AFD Ep 420 Links and Notes - From Electrochemistry to Electromagnetism [Bill/Rachel] - Recording Apr 3, 2022

- Note: This is probably a part one stage-setting episode for electrification, basically covering the necessary technological advances (mostly non-American) up to the 1880s (ending before the start of the current war after about 1888), with an emphasis on what was around before (things like arc lighting and coal gas lighting as well as in-house [factory] power generators without grid connectivity). Part two could be about urban electrification after the 1880s and things like electric street railways and the closely-related gradual ramping up of off-peak power production (instead of shutting off production during the middle of the day). Part three could be about rural electrification through the mid-20th century. And part four could be an epilogue stage-setting for future 3rd IR episodes on electronics, transistors, internet, and rural internet.

  The Electrochemistry Era
- In order to do anything technologically useful with electricity, there needed to be a way to create it and/or store it. Later in the episode we'll talk about electromagnetism as the breakthrough that unleashes the full power of the Second Industrial Revolution, but first we need to talk about the electrochemistry work of the First Industrial Revolution. Most of both of these topics are based on experiments conducted outside the United States, which is not something we usually focus on for this show, but it's extremely important foundational work that makes possible all of the technologically-driven economic advances of the United States during the 19th century.
- Italian scientist Alessandro Volta created the first battery in 1800, even though most of his understanding of how it worked was basically wrong. That made it difficult to correct some of the problems with that early battery, but various scientists kept working the problem – and in the meantime Volta's battery was at least good enough to study electricity and its potential uses in a more controlled way. Eventually in 1836, English chemistry professor John Frederic Daniell, teaching for the East India Company's military wing, invented the Daniell cell, which was about to become the basis for the first wave of very limited electrification in industrializing economies. To quote from the Wikipedia page on the History of the battery: The Daniell cell "*consists of a copper pot filled with a copper sulfate solution, in which is immersed an unglazed earthenware container filled with sulfuric acid and a zinc electrode. The earthenware barrier is porous, which allows ions to pass through but keeps the solutions from mixing. The Daniell cell was a great improvement over the existing technology used in the early days of battery development and was the first practical source of electricity. It provides a longer and more reliable current than the Voltaic cell. It is also safer and less corrosive. It has an operating voltage of roughly 1.1 volts. It soon became the industry standard for use, especially with the new telegraph networks.*"
- This battery was an example of electrochemical power. From the mid-1830s through the 1860s, various people were adding certain refinements or tweaks to the design of the Daniell cell, but the underlying acid battery with a relatively weak output was the same thing during this period. For example, Welsh scientist William Robert Grove developed the Grove cell in 1839, which was also acid based but included a very expensive platinum component and almost doubled the voltage per cell. The Grove cell variant ended up being preferred by the Americans and Canadians. We talked a fair bit about the limitations of telegraphy in our April 2021 episode on the Transatlantic Telegraph Cable, which was eventually laid with a brief success in 1858 and then laid again more successfully in 1866. One of the challenges all telegraphy faced was a weak signal that faded over distance. On land this was addressed with relay systems to essentially boost the signal, but this wasn't an option for the transatlantic cable. But one thing we didn't really talk about in that episode was the power source for all of this telegraphy, which

was revolutionizing communications and the operations of long-distance multi-jurisdiction businesses. And the answer to that is these acid-based Daniell cell or Grove cell batteries or their variants, apparently. Large banks of them were arrayed at telegraph offices to generate sufficient voltages to maintain long-distance pulses of dots and dashes on multiple parallel wires at a time. (Or just one or two cells if you were in a little office with only a couple wires.) The acid battery cells apparently had a nasty side effect of venting noxious gasses into the vicinity, nitric oxide in the case of the Grove cells, which was not ideal for the staff working in the telegraph office. It's a big no-no under modern OSHA standards. If they were lucky, they might have ventilation pipes carrying the fumes out of the building, but often they did not, and it was pretty rough. A modified Daniell cell from France called a "gravity cell" (because of its use internally of different gravity of various component ingredients) was developed in the 1860s and replaced Grove cells as the preferred telegraphy battery power source, not only because it produced more current but also because it didn't vent dangerous gas to its surroundings. It did however require continuous operation or else it would fail permanently. In general, these First Industrial Revolution wet batteries for telegraph systems had pretty short lives and had to be replaced every several weeks or so, and obviously they weren't rechargeable like many modern batteries.

