Electricity and the power grid 2

Electricity is fascinating.

> The energy used by a light bulb to light up a room is being produced **in almost the exact same time** at possibly hundreds of kilometers of distance, and we have no way to perfectly know from which power plant it comes from.

Most of us are lucky enough to experience and use electricity on a daily basis, in fact we may say that our lives rely heavily on the continuous availability of this source of power. This said, we generally know very little about the complexity behind its production and management.
This chapter is dedicated to the introduction of this incredibly interesting, though intricate, topic and has the goal to lay the foundations necessary to fully understand some of the decisions that were made in our statistical analysis.

I will therefore start with few notable historical notions around electricity, to then proceed with the description of how it is massively produced and transferred, thanks to current electrical grid systems.

2.1 Historical Notions

Many great personalities in the history of mankind have worked on this subject, contributing to our evolution and shaping our current society.
It's staggering to think that the first concrete studies on electricity date back to Ancient Greece and **Thales of Miletus**, who observed and described static electricity with rods of amber[1].

This said, the topic would remain little more than an intellectual curiosity for millennia [1], until major breakthroughs were achieved in the 18^{th} century, mainly due to **Benjamin Franklin**, who proved the electrical nature of lightnings.

[1] Exactly from this phenomena stands the etymology of the word "electric", indeed *elecktron* is the Greek word for amber.

However, the first big step forward in electrical science was made by the Italian physicist **Alessandro Volta**, who created the first battery (an electrochemical cell, made from alternating layers of zinc and copper) in the year 1800. The 19^{th} century also marked the birth of **electromagnetism** [1], a new branch of physics centered on the discovery of the unity of electric and magnetic phenomena. **Hans Christian Ørsted** observed that a compass needle was deflected from magnetic north by a nearby electric current, this idea captured the attention of the French physicist **André-Marie Ampère**, who begun developing a theory to understand the relationship between electricity and magnetism, stating the principle that later on became known as Ampère's law.

All the experiences and experiments presented so far have still very little in common with our modern idea of electricity, yet we may consider as a first *tangible link* the idea that alternating current technology (the one we experience and use nowadays) is rooted in **Michael Faraday**'s discovery in 1831 that a changing magnetic field can induce an electric current in a circuit.

In the last 200 years we have learnt how to massively produce and store electricity: we live in cities entirely powered by electric current and we have domestic appliances that we are able to plug in and use at any time of the day. Furthermore, electricity plays a big role in our safety and health.
As we may imagine, it not trivial to ensure that the correct amount of energy is produced and transferred where it is needed, at any time. The next section is devoted to delve more into the technicalities of this topic, presenting some aspects of the infrastructure behind electric energy of crucial importance and therefore to be considered in our future research work.

2.2 The Power Grid

In the introduction of this chapter I affirmed how the electricity we use in our daily lives has a very particular aspect, that is it must be consumed at the exact same time as it is produced, no matter how far the producer and consumer might be. In this section I will talk about the incredible infrastructure that enables this process and allows it at an incredibly large scale: possibly being [4] **"one of humanity's most important engineering achievements"**.

All notable notions to understand the functioning of this process are summarized in the concept of the **power grid** (or electrical grid), which deals with the generation, transmission and distribution of electricity. I will mainly keep the focus on the first two aspects, explaining some fine details that will be key to understand the production strategies of plants from different technologies.

Before doing so, let me just talk a little more about the immediacy between energy production and consumption in the power grid. This might appear counter intuitive at first glance, since we experience every day that

