Electricity Markets and Price Forecasting

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Abstract

In this essay for the course Fundamentals of Energetics, we aim to provide a comprehensive introduction to electrical energy markets. We will explore the rationale behind these markets, their mechanisms, and a brief historical overview. Special attention will be given to the Italian energy markets, setting the stage for a discussion on price-forecasting techniques. Finally, we will present a case study to demonstrate a practical approach to the forecasting challenge.

Contents

1 The Good

There is no need to say that electrical energy (EE) is a fundamental vector of energy in our society as of today. To get a numerical feeling, almost 40% of U.S. primary energy undergoes conversion to EE (fig.1). Indeed, balancing the disadvantage of a measly 35% average rate of conversion among all sources (fig.1) is easy: not only has EE historically been a mean of growth of humanity through lightning, other industrial and residential appliances, fairly easy long-range distribution and so on, but also it is the vector of choice -if not the only one- for renewable non-fuel primary sources, as it is outlined in fig.1 too.

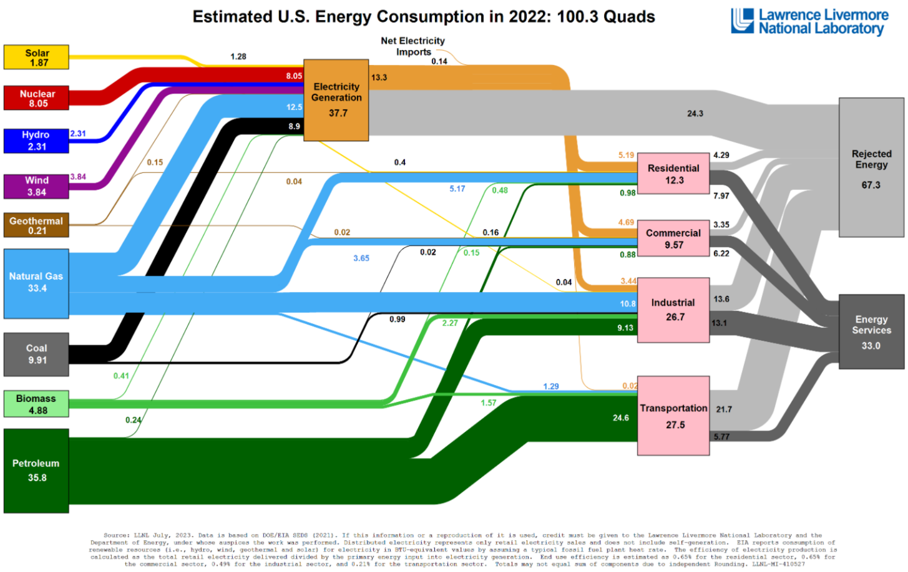


Figure 1: U.S. primary energy consumption estimated by LLNL energy department. Note that: A quad is a unit of measurement for energy equal to 10^{15} British Thermal Units (BTU). One BTU is the amount of heat it takes to raise 1 pound ($\sim$ 1 pint) of water by 1 degree Fahrenheit.

Wealth While discussing the importance of EE, one should also consider that, overall, electrical energy significantly improves the quality of life by providing the means for comfort and technological advancements. It indeed plays a central role in raising living standards and supporting economic development as it is shown in fig.2 where one can get a rough idea on how annual average electricity generation per person is correlated with the wealth of a country and fig.3 that highlights temporal trends in annual average electricity generation per person: developing countries like China and India show a clear rising in per capita electricity generation among the last decades [16].

Load electrification Furthermore, also developed countries like Italy are moving to a system that is more electric: heat pumps are now the heating device of choice for households and electric cars are estimated to be around 6 millions in 2030.

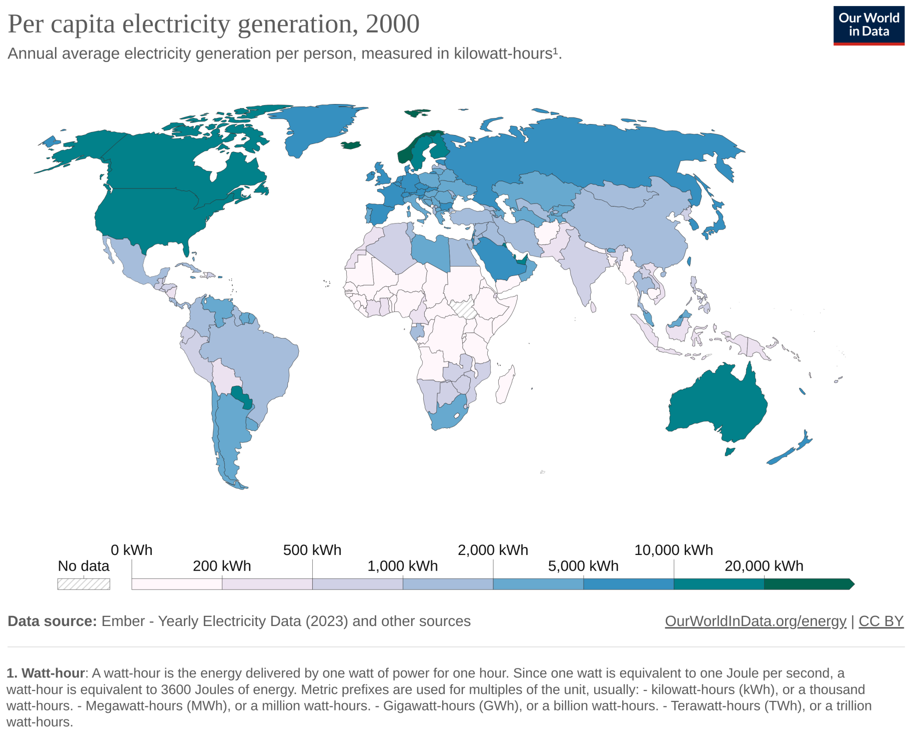


Figure 2: Per capita electricity generation in 2000 as reported by Our World in Data [16] project. It is interesting to look at the plot while also considering the wealth of each country.

Economics We would like to have a glimpse into capitals involved in the energy (and EE) business, as a tool to further investigate energy importance worldwide.

In economic sciences, goods are broadly divided into three categories: first necessity, standard and luxury goods. A good falls in a certain category depending on the shape of the *burden curve* associated to it: that is the curve representing the percentage of expense dedicated to the acquirement of the subject good versus the richness or wealth (following a certain

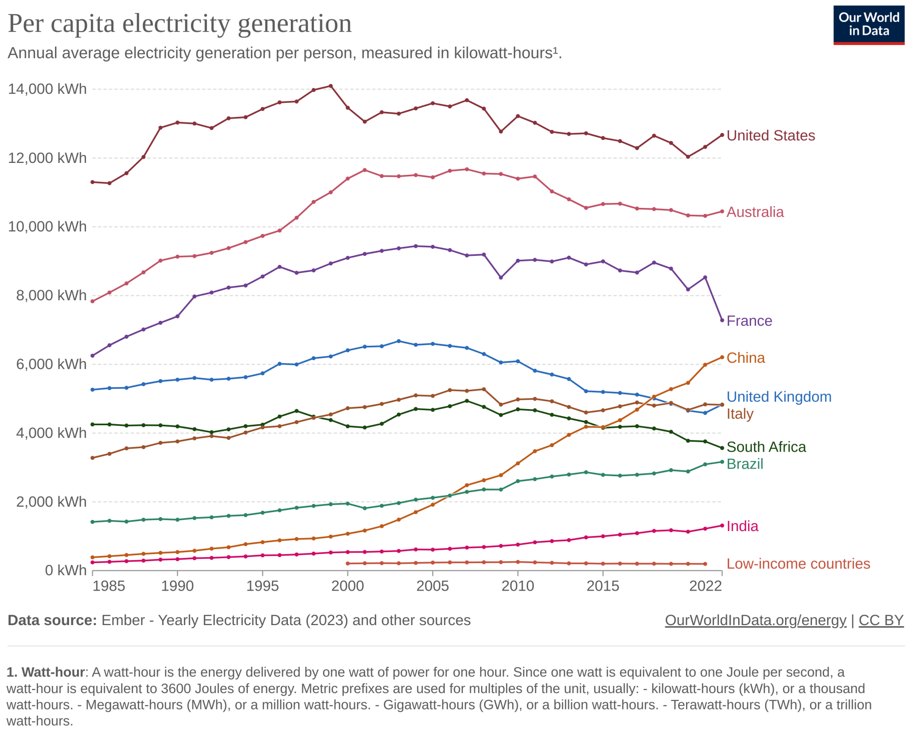


Figure 3: Temporal trend of per capita electricity generation for various countries among many years starting from 1985. It is interesting to note the overall increasing trend, which is exacerbated and present nowadays in developing countries, while it has become a plateau in developed countries. The latter phenomenon could be correlated to the aim for energy efficiency [16].

indicator) of the population. In case the curve rises we have a luxury good, if it is flat it is considered a standard good and when it declines then we are in front of an essential good. We report an analysis (Fig.4) made by the Italian news service *Staffetta Online* [2] showing EE's burden curve and that EE is indeed a first necessity good by economics terms.

How much of the world economic resources are devoted to energy and EE? How much does this weigh on the economical budget of a nation or a family? While Fig.4 is a good indicator, in Italy, for the latter question, answering the other questions is a challenging task, given the complexity of the good, the system and the business, as both private and public players are involved. Among the many indicators one could look into, we report the global energy investment in energy in Fig.5 (divided in clean

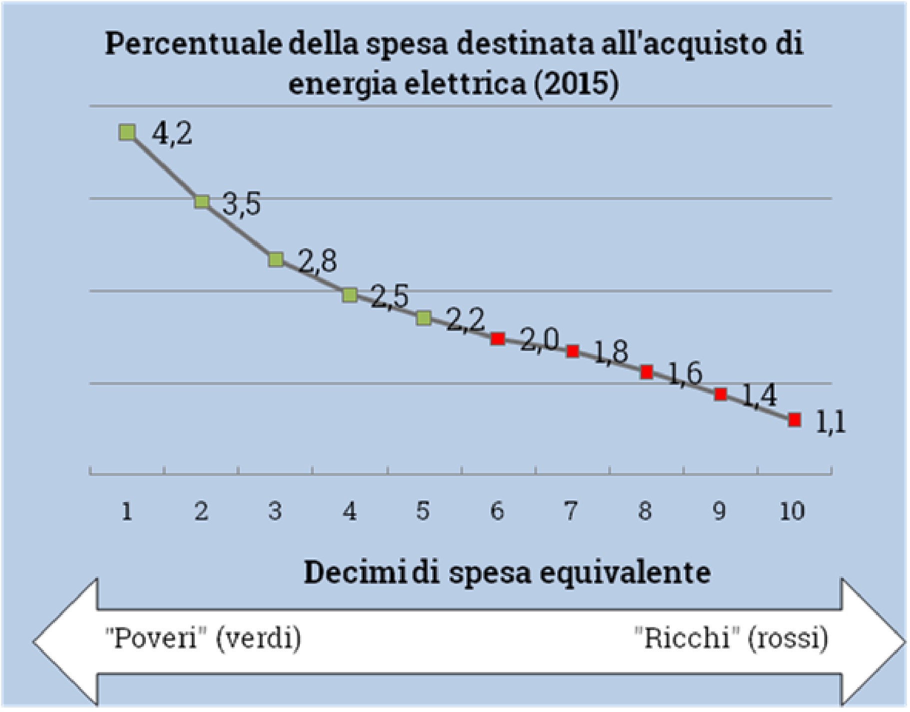


Figure 4: Taking as a source Istat data (Italian National statistics institute), from the poorer (left) to the richer (right) slice of the population, *Staffetta Online* [2] reports the percentage of expense dedicated to acquiring EE for the population. In this framework, EE is a first necessity good.

and fossil fuels), since we intend this to be a good metric for energy capitals: first of all the investments are closely correlated with the value of energy production, furthermore it is the demand in energy that justifies these investments.