- A lot of people during the period of the 1830s to the 1860s were continuing to work on ideas for totally different battery concepts or electricity generation sources. Telegraphy was the only meaningfully omnipresent use of electricity in industrializing countries during this period. But again, telegraph wires are a simple, low-current technology that doesn't really require huge amounts of power – a 2 volt battery cell was often enough to run a 20 mile telegraph wire connection and you could throw on some more cells to juice it a bit more. By contrast, almost any other practical application of electricity probably would need much more power than even an efficient mid-19th century battery could reasonably and cost-effectively deliver. We could and maybe eventually will do a whole episode on Second Industrial Revolution batteries or 20th and 21st century batteries, but in this episode we're trying to follow the early electrification story, so it's time to turn now to electromagnetism and power generators.

The Electromagnetism Revolution

- Chronological background from outside the US: Obviously there was lots of research, experimentation, and theorizing about electricity, magnetism, light and other rays, etc for thousands of years and especially during the 17th and 18th centuries. There was some sense that these were related and influenced each other, but they weren't unified as a complete system until the 1860s and 1870s.
- In 1865 and 1873, Scottish scientist James Clerk Maxwell had the paramount breakthroughs that it was all the same thing: *1865 – James Clerk Maxwell publishes his landmark paper A Dynamical Theory of the Electromagnetic Field, in which Maxwell's equations demonstrated that electric and magnetic forces are two complementary aspects of electromagnetism. He shows that the associated complementary electric and magnetic fields of electromagnetism travel through space, in the form of waves, at a constant velocity of 3.0 × 108 m/s. He also proposes that light is a form of electromagnetic radiation and that waves of oscillating electric and magnetic fields travel through empty space at a speed that could be predicted from simple electrical experiments. Using available data, he obtains a velocity of 310,740,000 m/s and states "This velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws." [...] 1873 – J. C. Maxwell publishes A Treatise on Electricity*

and Magnetism which states that light is an electromagnetic phenomenon.
https://en.wikipedia.org/wiki/Timeline_of_electromagnetism_and_classical_optics