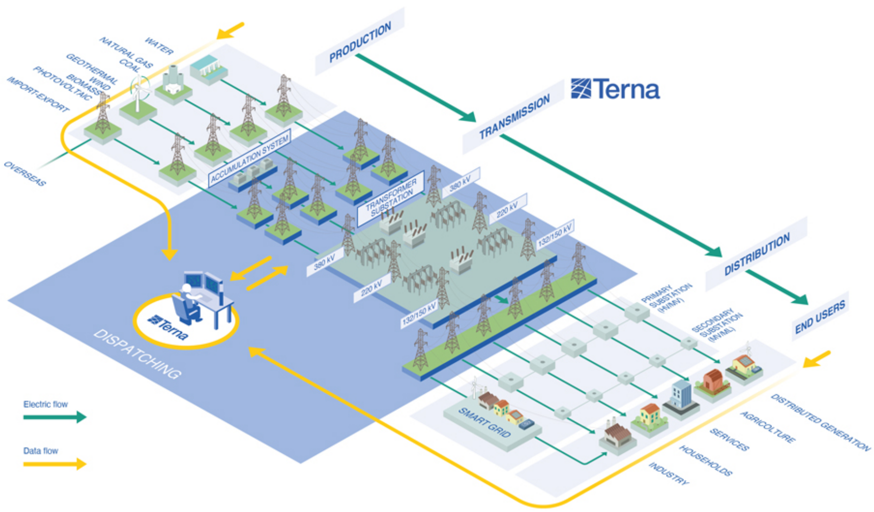

FIGURE 2.1: Visualization of the Italian Power Grid from [8]

electrical energy can be stored in the lithium batteries of our smartphones. This technology, though, only works at a low scale and trying to replicate it for the electricity used to power a manufacturing plant or a house is very hard and expensive.

This said, it actually exists a version of "battery" that operates at a large scale, but it has a completely different aspect than the usual concept of electrochemical energy generators. What I'm talking about is often referred to as *pumped-storage hydroelectricity* and deals with a specific type of power plants that is composed of two different water reservoirs located at different altitudes, an electric turbine close to the lower reservoir and a pump that links the lower water source to the upper one.

This setup stores gravitational energy in the water contained in the higher storage point, which is filled with water pumped from the lower reservoir. The pumping process requires energy (electricity) to happen, this is usually done in period of the day where electricity has a lower cost, at night for instance. Conversely, in the times of the day when energy is more demanded, the gravitational energy stored in the upper source is converted via a turbine into electricity: the upper source is gradually emptied and the lower one is filled, creating energy as a result. Obviously, most of the water is retained in this process, mimicking a process similar to that of a "common" battery.

2.2.1 Power Grid: Generation

The process of generating electricity is very broad and many types of power plants exists, of course with different characteristics, advantages and disadvantages. They may be powered by both renewable and non renewable resources, nevertheless, all the plants have in common the concept of converting a particular kind of energy, in a different one: electrical energy.

At the end of the previous section we have talked about conversion from gravitational potential energy, however, the he most widely used method to generate electrical power, comes from the conversion of heat and thermal energy. This accounts for many different ways by which water is heated to steam and the generated pressure and thermal energy is converted into the rotational energy used to move a turbine. Rotational energy is then transformed into alternating current by linking the turbine with a *rotor* (made of magnets) and a *stator* (generally composed by three coils of copper wire), which together form an electric generator. This process happens at an incredible large scale, with turbines that can reach 1500 MW of power. Examples of this kind of energy transformation are all the plants fueled by oil, coal or natural gas but also renewable geothermal plants.

The remaining methods deal with different types of energy conversion, generally from renewable resources. Examples of this are the conversion of potential energy within hydro stations or the direct conversion made by solar photovoltaic cells: from light, into electricity.

Solar energy is basically cost-free with respect to any fuel-powered source of energy, it's also incredibly more environmental friendly since it does not produce carbon dioxide as a side effect. However, it also has two major disadvantages, the first comprehensible to everybody: it is not always available, since it is affected by bad weather and stops after daylight hours. The second, though, is more subtle to understand and is represented by the absence of *inertia* of this power source.

As we have stressed in the previous parts, the energy needs to be consumed in the same instant it is produced, therefore it is crucial to ensure that supply meets demand at every time of the day. One way to make sure that this happens is through the momentum of the combined sources of power that are linked together to generate electricity and are made by huge rotating systems (turbines). When an additional load is added to the grid, this is felt instantly and has the effect of slowing partially the rotation of the generators, but still it does not create other threats to the system. This concept of being able to generate the right amount of energy even during localized faults or disturbances is called [4] *inertia* of the system, and plays a key part into keeping our energy supply stable and safe. Most importantly, it gives the energy regulators the right amount of time to adjust the amount of electricity to be produced, so that it always follows the actual load from the grid.