The plot from the International Energy Agency (IEA) outlines global energy investment after the Covid-19 pandemic [3]. While IEA focuses on the recovery from the slump caused by the Covid-19 pandemic and the response to the global energy crisis, showing that they have provided a significant boost to clean energy investment -IEA, comparing estimates for 2023 with the data for 2021, states that annual clean energy investment has risen much faster than investment in fossil fuels over this period (24% vs 15%)- we want to focus on the total capital invested in energy, e.g. in 2022: circa 2.6×10^{12} USD. Considering, just to get a loose estimate, that 40% of this budget is dedicated to the EE business (assuming that the typical ratio of EE to primary energy -Fig.1- is also the ratio between investments, which is definitely wrong yet we are focusing on order of magnitudes here) we get that worldwide investments in EE in 2022 are comparable to half the Italian GDP [4].

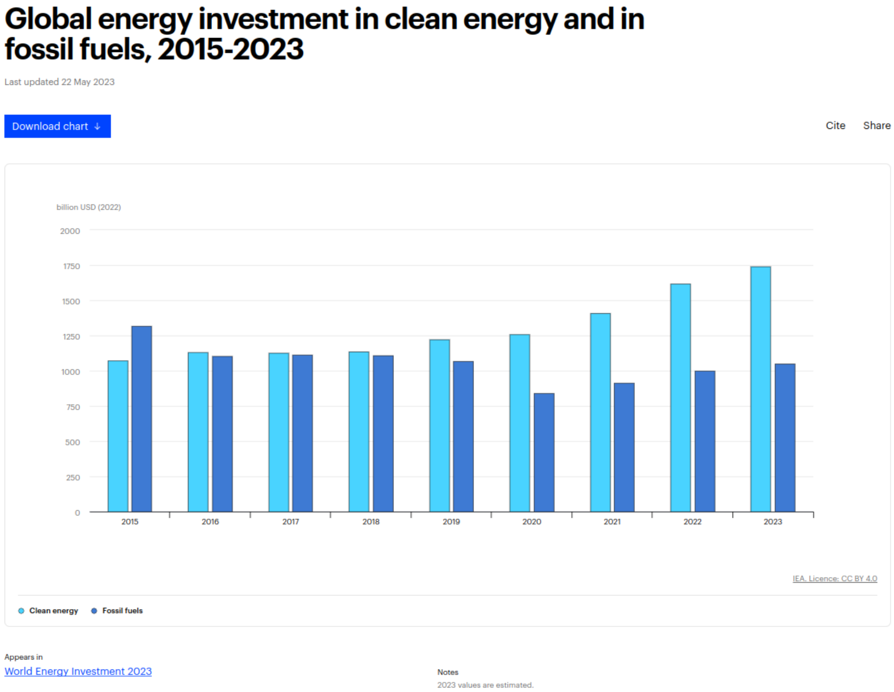


Figure 5: The recovery from the slump caused by the Covid-19 pandemic and the response to the global energy crisis have provided a significant boost to clean energy investment [3]. Looking at the total expense, around 2.6×10^{12} USD were invested worldwide in the energy business in 2022.

1.1 EE Characteristics

Among EE's many characteristics, *grid equilibrium* or simply *equilibrium* is fundamental: namely, the supply of electrical energy shall always match the demand. Not only having low supply would lead to a collapse of the system or blackouts, but also a supply that's too high can cause many problems such as overheating and wearing of the components (for examples, see Fig.25 in appendix A). In general, low variances of the supply can be tolerated by the system (the grid) up to certain values, yet the system should ensure continuity and quality of current parameters like voltage and frequency.

Quality of EE In Italy, EE supply parameters are subjected to the *CEI EN 50160* [12] regulation: in particular for low-voltage users, voltage slow variations should always be in the range $220V \pm 10\%$ and frequency tolerances around the nominal value of $50Hz$ should amount up to 5% all the time while being up to 2% for 95% of the time.

Load-supply imbalance How is the quality of current parameters, voltage and frequency, affected by the excess/scarcity of power supply compared to the load? As a thought experiment we can imagine that our energy system is comprised of just a combined cycle generator as the supplier that is in equilibrium with the loads. However when another load is switched on, a voltage drop will come upon our system. In other words, the power generated by the motor is not enough to power the new complex of loads. How can this be tackled? First of all one could accelerate the generator: by opening some valves one can burn fuel faster and increment the speed of the turbine. However, since mechanical rotation is transformed to AC with the same frequency, using this one generator to account for the voltage drop would lead to an increase in frequency.

The situation described above, however, is a strong simplification of the system: first of all the generator considered above is assumed to be of the *synchronous* type, i.e., for our purposes, mechanical and electrical frequency coincide all the time. But also *asynchronous* generators can be used, either coupled with an inverter (namely a frequency converter), a synchronous generator, or an accumulation system, where the EE is *stored* and retrieved back later, in which case the retrieval is truly a new generation, and can be implemented at the desired frequency.

Capacity, flexibility, smart grid Going back to our thought experiment, instead of having the one generator turn faster, we could increase the supply by turning on another generator, or ask some users to lower momentarily their consumption of power. Those two possibilities give birth to two important concepts: *capacity* and *flexibility*. With the first we intend the ability to book (and pay with options) power in advance: a certain supplier is remunerated to be ready to fire off an EE supply more or less last minute in order to balance the grid - note that, even if no energy is then asked to the supplier, still some kind of remuneration is due. Same can be true when the supply exceeds the load: some EE can be stored, or some could in principle be absorbed by a shedding load - this operation, even if it is a waste, could be the best option available in the presented situation. These options, together mainly with the disposability of a particular user to reduce their load momentarily, are described by the term flexibility. When integrating these solutions with intelligent algorithms and predictions, plus other innovative solutions, we call the grid a *smart grid*.

Non-dispatchability For our thought experiment to get close to reality, we must consider renewable energy sources (RES). Each source brings inherent differences when dealing with the produced EE: think about wind energy, which is generally converted to EE through an asynchronous generator (the blades angular velocity can not be controlled), or photovoltaic cells that first produce DC current, or biofuels that can be burnt in both synchronous and asynchronous generators. However, when dealing with some RES the main source of problem is indeed *non-dispatchability*: one cannot control when and how much electrical energy will be produced. This, and other factors like perturbations in the sky covering the direct sunlight or lowering wind speed, make some RES not consistently dependable and/or difficult to predict.

Storage Furthermore, although it is true that EE cannot be strictly created, stored, and provided at a later time, since it will change type of energy (e.g. mechanical energy in flywheels, gravitational in hydroelectric plants and chemical in batteries), and although storage, conversion and accumulation are costly by mean of efficiency and research effort, or just not feasible to some volumes of energy or power, storage is an important tool to assure grid equilibrium.

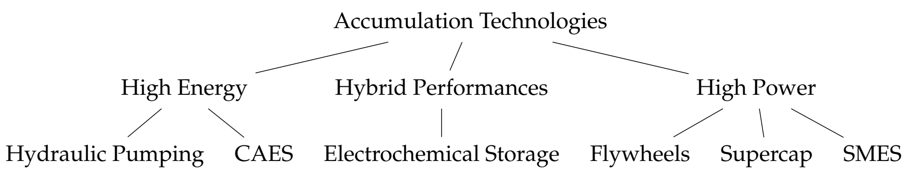


Figure 6: Different accumulation technologies are used for different purposes. The main categorization comes from Energy vs Power Output ratio: technologies on the left can accumulate more energy yet they will release it slowly, while technologies on the right will release far less energy but faster, thus they are able to deal for example with instantaneous peak loads.

Knowledge is key To sum up: ever-evolving different tools are used to tackle grid equilibrium and have an adequate electrical system, which is also changing as needs evolve. Since supply should always match demand, the question how much EE one should buy, is a complex one. The aforementioned factors are only some that come in relevant when dealing with how much energy should one buy in advance, strongly influencing the price of EE as a good. To conclude, making accurate predictions, when possible, can be a crucial tool.

1.1.1 Adequacy

Among the peculiarities of any electrical system is the need to ensure, moment by moment, that the energy demanded by the entire set of consumers (households and businesses) is always balanced by the energy produced by power plants. A system is considered adequate [1] when it is equipped with a sufficient level of production resources, storage, flexibility (e.g., consumers willing to voluntarily reduce their load), and transport capacity to meet the expected electrical demand at every moment, including a reserve to cope with forecasting errors in demand and production (e.g., from renewable sources) and the consequences of possible failures and network events (such as the opening of a line, breakdown of a production plant, etc.).

How to measure adequacy One of the main indicators to measure the adequacy (or inadequacy) of an electrical system is known by the term LOLE (Loss of Load Expectation), representing the total hours per year in which it is likely that a part of the consumers will experience disconnection because the expected demand exceeds the available resources to meet it. This indicator has been adopted as a measure of adequacy both at the European and Italian levels. Generally, an electrical system is considered adequate when there are no more than 3 hours of LOLE. This means that there is a probability of 0.03% that at least one consumer (but not necessarily all consumers) may be disconnected from the grid for adequacy reasons. The adequacy assessment is carried out through a probabilistic analysis to consider the (random and non-random) variations of key factors, including climatic phenomena (temperature, wind, irradiance, etc.). Terna, the National transmission system operator (TSO) that manages the Italian transmission grid, is obligated to conduct and update, on an annual basis, adequacy assessments and to present the results of its analyses by publishing them in an adequacy report.

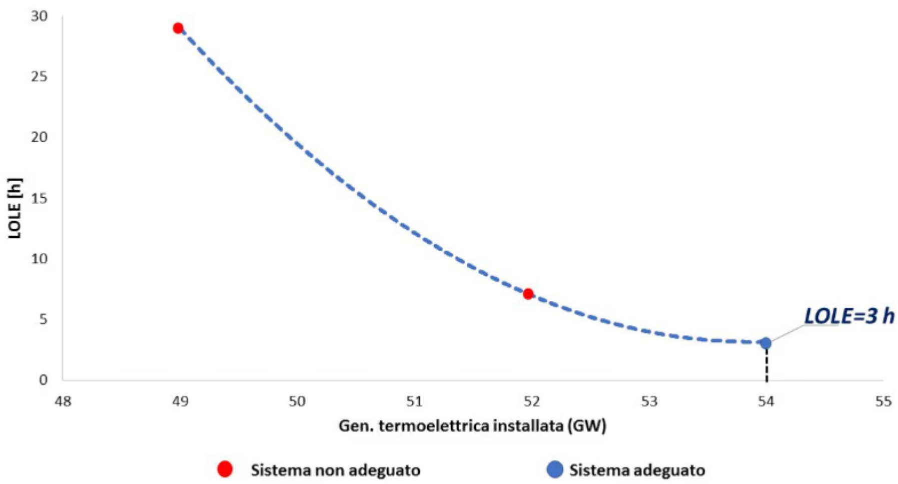


Figure 7: LOLE as hours per year vs installed thermoelectric generation power in Italy, as reported by Terna, the Italian TSO.