- As with Volta's battery from 1800 that Volta himself didn't really understand, there were inventors already working on the relevant technologies prior to Maxwell cracking the science on electromagnetism. The legendary English scientist Michael Faraday, who often personally knew and collaborated with some of the inventors we already discussed in electrochemistry, and whose research laid most of the observational foundations of Maxwell's theories on electromagnetism/light, was working on experimental magnetic dynamos back in the 1830s, although they were hand-cranked which is not all that useful. (Later, larger iterations were literally horse-powered.) Early dynamos also used permanent magnets instead of the more effective electromagnets. Therefore, this dynamo technology was refined significantly in 1866 as the breakthrough on electromagnetic science happened, which unlocks non-battery electric power generation. (more detail appears to be listed here: https://en.wikipedia.org/wiki/Electric_generator – all UK/Europe – and here https://en.wikipedia.org/wiki/Dynamo)
    - Hydroelectric power: Existing water wheels and water turbines were generally the first sources of electric power generation, which is probably no surprise (and is certainly more efficient than a hand-crank). In the US, this first appeared in Grand Rapids, Michigan, in 1880, when a chair factory's water turbine was used to generate power for a small number of nearby street lights to help enhance the business's storefront component. (Carbon arc lamp electric street lighting had been an available technology for quite some time but was always hard to implement because of the lack of power supply; so, traditionally for most of the 19th century up to this point, people used coal gas lighting instead for street or factory illumination.) In 1881, an existing flour mill at Niagara Falls had some of its turbine capacity reassigned for electric power to jazz up the site with lights for the benefit of tourists. In 1882, a paper mill in Appleton, Wisconsin actually used hydroelectric power to generate enough electricity for plant operations directly. Dozens more of these conversions happened across North America within just a few years. The first purpose-built hydroelectric dam was in Austin, Texas in 1893. https://www.eia.gov/kids/history-of-energy/timelines/hydropower.php
- In the late 1870s/early 1880s, Edison was about to induce demand for widespread generation of electricity (which, outside of in-house factory power generators, I guess was previously pretty limited to acid battery powered telegraph systems since the mid to late 1830s) with the innovation of a commercially viable lightbulb and construction of grid-based power distribution systems in 1878 and 1882. (We will eventually come back to grid electrification and lighting in its own right in a future episode, but it's a huge topic, so we're working up to it.)
    - Also, as a side note, his work on lightbulb design ended up with the Edison Effect and the first patent (1883) of an "electronic" device although that is a retrospective name and identification because "electrons" weren't named until 1897. https://en.wikipedia.org/wiki/Thermionic_emission
    - *The first large scale central power station in America was Edison's Pearl Street Station in New York, which began operating in September 1882. The station had six 200 horsepower Edison dynamos, each powered by a separate steam engine. It was located in a business and commercial district and supplied 110 volt direct current to 85 customers with 400 lamps. By 1884 Pearl Street was supplying 508 customers with 10,164 lamps.*[17] https://en.wikipedia.org/wiki/Electrification
    - Nikola Tesla was hired in Europe to install Edison lights and was quickly identified as a rising talent with an already very high level of relevant education, with the company moving him to the US by 1884

- *Although the first power stations supplied [direct current](#) (*the electric current only flows in one direction; the early acid batteries are an example of direct current generation.), *the distribution of [alternating current](#) (*the electric current periodically reverses direction) *soon became the most favored option. The main advantages of AC were that it could be transformed to high voltage to reduce transmission losses and that AC motors could easily run at constant speeds.*
- 1884 steam turbine dynamo (UK: Charles Parsons … his technology arrived in the US via Westinghouse at their Air Brake [discussed on our recent Air Brakes episode!] facility in Pittsburgh, although American-made competitors were already in use by 1895) https://collection.sciencemuseumgroup.org.uk/objects/co51109/parsons-steam-turbine-generator-1884-engines-steam-engines-generators-turbines: *Forerunner of the turbo-generators that today provide most of the world's electricity. It is the first experimental prototype produced by Charles Parsons, who promoted the turbine as a smaller and more efficient alternative to the steam reciprocating engine. In the turbine, the expanding steam works continuously as it passes through many turbine stages. This gives far higher efficiency than was possible with the steam engine. The turbine combines freedom from vibration with high speed (in this case, 18,000 revolutions per minute) suited to electrical generators. The turbine was also employed in marine propulsion. In 1894 Parsons launched his first turbine-powered boat, the SS Turbinia, which reached previously-unattainable speeds of up to 34 knots.*
- 1888 electromagnetic induction motors (Ferraris and Tesla, separately): https://en.wikipedia.org/wiki/Induction_motor
    - In 1824, the French physicist François Arago formulated the existence of rotating magnetic fields. He demonstrated this principle with a rotating copper plate and a magnetized needle. In 1879, Walter Baily also demonstrated this principle by manually turning switches that caused a fixed electromagnet to shift its magnetic fields between four successive poles, causing a copper disk placed above the electromagnet to spin as it was affected by the rotation of the magnetic forces. This was the first primitive version of an induction motor.
    - An induction motor consists of a stationary stator that has coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft producing a second rotating magnetic field. The rotor magnetic field may be produced by permanent magnets, reluctance saliency, or DC or AC electrical windings.
    - An early single-phase induction motor was created by Hungarian scientist Ottó Bláthy. A single-phase induction motor does not have a unique rotating magnetic field, but has two poles that reverse polarity. A secondary magnetic field is needed to determine the direction of rotation for the rotor. His major innovation is that his motor didn't require any switches, or commutators, to keep the magnetic fields rotating. Bláthy's invention was later used for the purpose of … electric metering, which is obviously important for the future power utilities.
    - *The first AC commutator-free polyphase induction motors were independently invented by Galileo Ferraris and Nikola Tesla, a working motor model having been demonstrated by the former in 1885 and by the latter in 1887. Tesla applied for US patents in October and November 1887 and was granted some of these patents in May 1888. In April 1888, the Royal Academy of Science of Turin published Ferraris's research on his AC polyphase motor detailing the foundations of motor operation. In May 1888 Tesla presented the technical paper A New System for Alternating Current Motors and Transformers to the American Institute of Electrical Engineers (AIEE) describing three, four-stator-pole motor types: one having a four-pole rotor forming a non-self-starting reluctance motor,*