2.2.2 Power Grid: Transmission

Power plants are generally located far from urban areas, for a matter of cost reduction or, as for the case of renewable-energy power plants, for a matter of accessing easier the primary resources used.

This is the reason why electrical energy usually needs to be transmitted for long distances: from power plants, to the most densely populated or industrial zones, where it is consumed.

Transmission usually happens in three phases and at a high voltage: the current is boosted in voltage by transformers at the power plants before entering the transmission phase, to ensure that the energy dispersed by Joule effect is minimized in the transportation. This happens at a cost of a greater safety concern, since current in high voltages is able to flow across materials where it usually can't[2].

The example above is just one of many expedients used to reduce as much as possible the waste of energy in the transmission phase, since all the power lines are engineered and built with this precise scope.

This, though, is not the only important aspect of the energy transmission problem, since we should also consider how the various transmission networks are connected. This issue is so crucial that we will analyze more in depth an example underlying the importance of this case in the last section of this chapter. Subsequently, we will also tackle the Italian case, in the following chapter.

All in all, the continuous rise of renewable sources of energy, electric panels and the related process of decentralization of energy production, will most likely contribute in the following years to a change in the structure of the transmission infrastructure. This said, the topic remains one of crucial importance and we will encounter it again in our analysis.

2.2.3 Power Grid: Distribution

The last component of the Power Grid is distribution. We have talked in the previous sections about how energy is transmitted towards urban areas, where it is mostly consumed, at a high voltage. Very close to big urban areas are then located some facilities known as *substations*, where transformers reduce the voltage of the alternating current arriving from the power plants, both for safety reasons and also to make it more easily disposable. One different, but equally important feature of substations is represented by the so called *breakers*, mechanisms that serve the goal of isolating parts of the grid, in case of fatalities.

We know that electric energy flows almost in real time from the power sources to the consumers, thus if errors occur in the grid, these may propagate instantly to every connection in the system, creating a cascade of problems and posing a serious threat to the stability of the whole infrastructure.

Substations are made to mitigate any problem that may occur and they do so by interposing a layer between energy generation, transmission and its distribution to the public and industry. From there are also managed

[2]Such as, for instance, air, creating an extremely dangerous phenomenon called *electric arc*.

all the finer processes of distribution of electric current to any industry and building that may need it.

2.3 US Texas: 2021 Power Crisis

It is crucial that every part of the previously presented system works as is supposed to, with particular emphasis to the equilibrium between the energy produced and consumed in real time.
To further stress the importance of this topic, we may just consider the devastating **power crisis** occurred in Texas in February 2021. From February 10, in fact, the US State was hit by a series of severe winter storms, which caused great damages to some of the power plants in Texas, freezing part of the wind turbines and leaving all the power equipment which was not correctly winterized, vulnerable to the extraordinarily low temperatures.
This, together with the increased demand of energy due to the cold temperatures, created a big unbalance between the production and supply of electricity.

To cope with the dangerous situation, the ERCOT[3] decided to began rotating outages [2], a procedure that consists in removing power from area to area, so that no single neighborhood is down for long time, and has the aim to lessen the stress on the electric system.
This managed to avoid completely frying the grid for just a matter of minutes, leaving though more then 4 million people without power and causing damages to properties for approximately 195 millions of US dollars.

This said, the extreme meteorological conditions were not the only cause of the power crisis in Texas [3], since we need also to take into account the very peculiar characteristics of the grid in this state. In fact, Texas is the only US state to be almost autonomous for what concerns the production and distribution of energy, and has an isolated power grid from all the other states. This decision was taken with the mainly political aim of obtaining greater autonomy in the regulation and commercialization of electric energy, and implied that Texas was unable to import enough energy from other states in a moment of desperate need and was finally unable to cope with the internal shortages.

This example highlights how critical is to operate the grid in a safe and controlled way, but also stresses the importance of the prevention of possible shortages via the construction of powerful connections with neighbouring states, to be used in case of need. Indeed, this is what happens in Italy and Europe, where things work in a very different way.
In the following chapter we will start explaining exactly how the Italian electricity market is divided into six different *bidding zones* which are interconnected and also able to transfer electricity from and to all the neighbouring states.

[3]Electric Reliability Council of Texas, in charge of operating Texas' power grid and managing part of the related (deregulated) market