Capacity and technology In general, an increase in the overall power of production facilities, under the same other conditions, leads to an improvement in the adequacy of the system. However, the contribution to adequacy varies significantly depending on the technology: it is important to distinguish between the effectively available capacity and the installed capacity. Traditional thermoelectric sources, for example, on average provide a contribution to adequacy almost 10 times higher than that provided by non-programmable renewable sources, whose availability depends on the availability of the resource itself (e.g., sun and wind), which cannot always be guaranteed during peak demand hours. In a medium to long-term perspective (2025-2030), Terna's analyses highlight that the Italian electrical system requires an installed capacity of thermoelectric generation not less than 54-55 GW to meet the adequacy criterion of a maximum of 3 hours of LOLE (Fig.7).

1.2 Dispatching

Since it is crucial than EE's supply always meets the demand, dispatching electrical energy, i.e. delivering EE from the source to the user, is a key element in an electrical system. Let us take a look at Italian electricity system through Fig.8. In this sketch by Terna, the Italian TSO, the system is divided into four main components: production, transmission, distribution and end users.

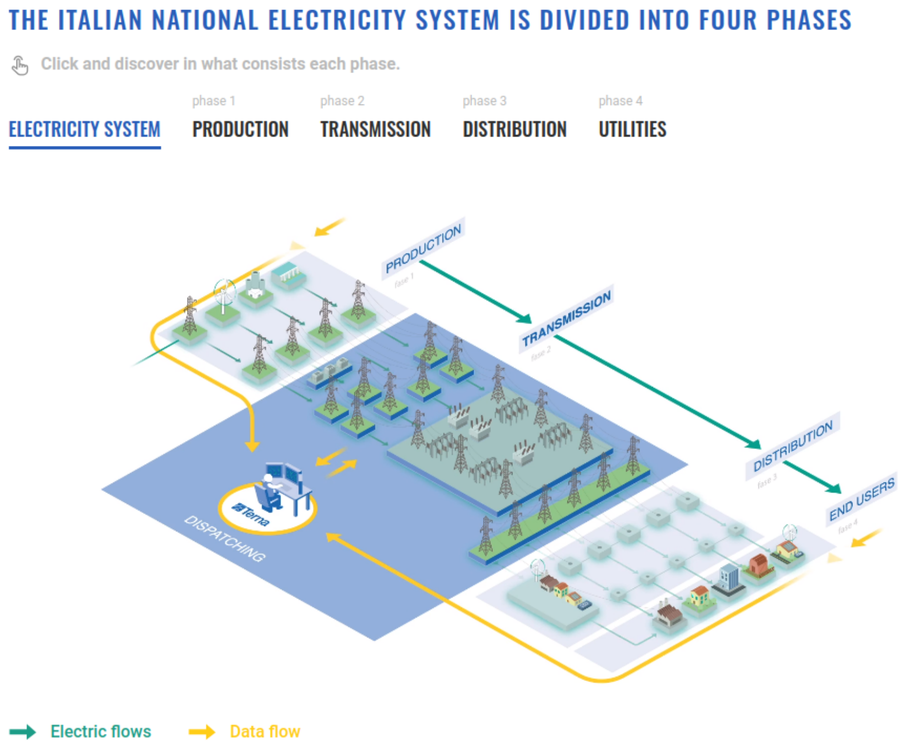


Figure 8: Sketch of Italian electricity system by Terna, the Italian TSO. Energy flow is depicted, as well as data flow, which is important for a good management.

Transmission and distribution lines are the physical mean of connection from production plants, which may in principle be operated by the government or privates, and users, which can again be privates, in the form of households, industries, commercial activities, or civic users as hospitals etc. Here we are not focusing on deals that can be made between users and suppliers (or national entities) to choose the best or nearest source of energy, or the best client for a production plant, or how the territory of a country can influence the electricity system: we are just focusing on EE as a whole, and such a good must on the first place flow through a physical transmission and distribution line.

Transmission The transmission line operates on long distances and high voltages. This is done to connect far away regions or out of the way power plants, and high voltage ($220kV$ or $130kV$) is thus required to limit energy losses. In Italy, the Transmission System Operator (TSO), which is the owner and manager of the transmission infrastructure, is Terna. Unlike the generation sector, this sector is not managed under a free market regime: here, the operator is a single entity across the entire national territory operating under a monopoly. As Terna is the sole operator in this sector of the electrical supply chain, in order to ensure it functions correctly for all consumers, it is subject to constant and meticulous monitoring of costs and activities by the *Autorità per l'energia reti e ambiente* (ARERA), an independent public administrative body (established in 1995) that operates to promote competition and efficiency in public utility services and protect the interests of users and consumers. Terna owns more than 74 thousand kilometers of electrical lines and the services offered are charged to consumers in the bill - these include transmission, but also management of the lines and the **ancillary markets** to provide quality of EE - and they amount to approximately 4.2% of the Italian electricity bill as of the first quarter of 2024 (Fig.11).

Figure 9: Terna's control center, *the heart of the Italian electricity system*.

Distribution In local areas, EE arriving at high voltage from transmission lines is outsourced to consumers through a distribution grid. Usually they have a radial shape, where energy comes from a central hub, where high voltage EE is transformed in a form readily disposable for consumers: e.g. $400V$ for commercial activities or $230V$ for households. Some big industrial plants may source the energy directly from the TSO and also medium-voltage lines exists at around $15 - 20kV$: nonetheless low voltage distribution lines cover the longest distances in Italy thanks to capillarity - 780 thousand kilometers of cables are estimated to be on the whole territory. Just like transmission, distribution is not managed under a regime of free competition but rather as a monopoly, under the close surveillance of ARERA. The difference compared to transmission lies in the fact that while Terna operates under a national monopoly, distribution is managed in zones (local monopolies); therefore, there isn't a single entity managing the entire distribution network, but rather many different companies managing portions of it (in Italy, there are more than 120 such companies). DSOs usually recover their costs through tariffs charged to electricity consumers (in the bill). These tariffs are decided and approved by regulatory authorities like ARERA in Italy. The tariffs cover the costs associated with operating, maintaining, and upgrading the distribution network, as well as a reasonable return on investment. To get an idea of the amount of such tariffs, we could very roughly estimate that around or more than twice that is destined to the TSO is paid to the DSOs: as an example we report US data for average price of electricity in 2022, divided among distribution, transmission and generation cost from the US Energy Information Administration (Eia) in Fig.10 (see Fig.11 for Italy).

1.2.1 Distributed Generation

Distributed generation or production means that in a system EE is inputted in the grid not only by classical power plants, but for example also by small photovoltaic panels on private rooftops, or EE from idle electric cars connected to the grid. Users become, at times, also producers, and they shall then be remunerated. The transition towards a system of distributed generation, mainly of renewable sources, is rapidly modifying the market with the rise of a *prosumer* model (producer and consumer together), gradually replacing the traditional consumer, and with the consequent exponential growth of the active resources connected to the grid. This context poses an increasingly challenging task to maintain the complete observability of resources — as regards both inputs and withdrawals of energy — which has an impact on demand forecasts and, con-

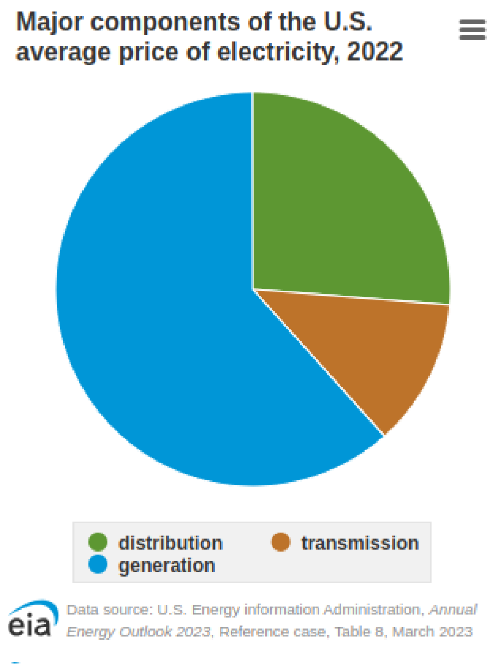


Figure 10: In the US, distribution cost is around double the transmission cost [11].

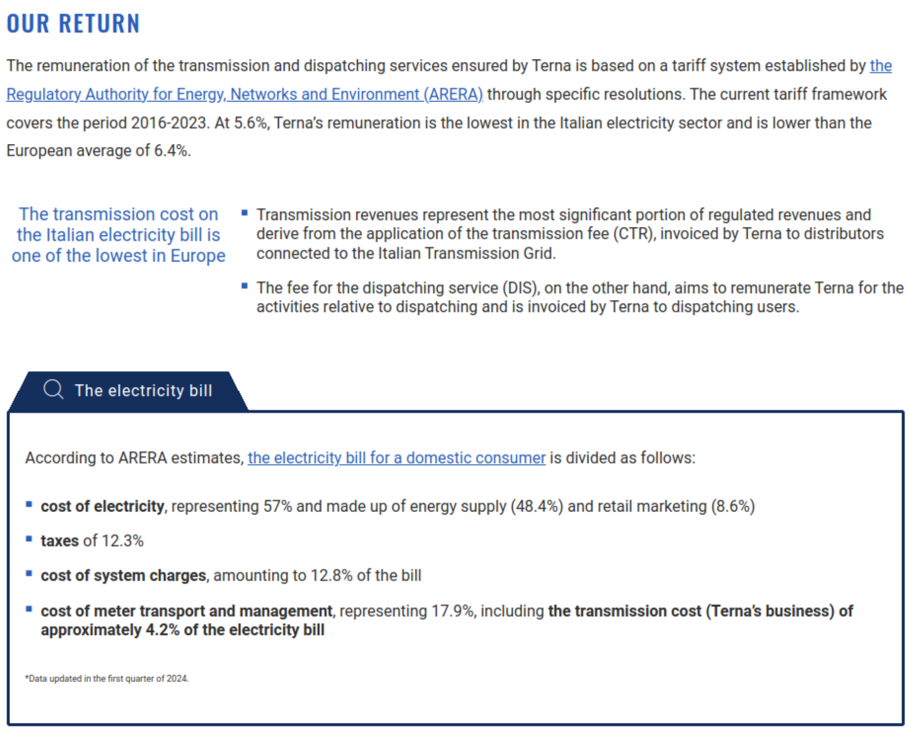
sequently, on the correct management of generation resources. For this, highly evolved forecasting and planning tools, flexibility resources and innovative data management & analytics solutions are needed.

1.3 The Bill

Before concentrating on EE energy prices as a raw material, it is interesting to take a quick detour just to see that the price as a raw material is typically not what a user pays. Infact, taking as an example the Italian bill for households (up to $2700kWh$ per year) from the first quarter of 2024, a fair slice is not dedicated to raw material (Fig. 11):

- Taxes and *cost of system charges*, which include public research on energy and public incentives, cover around $\sim$ 25% of the total.
- Cost of meter transport and management takes up around 15% of the bill. This includes the costs associated to the ancillary services run by the TSO to assure quality of EE.

- The local tariff applied by the DSO is aggregated in the last slice with the following:
- The raw EE price at that moment (which may also depend on the location, but it is not the case for Italy, where a unified price is applied). In principle it may also depend on the retailer or the producer of choice, and we will discuss this further on the next sections.
- A retailer share, it being the DSO itself, the producer, or a third party wholesaler, which is the hallmark of a free market.



