1881. The cluster of arc lights atop the 237-foot tower illuminated the city with 24,000 candlepower. Moonlight towers were “the most energy efficient way of lighting a whole city” because they minimized the need for multiple individual arc lights, typically strung out on a series of lamp posts that lined long streets. The moonlight tower was therefore “the cheapest available method to light a complete city” [29]. The tower arc lights took root and endured especially in flat mid-western towns where skyscrapers were slow to sprout up and block the technology’s brilliant light.

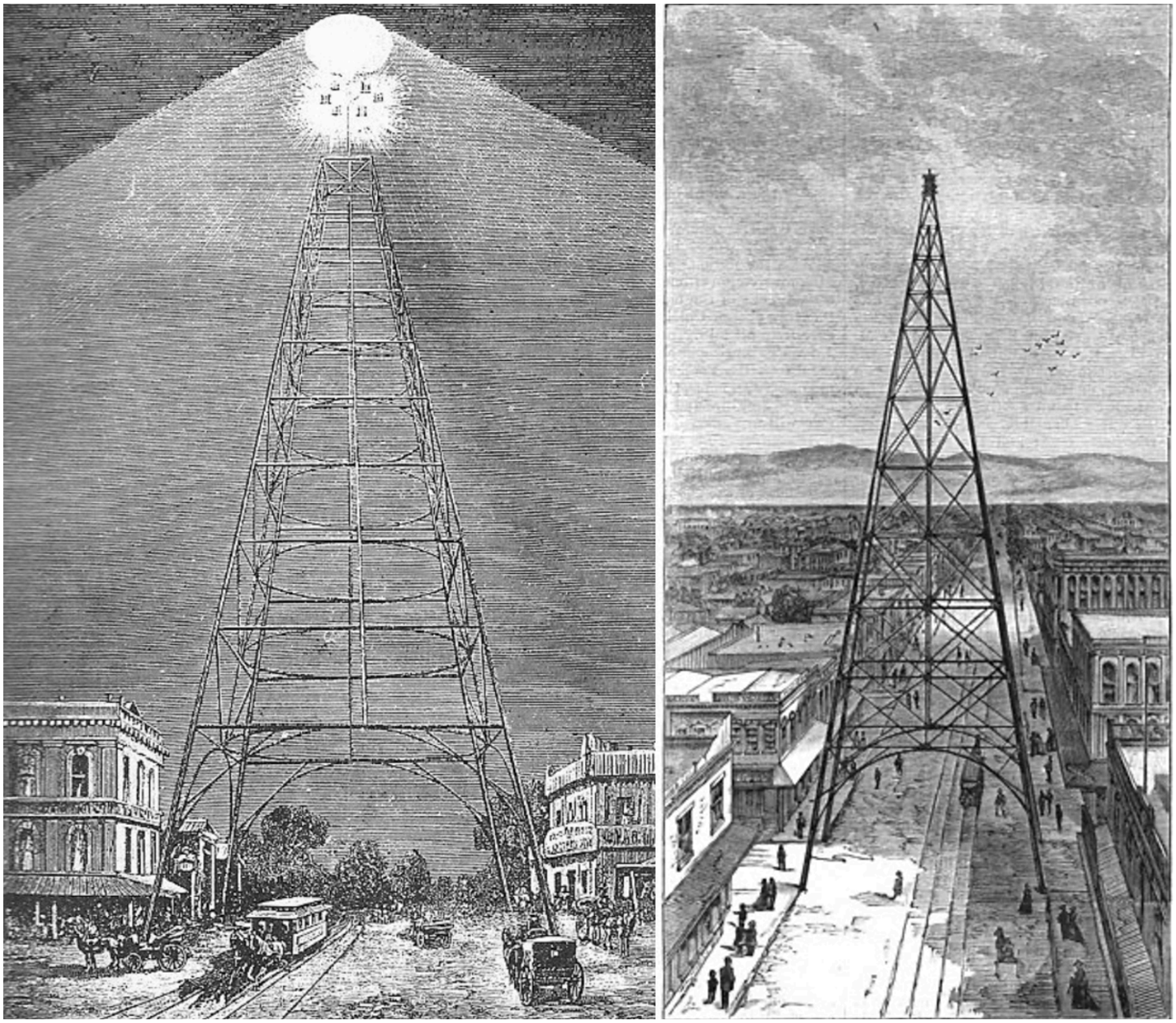

Figure 5: The pioneering 237-foot moonlight tower in San Jose, California was built and installed in 1881. The right side of the figure shows the tower during daytime and gives a sense of the scale of these towers, some of which exceeded 300 feet in height, that lit towns across the United States for decades. SOURCE: https://duckduckgo.com/?q=drawing+of+san+jose+historic+arc+lamp&t=h_&iax=images&ia=images&iai=https%3A%2F%2Fkrisdedecker.typepad.com%2F.a%2F6+++a00e0099229e88833010536e11adb970c-600wi

The arc lamps lit city streets and public spaces in North America and Europe well into the 20th century, but they had limitations. "When the arc light came indoors, illuminating large interiors such as railway stations, exposition halls, and ballrooms," the lamps "emitted an unpleasant hum that some compared to the sound of swarming bees. More damning, the harsh light beached out colors" and "cast an unforgiving spotlight on the human face, exposing every wrinkle, blemish, and stray hair" and many "vowed never to be seen near an electric light again" [30]. Arc lamps were not only too bright for ordinary residential and office spaces, but their voltages and intense heat were too dangerous for most indoor use.

One inventor, Thomas Edison, understood the limitations of the arc lamp, as well as the almost unlimited market opportunity those limitations created. In 1878, he started to make plans for an alternate system, one that would revolutionize indoor lighting and social relations over the course of the next century.

Edison and his "one-machine" vision of the grid is the subject of Part Two of this series on the electrification of the world.

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