    another with a wound rotor forming a self-starting induction motor, and the third a true synchronous motor with a separately excited DC supply to the rotor winding.
  - *George Westinghouse, who was developing an alternating current power system at that time, licensed Tesla's patents in 1888 and purchased a US patent option on Ferraris' induction motor concept. Tesla was also employed for one year as a consultant. Westinghouse employee C. F. Scott was assigned to assist Tesla and later took over development of the induction motor at Westinghouse. Steadfast in his promotion of three-phase development, Mikhail Dolivo-Dobrovolsky invented the cage-rotor induction motor in 1889 and the three-limb transformer in 1890. Furthermore, he claimed that Tesla's motor was not practical because of two-phase pulsations, which prompted him to persist in his three-phase work. Although Westinghouse achieved its first practical induction motor in 1892 and developed a line of polyphase 60 hertz induction motors in 1893, these early Westinghouse motors were two-phase motors with wound rotors until B. G. Lamme developed a rotating bar winding rotor.*
- 1880s: On-board auxiliary power for (passenger) trains using the steam power for electricity functions inside the train https://en.wikipedia.org/wiki/Head-end_power
  - *The North British Railway in 1881 successfully generated electricity using a dynamo on the Brotherhood steam locomotive to provide electrical lighting in a train, a concept that was later called head-end power. High steam consumption led to abandonment of the system. Three trains were started in 1883 by London, Brighton and South Coast Railway with electricity generated on board using a dynamo driven from one of the axles. This charged a lead-acid battery in the guard's van, and the guard operated and maintained the equipment. The system successfully provided electric lighting in the train.*
  - *In 1885, electric lighting was introduced in trains in Frankfurt am Main using a Moehring-type dynamo and accumulators. The dynamo was driven by pulleys and belts from the axle at speeds of 18 to 42 mph, and at lower speeds the power was lost.*
  - *In 1887, steam-driven generators in the baggage cars of the Florida Special and the Chicago Limited trains in the US supplied electric lighting to all the cars of the train by wiring them, to introduce the other form of head-end power.*
  - *The oil-gas lighting provided a higher intensity of light compared to electric lighting and was more popularly used until September 1913, when an accident on the Midland Railway at Aisgill caused a large number of passenger deaths. This accident prompted railways to adopt electricity for lighting the trains.*
  - *Throughout the remainder of the age of steam and into the early diesel era, passenger cars were heated by low pressure saturated steam supplied by the locomotive, with the electricity for car lighting and ventilation being derived from batteries charged by axle-driven generators on each car, or from engine-generator sets mounted under the carbody. Starting in the 1930s, air conditioning became available on railcars, with the energy to run them being provided by mechanical power take offs from the axle, small dedicated engines or propane.*
  - *The resulting separate systems of lighting power, steam heat, and engine-driven air conditioning, increased the maintenance workload as well as parts proliferation. Head-end power would allow for a single power source to handle all those functions, and more, for an entire train.*