OUR RETURN

The remuneration of the transmission and dispatching services ensured by Terna is based on a tariff system established by the Regulatory Authority for Energy, Networks and Environment (ARERA) through specific resolutions. The current tariff framework covers the period 2016-2023. At 5.6%, Terna's remuneration is the lowest in the Italian electricity sector and is lower than the European average of 6.4%.

The transmission cost on the Italian electricity bill is one of the lowest in Europe

- Transmission revenues represent the most significant portion of regulated revenues and derive from the application of the transmission fee (CTR), invoiced by Terna to distributors connected to the Italian Transmission Grid.
- The fee for the dispatching service (DIS), on the other hand, aims to remunerate Terna for the activities relative to dispatching and is invoiced by Terna to dispatching users.

The electricity bill

According to ARERA estimates, the electricity bill for a domestic consumer is divided as follows:

- **cost of electricity**, representing 57% and made up of energy supply (48.4%) and retail marketing (8.6%)
- **taxes** of 12.3%
- **cost of system charges**, amounting to 12.8% of the bill
- **cost of meter transport and management**, representing 17.9%, including **the transmission cost (Terna's business) of approximately 4.2% of the electricity bill**

*Data updated in the first quarter of 2024.

Figure 11: Terna's remuneration (Italian TSO) as established by the regulatory authority ARERA and a brief explanation of the subdivision of the bill.

2 The Energy Free Market

In the last 30 years, countries worldwide have taken steps towards a *free market* in the energy business, i.e. very broadly various movements toward a market-driven economy – or any movement that diminishes public ownership and control and increases private ownership and control. The process has been widespread in electrical power generation, transmission, and distribution as well as in the energy business in general.

To understand better, we can break down the phenomenon into two wide steps:

- privatization (or **liberalization**) of state-owned energy industries - breaking the production monopoly.

- institution of a free market (or **deregulation**) where clients can choose to buy the product from different offers and/or agents of the market (producers, retailers, ...) - breaking the single seller monopoly.

The means and the extent by which different countries have moved towards a free market (e.g. privatizing state-owned industries or deregulating the market) vary considerably depending on politics, development considerations, openness to foreign investments, historical reasons... And while we can say that privatization has been a sure trend, about deregulation, consider this example: in most countries of the U.S., nowadays there is a single seller monopoly in the EE business.

Regulation Authority It is important to highlight, that although *free*, the market is intrinsically artificial: by acknowledging that EE is a first necessity good since everyone benefits from access to power, in order to ensure uninterrupted service, markets were established with rules to preserve reliable delivery of service. Furthermore, these structures offer participants (generators or wholesaler) the chance at a rate of return that justifies their investment and continued participation in the market. These measures work within market structures in principle to incentivize the build out of additional resources that benefit the public. Market participants do not simply exist in a vacuum where they are immune from the realities of the political and regulatory environment.

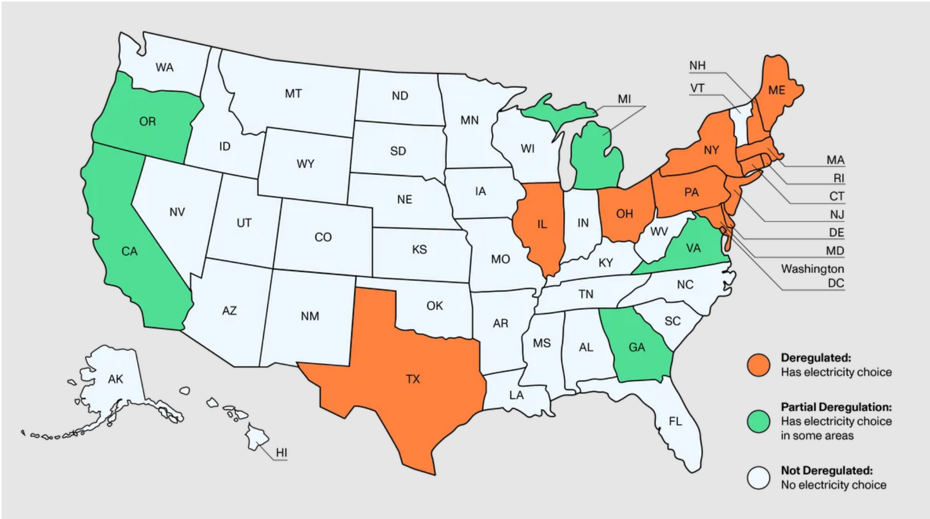


Figure 12: The single seller paradigm is the most frequent among states in America, as it can be seen from this infographic by CNET.

2.1 History

2.1.1 Privatization and Globalization

The following global historical considerations are taken from the *Report on Privatization and the Globalization of Energy Markets by Eia* (Energy Information Administration in the U.S.) [8]. Although privatization efforts differ substantially from country to country, there is a strong common economic rationale underlying the various decisions to privatize state energy resources. In general, nations have privatized state-owned energy industries to achieve one or more of several objectives. These objectives include: 1) raising revenue for the state; 2) raising investment capital for the industry or company being privatized; 3) reducing government's role in the economy; 4) promoting wider share ownership; 5) increasing efficiency; 6) introducing greater competition; and 7) exposing firms to market discipline.

The privatization of state-owned industry is a development of historic dimensions. For many nations, their formerly-state owned energy companies have been among the largest of companies to be privatized. Energy companies that have been privatized include some of world's largest petroleum companies based in the industrialized nations. Global giants, such as British Petroleum, British Gas, Elf Aquitaine (France), ENI (Italy), Petro Canada, Repsol (Spain), and TOTAL (France), have all undergone transitions from state-owned to some significant degree of private ownership.

Privatization represents a reversal of the process of nationalization begun early in the century. At the time, European governments of divergent political viewpoints were largely in agreement over the benefits of a strong state role in their domestic economies. ”Nationalization represented a cherished post-war European ideal to create large vigorous state-owned businesses that provided pools of public jobs and allowed European politicians to wield influence over their economies. A wide consensus of European politics after held that a strong, government-owned industrial sector was necessary for prosperity and middle-class stability”. In the 1930's Spain, the Franco government nationalized the state petroleum resources, which later emerged as Repsol, Spain's state oil company. The Mussolini government in Italy did the same and formed what was to become ENI, Italy's state petroleum company. Energy resources were nationalized at about the same time elsewhere in Europe - although in other nations often by more freely-elected governments (however Italy's state EE company, ENEL, was instituted in 1962).

2.1.2 In Italy

The liberalization of the energy market in Italy was introduced by the D'Alema government with the issuance of the Bersani Decree of 1999. The document reflected the indications of the European Community Directive 96/92/EC of December 19, 1996, aimed at creating the Single European Energy Market. The document envisaged a gradual liberalization of activities along the entire value chain (production, export, import, purchase, and sale of electricity) to promote free competition in the energy sector for the benefit of consumers and in compliance with public service obligations. It was followed by Legislative Decree No. 164 of May 23, 2000, which established the effective liberalization of the gas market.

Regulation Authority For the regulation of the entire market, the ”Autorità per l'Energia Elettrica e il Gas” (Authority for Electricity and Gas) was created in 1995, an independent administrative authority later renamed **ARERA** (Regulatory Authority for Energy Networks and the Environment). Its task was to ensure the promotion of competition and efficiency in public utility services, safeguarding the interests of users and consumers.

EE from National to private Among the decree introduced towards liberalization, it was established that since 2003 no entity could produce or import more than 50 percent of the total electricity generated and imported in Italy. For this purpose, the decree mandated that by the same date, ENEL must had divested no less than 15,000 MW of its production capacity based on a divestment plan to be submitted for government approval. In 1999 the plan was approved, leading with the establishment by Enel S.p.A. of three joint-stock companies (Eurogen, Elettrogen and Interpower) and the subsequent sale (alienation) by ENEL of its respective shareholdings. [6]

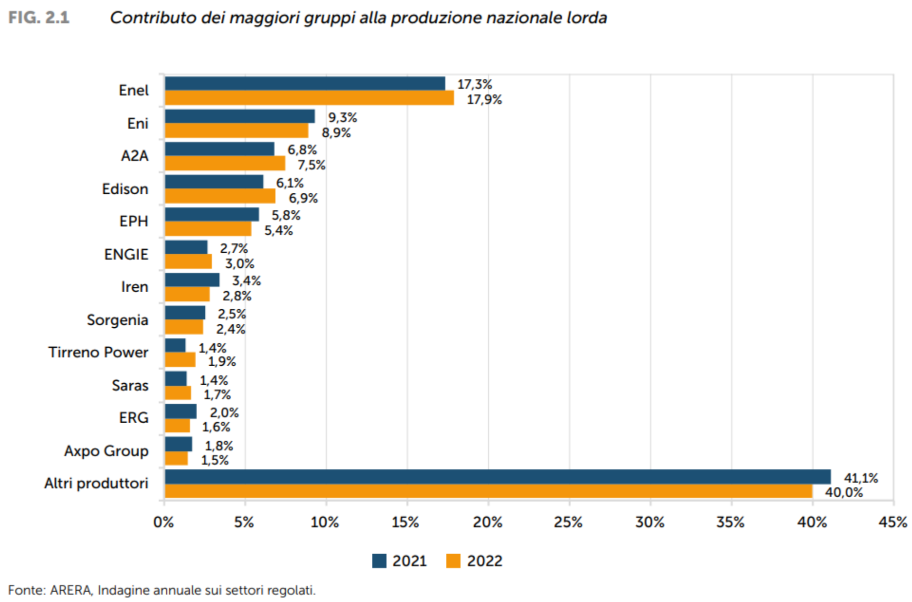


Figure 13: The share of contribution of the main corporate groups to gross EE generation in 2021 and 2022 as reported by ARERA in the annual report of the year 2022 [7].

Market Institution The decisive impulse towards the liberalization of the Italian electricity market resulted from the creation of the wholesale electricity trading market (together with the institution of a **market operator**), as generally envisaged by the aforementioned legislative decree No. 79/99. In theoretical terms, a competitive market can take various organizational forms, which can be distinguished as: models based on the Single

Buyer; wholesale power exchange or market; and bilateral exchanges. In the experiences of some liberalized countries at that time, the model of the power exchange and that of bilateral transactions coexisted, giving rise to hybrid organizational forms, while the Single Buyer model, which purchases and resells all the electricity traded for all market users, had found limited application.

The Single Buyer However the Italian case represented an exception, where Legislative Decree No. 79/99 provided for a Single Buyer who assumed responsibility for the procurement of electricity and the related capacity guarantee for a portion of the market only, the regulated market, while eligible customers could trade electricity on the exchange market. Since the supply sector was also liberalized, all final consumers were able to purchase directly from the exchange or conclude bilateral contracts. However since liberalization concerned only a portion of final customers, it was the Single Buyer - as long as it existed - and the distributor who were to meet the demand of regulated customers. [6]

ENI privatisation As a sidenote, we report that "The ENI privatisation started in 1992 when the Italian government decided to open the path to a radical change for this industrial group ... ENI's quotation on the main world financial markets was rightly considered as one of the most important operations of privatisation at the international level" (from AIEE - The Italian Association of Energy Economists).

2.2 Shapes

As briefly introduced before, different possibilities of electrical energy market are possible, regarding how producers, consumers and retailers - if they exist - interact with each other. In simple and general terms, three paradigmatic shapes are exemplified and sketched in Fig.14. Going from (a) to (c) more freedom is introduced in the system: while in (a), the **vertical** market, a strong monopoly occurs since consumers are tied to specific producers - we could refer this as a pre-liberalization market -, in (c), the **bilateral** electricity market, each participant is *free* to sign deals with other consumers, producers and wholesale retailers.

Let us remind however, that this *freedom* is always subjected to some central functions, namely:

1. **Regulations** by a central authority.

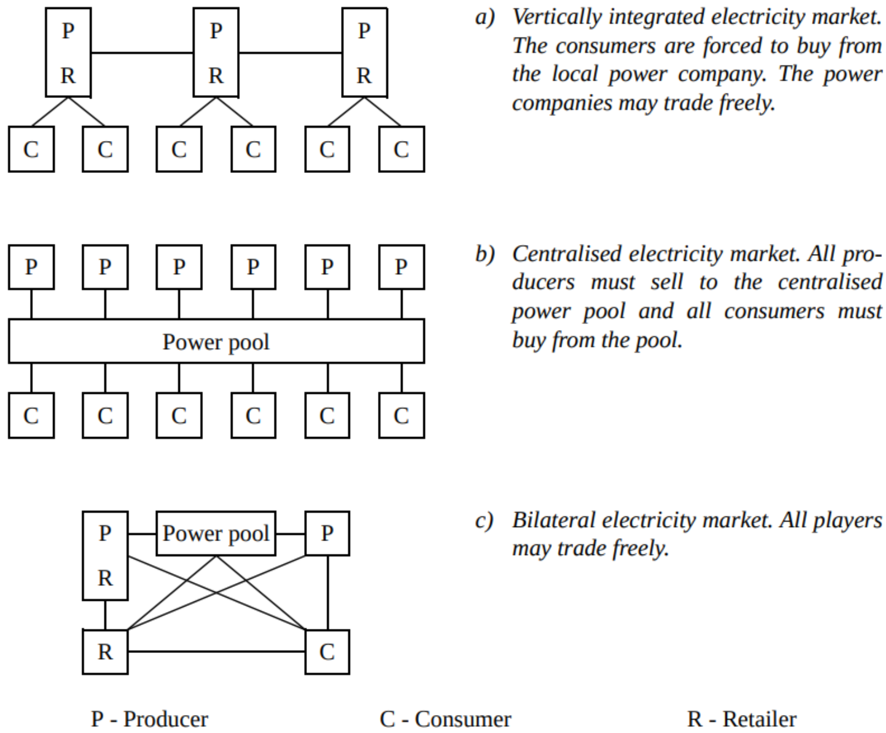


Figure 14: Possible shapes of an electricity market. Image from Mikael Amelin's Doctoral Thesis, *On Monte Carlo Simulation and Analysis of Electricity Markets* [5].

2. **Network disposability**: in theory each producer could build an own power distribution grid, but in practice such parallel grids would be unprofitable. All producers and consumers are therefore forced to share a common grid.

3. **Network management**: the Transmission System Operator (TSO), is responsible for managing, maintaining, and developing the transmission network and determining the use of interconnections with producers, consumers or other sources to ensure supply and the quality of EE - assuming that the average production and consumption during a certain period is in balance, no responsibility for the instantaneous balance is attributed to the producer or the consumer: this responsibility is given to the system operator instead.

4. **Market management**: the Market Operator manages the exchanges for short-term production scheduling (daily or intraday market), ad-

ministers the price determination system (usually assisted by complex software), and collects bids on the market, determining aggregate demand and supply curves based on predetermined rules.

Vertical market Each market scheme has its own pros and cons. The advantages of (a) are simple technical solutions to address technical issues, yet these are counterposed by a strong disadvantage: no pressure of competition between power companies. This was one of the main drivers bridging the market from what we could now consider old fashion -regulated- to de-regulated markets. In "newer" markets competitive activities (production and possibly retailing) are separated from the remaining monopolies (system operator and grid owners).

Centralised market Among the restructured electricity markets we can distinguish centralised (b) and bilateral (c) electricity markets. Characteristic of a centralised electricity market is that producers and consumers may not trade directly. The producers have to submit their sales bids to a central power pool, which is managed by the system operator. In some cases the consumers (maybe represented by a retailer) submits purchase bids to the power pool, stating its needs, whereas in other cases the system operator forecasts the load during the trading period and buys the same amount from the power pool; thus, the system operator serves as retailer for all consumers.

Bilateral market In a bilateral electricity market the system operator has a more supervising role. The players do not have to trade through a power pool, but may sell and purchase freely (all transactions must however be reported to the system operator, so that after the trading period it is possible to control that the players have fulfilled their undertakings). There is no official electricity price, however generally there is a power pool also in bilateral electricity markets and the price of the pool serves as a guideline to those players trading bilaterally

Ancillary services Along EE main market, the markets for ancillary services are crucial for the overall well-being of the system (i.e. when the system operator rather than building and owning necessary technical systems buys the services from other players in the electricity market - for example accumulation systems or shedding loads) or markets which are used to lead the players of the electricity market in a desirable direction, for example towards more environmentally benign electricity generation (thus in a wide sense, Green Certificates associated with the production of

EE from renewable sources and its market could broadly fall in the ancillary markets).

2.3 Are pure traders good?

As the players may trade freely in a bilateral electricity market, a business opportunity opens up for pure retailers (which are often referred to as independent traders). Their idea is to buy power directly from the producers or the power pool and sell it on to the consumers. It might appear as if these retailers were just unnecessary, price increasing middlemen—and in the worst case this might actually be true— but they can also supply important functions to the electricity market. Primarily the existence of retailers means larger freedom of choice for the consumers, resulting in increased competition compared to if retailing was run by producers only. The increased competition may not just apply to the electricity price, but it is also possible that enterprising retailers offer better service (for example more employees answering the telephones at the customer service) or special electricity products (such as for example power produced in environmentally benign power plants). The retailers may also take over part of the risks (both towards producers and consumers) by offering stable prices during longer periods than one trading period.

In principle Consider for example the airline industry: when in the winter the airline Ita Airways schedules a flight from Milan to Palermo in August, they are happy to sell some of the tickets to providers during the first winter months - not only this is a risk insurance avoiding too much unsold, but it delegates some marketing to the provider and above all provides immediate cash in-flow to the airline company. Of course, as our intuition suggests, the airline is leaving some money on the table: we can expect the price of the tickets to increase monotonically over time. This, plus having control over the prices of their products, is a reason for the airline to keep some tickets to sell directly to consumers; but the overall strategy is a win for the airline. From the point of view of the provider, if they can do good forecasting and risk analysis, a profit is guaranteed: as long as they sell a good amount of tickets, the earlier they buy and the latest they sell the higher the margins. What about the costumer? If the only airline was selling tickets, the price would be fixed by the airline. However, since many providers are now challenging each other in a battle of wits (can they sell all the tickets? can they take more risks and sell the tickets later or buy them earlier?), the sellers are not able to squeeze the costumer as a sponge, yet their prices are "tied to the market" - a balances between request and offer. This, *in principle*, leads to a win-win-win situation.

Spot and forward market There is a huge difference however, between airline tickets and electrical energy: you can buy tickets, store them digitally and sell them one year from now with almost no cost. But EE's storage is a totally different story. First of all, depending on the volume of energy (quantity of energy, Wh) and the ability to retrieve it fast (power, W) one should lean toward different accumulation technologies (see paragraph 1.1). This is extremely useful and usually done. However, time-induced losses and above all converting energy form is a heavy cost. Moreover, if every provider had to own a storage plant of the right volume and power for each and every transaction they made, not only a lot of providers would be cut out of the market, but also this would make the overall EE system incredibly inefficient. From these considerations it sprouts the forward market: simply put, the providers can buy or trade a product that will exist -and so be their property- in the future on a settled date. More strictly: a forward market is a market where financial instruments are traded for future delivery or settlement. In a forward market, the buyer and the seller agree on the price, quantity, and delivery date of the financial instrument. The transaction is executed on a future date, as agreed upon by both parties. The settlement of the transaction happens on the delivery date of the financial instrument. This is very common e.g. for agricultural goods, where for example a wholesaler can assure a batch of cherries in January, deciding a price and a delivery date later during the summer together with the producer. You can see how important is, while stipulating these financial instruments, how important price forecast is.

If the time delay between agreement and physical delivery is two or less days, the exchange is considered "immediate". Such market is called the spot market - the transaction is executed on the spot. The prices are mainly dictated by the actual market conditions, making this market highly liquid (the volume of transactions is high) and transparent. However if you think about long term fluctuations, the forward market also allows traders and investors to *lock in* a price for a financial instrument, which could be a better tool to reduce risks.

Hydroelectric re-storage in Italy As a non-exhaustive clue and non-argumentative claim (a discussion on the actual benefits or disadvantages of free markets from us would be very lackluster in terms of digits, data and proofs) we just want to report a plot of production of EE from pumping in hydroelectric plants in Italy vs the year (Fig.15, courtesy of Enrica Micolano RSE from original data by Terna). This energy is not conventional EE produced by plants exploiting gravity and the water cycle, yet it is past surplus EE that was converted to potential gravitational energy by pumping water up the hydrological basin in order to store EE for later use, at the cost of around 25% of the energy itself. We can see a rising trend until the early 2000s, and then a plummet. A plausible interpretation, since the peak is reached at the start of the EE free market in Italy, would claim that the start of the market brought a more optimal targeted generation and use of resources.

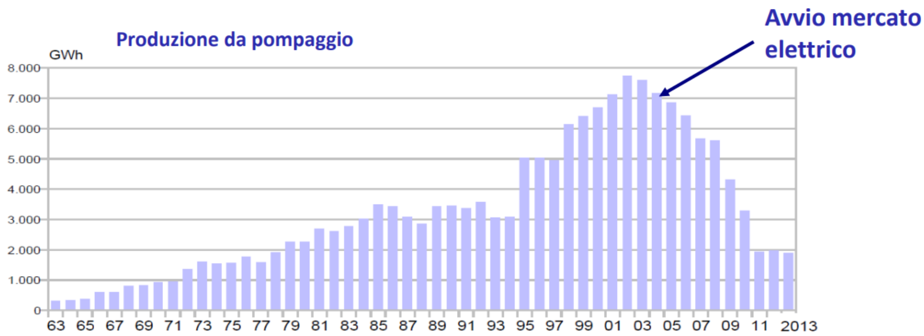


Figure 15: Production of EE from pumping in hydroelectric plants in Italy vs year, courtesy of Enrica Micolano, RSE (from original data by Terna, 2013). The peak was reached when Italian free market was instituted.

2.4 Stages

Since many players are involved in the electricity market and many unforeseen circumstances could happen, it is crucial to divide the market in different time periods, or stages. Let us say our city has bought in advance a certain amount of MWh of power that is just enough for the typical summer high noon, yet an even particularly hot weather strikes, leading with a massive usage of air conditioning and heat pumps: in order to mantain power balance the city has to be ready to buy more energy on the spot.

Otherwise the energy should have been "booked" in advance - or better, it is power generation that should have been booked: a supplier that is ready to fire off the power plant when needed to account for last minute necessities. You can see how different stages and various modality of trading are needed in order to arrange for unpredictable demands and problems in production, plus keeping the quality of current, voltage and frequency parameters in the grid. For this reason, across the world EE markets are differently structured and organized in stages, and in order to try to understand the important bits, we will now sketch a skeleton of these stages in chronological order with respect to the delivery of energy to the consumer:

1. **Forward Market** It is a bilateral market where theoretically anyone can participate and buy EE - yet it is often based on financial agreements, also between different wholesalers. The delivery date of energy is decided upon stipulation, and it can be up to years in the future.

2. **Capacity Market** The product of this market is not electrical energy, but electrical power: the TSO or the consumers (usually wholesalers for them) can book electrical power (or storages, or shedding loads if we look at the broader **Flexibility Market**) in advance to be ready for possible variations of loads or varying, non-dispatchable RES. It is important in order to mantain the adequacy of the system while dealing with long-term prices (which are generally lower than short-term prices when considering operational costs) [10]. Deals can happen months or years in advance and capacity market can exist at local level, for example DSOs can participate in smaller ones (see for example [9] for a local market in Italy's capital city integrating a flexibility, a local day-ahead and a local intraday market). These long term supplying deals are often signed through competitive auctions.

3. **Ahead (day-ahead) Market** Through good forecasting, players in the EE market can purchase the biggest slice of energy to cover the near-future demand: sometimes this is done 24 hours prior to the usage (day-ahead), which makes this a spot market of electrical energy. Having the widest share of transactions done the day before allows for a better organization of the system and the grid: reducing

to the minimum the adjustments that will be done in real time minimizes also the costs. The **marginal pricing** is usually applied to the producers bids to decide a final price, as we will discuss in the next section.

4. **Real-time (intraday) Market** A real-time market is needed for several reasons. One is that power plants selling to the ahead market may fail and have to be replaced by other generating units. Moreover, when trading in the ahead market it may be difficult for many players to predict how much they actually will produce or consume. This is for example the case for wind power plants, where the available generation capacity depends on the wind speed, which is hard to predict even just a few hours ahead, or retailers whose customers have so-called *takeandpay* contracts, which means that the customer may consume any amount of power up to a specified limit. Finally, it is not certain that the ahead market has taken enough consideration to the limitations of the common grid, which may force the system operator to redispatch production and consumption so that the grid is operated safely [5]. These reasons, particularly the last, also lead to (and overlap with) the balancing and frequency control markets. The differences between them are twofold: firstly, the latter are usually held and supervised by the TSO and focus on the grid rather than the consumer; secondly, the time windows for the former are of the order of hours, while the latter can have only minutes between the deal and the delivery of energy to the grid. Bids are activated by the system operator depending on the need: an up-regulating bid corresponds to buying energy to inject in the system, as opposed to a down-regulating bid. Marginal pricing is adopted also for the sets of up or down regulating bids.

5. **Balancing Market & Frequency Controls** As previously mentioned, the TSO can organize its own ahead and intraday market in order to keep the grid balanced. We could call this the balancing market. Indeed, a faster (shorter delivery times) market is necessary to deal with abrupt and unpredictable events: frequency control services need to rely on reserves with an activation time down to just seconds. At European level, the power system frequency control is organized in three hierarchical levels, called primary, secondary

and tertiary control, with a different involvement of resources (reserve of power). The primary frequency control is automatic and based on the synchronous generators connected to the electric grid and running, that have to vary the power supplied, to restore the energy balance and to bring the frequency to a value closer to the nominal one (50Hz). Primary reserve and regulation is currently not traded in markets but it is a mandatory requirement for all relevant connected units. The secondary control is automatic and still based on the generators connected to the grid — they have to vary their power supply in order to restore the nominal value of the frequency. The service must be completely delivered within 180 s, so only some generators can provide it, and this is subject to the real time market. The tertiary frequency control is based on a set of different tertiary reserves, which are active power reserves used for restoring the necessary FRR as well as to cope with forecast uncertainties and/or unexpected events. There are two types of tertiary control reserve: spinning tertiary control reserve, fully delivered within 15 min, in order to restore the secondary reserve; and replacement tertiary control reserve, fully delivered within 120 min and necessary to restore the tertiary reserve against shifts in demand, injection from IRES, long-lasting faults of power plants. [14]

6. **Post Market** It is inevitable that smaller or larger deviations will occur between the planned trading and what actually is traded. The post market is necessary to compensate for these deviations and to make sure that somebody pays for all energy supplied to the system during a trading period. However, the players do not need to take responsibility themselves for the differences between ahead trading and what is actually produced and consumed, but it is possible to introduce certain balance responsible players. Being balance responsible is a purely financial undertaking and the balance responsible player does not need to be a producer or consumer, but may act as an agent for others. The balance responsible players then have to trade at the post market to settle the imbalance. Players having positive imbalances (i.e., they have supplied more energy than they have extracted) sell balance power to the system operator. If there is a negative imbalance instead then the player has to buy balance

power from the system operator.

As a note: sometimes the capacity market and the balancing market are considered part of a wider **Ancillary Services Market**.

2.4.1 Marginal Pricing

The marginal price, also known as the marginal cost, is the cost of producing one additional unit of a good or service: it refers to the price at which the last unit of electricity needed to meet demand is sold and it is usually used in the day ahead market.

1. Generators submit bids indicating how much electricity they can produce and at what price.

2. The bids are ordered from the lowest to the highest price. This is known as the merit order.

3. The market is closed at the price of the last bid needed to meet the demand. This clearing price is the marginal price and all producers whose bids are below this price still get paid the marginal price for their electricity.

Why is the marginal pricing used? Mainly because it encourages efficient production and allocation of resources, competition, investments and technology advancements: Producers who can generate at lower costs will always be in the market and make a bigger profit. For a similar reason, namely being appetible for producers, up and down regulating bids in the intraday market often use the marginal price too.

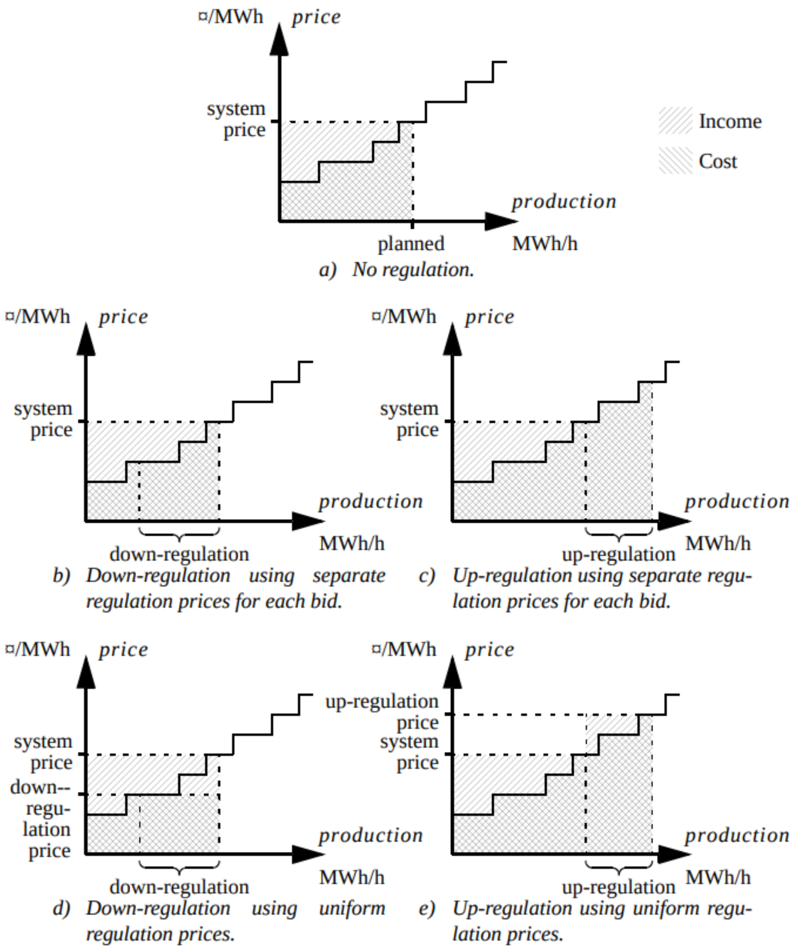


Figure 16: In the picture the (a) panel refers to the closed day ahead market: seven generation plants proposed a bid and a clearing price was determined via the marginal price. In the subsequent panels different down-regulation and up-regulation schemes are applied for the intraday market (assuming the bid remains the same as the ahead market), (b) and (c) being ”pay as bid” and (d) and (e) applying the marginal pricing. Source: [5]

2.5 In Italy

The electrical energy market in Italy is organized in a Spot Electricity Market (named in Italian, Mercato a Pronti dell’Energia, MPE) and a Forward Electricity Market (named in Italian, Mercato a Termine dell’energia, MTE). The Spot Electricity Market includes primary energy markets and ancillary services markets, in particular:

- A Day-Ahead Market, called in Italian Mercato del Giorno Prima (MGP), as a first stage of the energy market;
- An Intra-Day Market, called in Italian Mercato Infragiornaliero (MI), as a second stage of the energy market;
- An Ancillary Services Market, called in Italian Mercato del Servizio di Dispacciamento (MSD). It is subsequently divided into the planning stage (Ex-Ante MSD in Italian), where the operator (TERNA) accepts offers and bids for avoiding congestions and creating adequate reserve margins and a real-time Balancing Market (Mercato del Bilanciamento, MB, in Italian), where TERNA accepts offers and bid in real time for balancing the system and for relieving congestions.

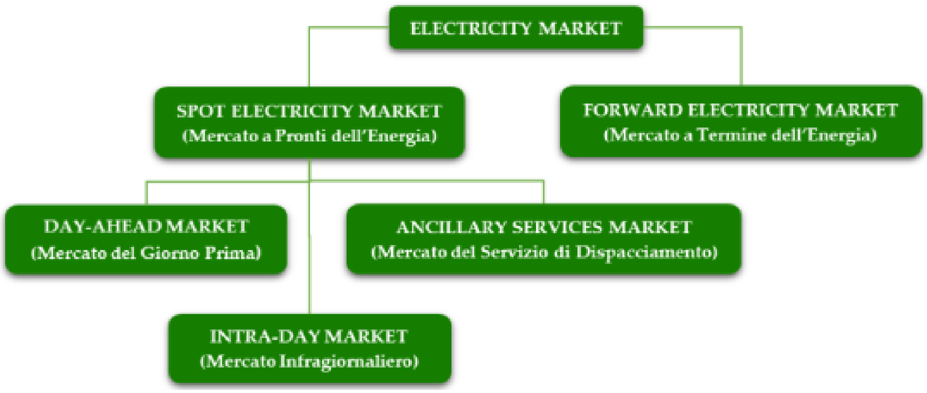


Figure 17: The structure of the Italian Electricity Market, providing the right match between the general definitions and the Italian name of each market session; from [14].

In the MGP and MI, that is, in the energy markets, producers and end-users buy and sell wholesale electricity quantities for the delivery day. The energy markets are managed by the Italian Market Operator, named Gestore dei Mercati Energetici (GME). In fact, GME is the Italian NEMO (Nominated Electricity Market Operator) for the day ahead and intraday markets. Both the energy markets are centralized non-discriminatory auctions — the rule for the definition of the final price for the bids accepted is the clearing price. In the MSD and in the MB, that is, in ancillary services markets, the Italian TSO, named TERNA, gets all the means that it needs to operate the national power system, coping with all the relevant security constraints. It consists of centralized discriminatory auction—the adopted pricing rule is based on a "pay as bid" mechanism. TERNA operates in this market to obtain resources for solving congestions, procuring frequency reserves and ensuring the real-time balance of the power system. Last, the MTE is a Forward Energy Market, where the exchange of energy is based on bilateral contracts between two market operators at freely negotiable prices.

2.5.1 Pun and Zonal Prices

Italy applies an additional pricing scheme based on territoriality and transmission complications: the nation is divided into seven macrozones (see Fig.18) where an inherent clearing price destined to producers is determined individually for each zone - the zonal price.

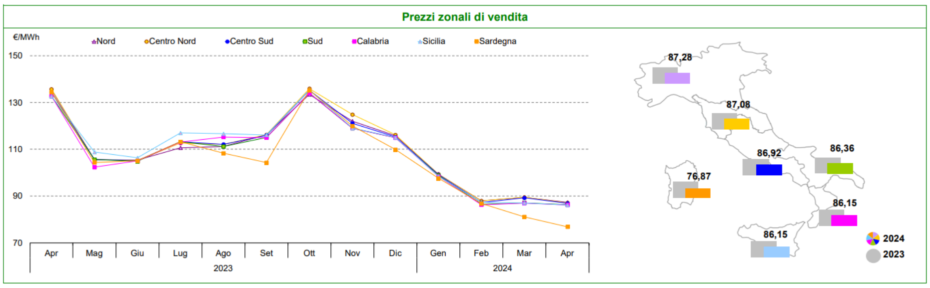


Figure 18: The average monthly zonal prices in Italy for the seven macrozones from April 2023 to April 2024. In the centralized Italian market this is the price paid to producers. The source is the GME.

Upon the seven zonal prices then an unique national price (PUN) is calculated: it is the weighted average of the zonal prices on the basis of zonal consumptions. Therefore each client pays the PUN per MWh of EE, while producers are compensated with the zonal price given the origin of the offer.

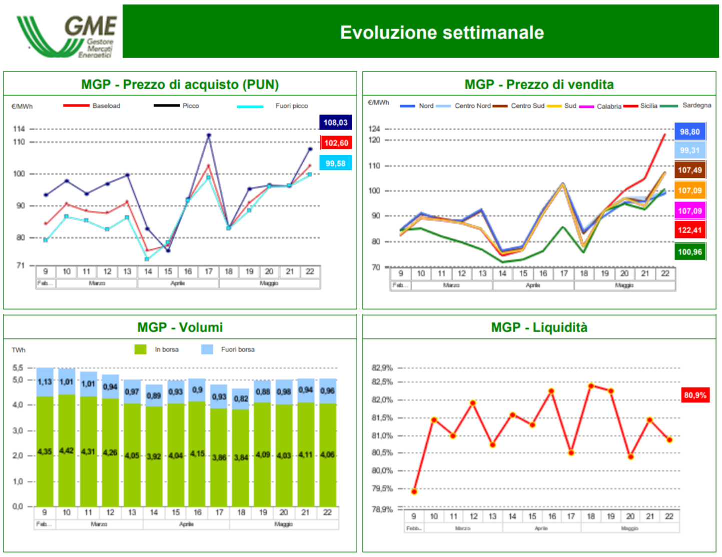


Figure 19: Weekly exit values of the MGP in the weeks of March, April and May 2024. The GME reports the average weekly PUN (top left panel) divided into three categories - thus three averages considering different periods: peak load, base load and off-peak load. **Peak load** refers to the highest level of electricity demand within a specific period. This demand typically occurs during times when energy consumption is at its highest, such as during hot summer afternoons when air conditioning use is at its peak. **Baseload** is the minimum level of demand on an electrical grid over 24 hours needed at all times for essential services. **Off-peak load** refers to periods of lower demand for electricity, for example during nighttime or other times when essential usage drops and it is then lower than baseload.

Volumi venduti per fonte

	Totale	Media	Variazione	
	MWh		MWh	%
Tradizionali	**1.522.286**	**9.061**	***+794***	***+9,6%***
Gas	1.173.033	6.982	*+635*	*+10,0%*
Carbone	64.206	382	*+49*	*+14,8%*
Altre	285.047	1.697	*+110*	*+6,9%*
Rinnovabili	**2.520.906**	**15.005**	***-199***	***-1,3%***
Idraulica	1.435.349	8.544	*+129*	*+1,5%*
Geotermica	96.965	577	*-35*	*-5,7%*
Eolica	293.045	1.744	*-352*	*-16,8%*
Solare e altre	695.548	4.140	*+59*	*+1,4%*
Pompaggio	**115.356**	**687**	***-48***	***-6,5%***
Totale	**4.158.549**	**24.753**	***+547***	***+2,3%***

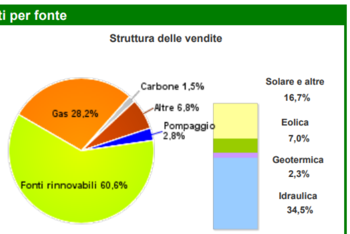


Figure 20: In the week from the 27th of May to 2nd of June 2024 the volumes of EE that entered the Italian MGP market at clearing are reported in this picture by the GME divided by source - the bigger share is from hydroelectric powerplants.

3 Price Forecasting

As we have outlined up to now, price forecasting of electrical energy is both a very complex problem and an essential task for players in the EE market. Indeed, in the current deregulated scenario, the forecasting of electricity demand and price has emerged as one of the major research fields in electrical engineering - quoting [13], a review on the topic which will be now followed as a source to delve into price forecasting ideas and methodologies.

The problem is a rich blend of two interesting subject: on the one hand we have the load and supply forecasting of EE - in itself based on physical phenomena or statistics of behaviours possibly based on measurable conditions (e.g. temperature dictates the consumptions from heat pumps) -, on the other hand there is a purely financial and economical phenomenon. The latter makes the load and supply forecasting in itself not enough, yet at the same time differs from the common financial problem of stock pricing because electrical energy is a too peculiar good on its own: whereas load forecasting has reached advanced stage of development and load forecasting algorithms with mean absolute percentage error (MAPE) below 3% are available, price forecasting techniques are still in their early stages of maturity. In actual electricity markets, price curves exhibit considerably richer structure than load curves. The price curve (Fig.21) has in general these characteristics: high frequency, nonconstant mean and variance, multiple seasonality, calendar effect, high level of volatility and high percentage of unusual price movements. All these characteristics can be attributed to the following reasons, which distinguish electricity from other commodities:

1. non-storable nature of electrical energy,
2. the requirement of maintaining constant balance between demand and supply,
3. inelastic nature of demand over short time period (the quantity of electricity demanded does not change significantly in response to changes in price within that short timeframe),
4. oligopolistic generation side,

5. market equilibrium is also influenced by both load and generation side uncertainties.

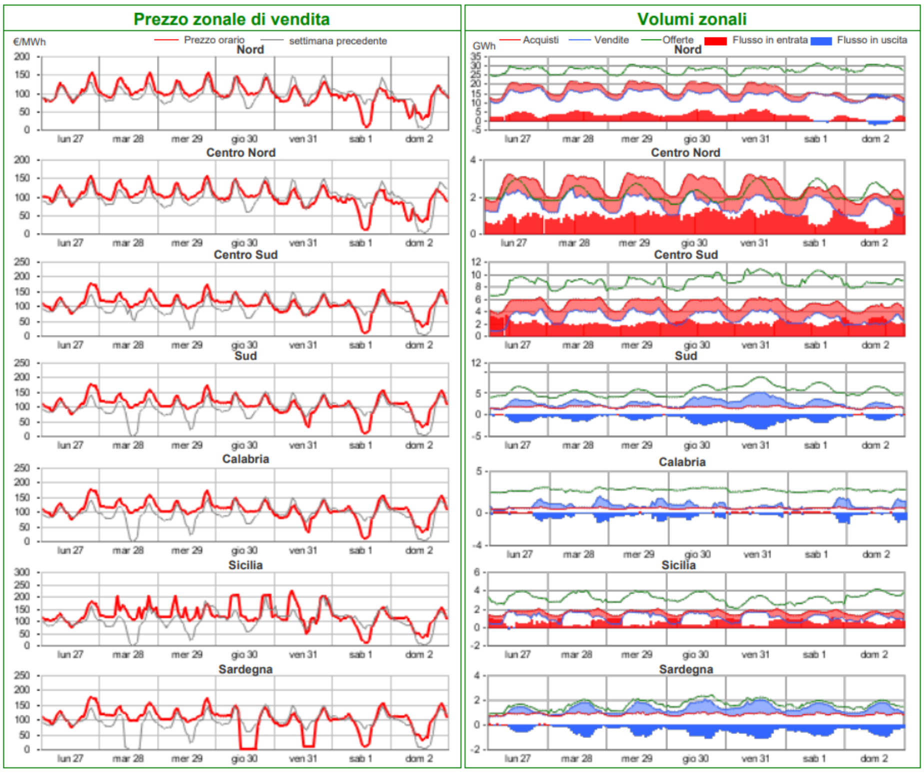


Figure 21: Hourly zonal price curves and volumes/load curves in the Italian MGP in the last week of May 2024 compared to the previous week (GME).

3.1 Factors Influencing Electricity Prices

In order to build a model to forecast EE prices, one should build a catalogue and consider all possible influencing factors. Which of these influencing variables a model incorporates and how it incorporates them then makes for a different model with peculiar scope and characteristics. The factors influencing spot prices may be classified on the basis of: *C1* – market characteristics, *C2* – nonstrategic uncertainties, *C3* – other stochastic uncertainties, *C4* – behavior indices, and *C5* – temporal effects. There are as many as 40 variables used by different researchers - most of the researchers have utilized past experience in selecting the input variables for their respective model and choice of best input variables for a particular model is still an open area of research.

Class	Input variable	Time period whose data is used as input
C1	(1) Historical load	f(load); $(d-m, t)$, m=1, 2, 3, 4, 7, 14, 21, 28
	(2) System load rate, (3) imports/exports, (4) capacity excess/shortfall	(d, t), $(d, t-1)$, $(d-1, t)$, $(d-2, t)$, $(d-7, t)$
	(5) Historical reserves	$(d, t-2)$, $(d, t-1)$, (d, t)
	(6) Nuclear, (7) thermal, (8) hydro generation, (9) generation capacity, (10) net-tie flows, (11) MRR, (12) system's binding constraints, (13) line limits	(d, t)
	(14) Past MCQ (market-clearing quantity)	$(d-1, t)$
C2	(15) Forecast load	$(d, t-2)$, $(d, t-1)$, (d, t)
	(16) Forecast reserves, (17) temperature, (18) dew point temperature, (19) weather, (20) oil price, (21) gas price, (22) fuel price	(d, t)
C3	(23) Generation outages, (24) line status, (25) line contingency information, (26) congestion index	(d, t)
C4	(27) Historical prices	f(price); $(d-m, t-n)$, m=0, 1, 2, 3, 4, 5, 6, 7, 8, 14, 21, 28, 364 and n=0, 1, 2, 3, 4.
	(28) Demand elasticity, (29) bidding strategies, (30) spike existence index, (31) ID flag	(d, t)
C5	(32) Settlement period, (33) day type, (34) month, (35) holiday code, (36) Xmas code, (37) clock change, (38) season, (39) summer index, (40) winter index	(d, t)

C1 – market characteristics, C2 – nonstrategic uncertainties, C3 – other stochastic uncertainties, C4 – behavior indices, C5 – temporal effects, d – day, t – settlement period number of the day.

Figure 22: Factors influencing electrical energy prices used by researchers in the literature, divided into five classes. [14]

The widely used input variable is the electricity price of previous days. Researchers have used as much as past 1–7, 14, 21, 28, 364 days price lags to capture the complete seasonal/calendar variations namely daily, weekly and yearly variations. As price is strongly correlated with demand, next most often used input variable is demand; a few have predicted the demand first and then used it as input variable for the price-forecasting model. Many researchers have also used historical load data as input variables. Moreover capacity excess or surplus is the total available capacity minus the required capacity at peak hour, and it has been used by most of the researchers as input variable, because it may affect the price significantly in case surplus goes below certain threshold level and thereby prompting some major participants to utilize this period as an opportunity to exercise their market power. Since temperature is the main exogenous variable that affects the system load, authors have used temperature as input variable in their respective models. To take the effect of inflation and cost of fuel prices on electricity price, fuel and oil prices have also been used as input variables. Must run ratio (MRR) is the generation concentration index (an indicator of oligopolistic nature of the market), which has been used as an input variable and has been shown to have considerable impact on market price.

3.2 Price-forecasting Methodologies

Numerous methods have been developed for electricity price forecasting - these models have been classified in three sets and further subsets:

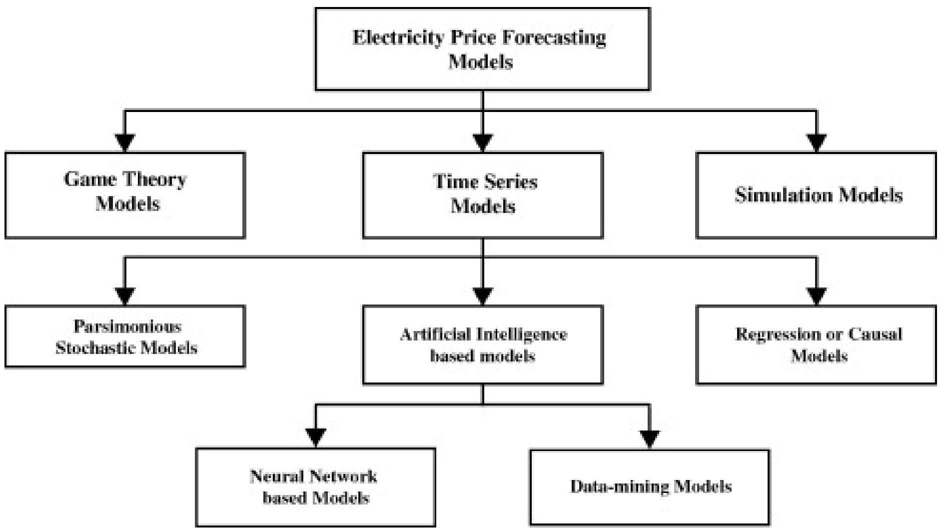


Figure 23: Different price-forecasting algorithms as categorized by the literature [14].

3.2.1 Game Theory Models

The first group of models is based on game theory. It is of great interest to model the strategies (or gaming) of the market participants and identify solution of those games. Since participants in oligopolistic electricity markets shift their bidding curves from their actual marginal costs in order to maximize their profits, these models involve the mathematical solution of these games and price evolution can be considered as the outcome of a power transaction game. In this group of models, equilibrium models take the analysis of strategic market equilibrium as a key point. There are several equilibrium models available like Nash equilibrium, Cournot model, Bertrand model, and supply function equilibrium model. Study of game theory models in itself is a major area of research.

3.2.2 Simulation Models

These models form the second class of price-forecasting techniques, where an exact model of the system is built, and the solution is found using algorithms that consider the physical phenomenon that governs the process. Then, based on the model and the procedure, the simulation method establishes mathematical models and solves them for price forecasting. Price forecasting by simulation methods mimics the actual dispatch with system operating requirements and constraints. It intends to solve a constrained optimum problem by deterministic equations or Monte-Carlo methods. Simulation methods are intended to provide detailed insights into system prices. However, these methods suffer from two drawbacks. First, they require detailed system operation data and second, simulation methods are complicated to implement and their computational cost is very high.

3.2.3 Time Series Models

Time series analysis is a method of forecasting which focuses on the past behavior of the dependent variable. Sometimes exogenous variables can also be included within a time series framework. Based on time series, there are further three types of models.

- **Parsimonious stochastic models** Many stochastic models are inspired by the financial literature and a desire to adapt some of the approaches that are well known and widely applied. Stochastic time series can be divided into stationary process and non-stationary process. As electricity price is a non-stationary process, the class of models of interest is the one where the constant variance assumption does not need to hold, and is named heteroskedastic. For example GARCH (generalized autoregressive conditional heteroskedastic) models consider the conditional variance of the process as time dependent. In stochastic models price is expressed in terms of its history and a white noise process. If other variables are affecting the value of price, the effect of these variables can be accounted for using multivariate models like TF (transfer function) and ARMA (autoregressive moving average) with exogenous variables (ARMAX) models. As electricity price exhibits daily, weekly, yearly and other periodicities, a different class of models that have this property, designated as seasonal process model, can be used.

- **Regression or causal models** Regression type forecasting model is based on the theorized relationship between a dependent variable (electricity price) and a number of independent variables that are known or can be estimated. The price is modeled as a function of some exogenous variables. The explanatory variables of this model are identified on the basis of correlation analysis on each of these independent variables with the price (dependent) variable.

- **ANN based models** These may be considered as nonparametric models that map the input–output relationship without exploring the underlying process. It is considered that AI models have the ability to learn complex and nonlinear relationships that are difficult to model with conventional models. These models can be further divided into two categories: (i) artificial neural network (ANN) based models and (ii) data-mining models.

4 Case Study

4.1 A GARCH forecasting model to predict day-ahead electricity price [15]

In our opinion, the models proposed in the former section range from being ”full of ideas, rich in meaning and thus complex”, to being ”capable of capturing statistical features flawlessly but distant from the underlying processes”. Exacerbating the philosophy of the methodologies: while in the former case one aims to build the perfect system *a priori* to reproduce the real world in minute detail, the latter might optimize a model that is merely a string of linear and non-linear combinations of dull parameters.

These two extremes each have their drawbacks: in the first case, the phenomena to be described may be too complex to grasp *a priori*, making it impractical or impossible to model accurately. In the second case, while forecasting can be achieved with great precision, no underlying idea or wisdom may be gained in the process.

For this reason, we have chosen to go into detail of a GARCH model to study and forecast the EE price time series: this way we avoid the complexity of a game theory or simulation model, yet we can build a stochastic model based on a phenomenological idea - electrical energy prices are highly volatile, and one wants to capture this feature by implementing direct dependence of the time series not only on previous behaviour but also on previous fluctuations and shocks (fluctuations: high volatility means that the price of an asset can change dramatically over a short period in either direction, while low volatility indicates that the price of the asset tends to remain relatively stable).

4.1.1 ARMA and GARCH

An autoregressive model of order p - AR(p) - is defined by the linear equation

$$y_t = c + \varepsilon_t + \sum_{i=1}^{p} \phi_i y_{t-i} \tag{1}$$

that correlates the time series y at time t with the previous time steps through certain coefficients ϕ_i, a constant c and a random white noise $\varepsilon_t \sim \mathcal{N}(0, 1)$ applied stochastically at each time step. This way the process is strongly dependent on the previous p steps, p being a choice of the modeler: the greater the p, the greater the memory of the process. The AR(p) model is useful to capture the behaviour of a system that depends on its own previous behaviour. However, to capture volatility, we would like the model to describe a system that depends on (unexpected) *shocks*. For this reason the MA(q), moving-average, model is introduced, making the y_t depend on previous noise terms (noise memory). Putting it all together we get the ARMA(p, q) model, with p autoregressive terms and q moving-average terms:

$$y_t = c + \varepsilon_t + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} \tag{2}$$

In traditional ARMA estimation, the basic assumptions on the error terms include zero mean and constant variance, or specifically (i) $\langle \varepsilon_t \rangle = 0$, (ii) $\langle \varepsilon_t^2 \rangle = \sigma^2$, and (iii) $\langle \varepsilon_t \varepsilon_s \rangle = 0, s \neq t$. In particular, the homoskedastic assumption (ii) of constant variance, does not necessarily need to hold. The class of models where the constant variance assumption does not hold is named heteroskedastic. The authors of [15] have found that the generalized heteroskedastic error specification is strongly supported by the hourly electricity price data applied in their work. This specification significantly improves both goodness of fit and out-of-sample predictive ability to estimate energy price movements.

To accommodate the possibility of serial correlation in volatility, the Autoregressive Conditional Heteroskedastic (ARCH) class of models was introduced by Engle. The ARCH(n) model considers the conditional variance as time dependent, $V(\varepsilon_t | \varepsilon_{t-1}) = h_t$,

$$h_t = c + \sum_{i=1}^{n} \beta_i \varepsilon_{t-i}^2 \tag{3}$$

namely the variance is now conditional on the observations of previous n variances.

An extended ARCH(n) model called GARCH(m, n) (Generalized Autoregressive Conditional Heteroskedastic) model was proposed by Bollerslev where ε_t^2 takes the form

$$\varepsilon_t^2 = \nu_t^2 h_t, \qquad \nu_t \sim \mathcal{N}(0, 1) \tag{4}$$

and more importantly

$$h_t = c + \sum_{i=1}^{m} \alpha_i h_{t-i} + \sum_{i=1}^{n} \beta_i \varepsilon_{t-i}^2. \tag{5}$$

Summing up, the GARCH model used by the authors of [15] can be written using the time shift operator $L^i y_t = y_{t-i}$:

$$\begin{cases} h_t = c + \sum_{i=1}^{m} \alpha_i h_{t-i} + \sum_{i=1}^{n} \beta_i \varepsilon_{t-i}^2 \\ \varepsilon_t^2 = \nu_t^2 h_t, \qquad \nu_t \sim \mathcal{N}(0,1) \\ \left(1 - \sum_{i=1}^{p} \phi_i L^i\right) \log(y_t) = c + \left(1 + \sum_{i=1}^{q} \theta_i L^i\right) \varepsilon_t \end{cases} \tag{6}$$

where the logarithm has been applied to the time series, which is always positive, to smooth it.

4.1.2 Tuning the Model

In order to do proper forecasting the process of choosing the model and fitting it follows the following steps:

1. A class of models is considered assuming a certain hypothesis, in this case a parsimonious stochastic model.

2. Based on data analysis, a subset of models is identified (i.e., in our case, a GARCH model). Furthermore how many parameters and which shall be decided - the least the better, and that is what parsimonious stands for.

3. The model parameters are estimated on a first (training) subset.

4. The model is validated using statistical hypothesis testing, if the validation is positive go to step (v); otherwise return to step (ii) to refine the model.

5. The model parameters are defined and out-of-sample forecasting can be initiated.

In the considered research, the author settled for a GARCH(1,3) and, looking at the autocorrelation plots of the data, used ARMA with autoregressive terms up to $p = 504$ to catch both seasonality and the time-varying nature of volatility. In their empirical analysis, the proposed GARCH specification is applied to the Spanish and California electricity data. The Spanish data set consists of hourly electricity prices from September 1, 1999 to November 30, 2000, whereas the California data set consists of hourly electricity prices from January 1, 2000 through December 31, 2000. The analysis is performed on both markets for twelve months of the year taking into account low and high periods of electricity demand.

The validated model can be used to predict future price values that are usually 24 hours ahead. However, a different time window can be applied in this step. During their analysis, for the Spanish market the average time window applied was 21 weeks, and for the California market it was 15 weeks.

4.1.3 The Forecast

The GARCH forecast of price volatility in the Spanish marketis shown in subfigures 2 and 3 of Fig.24. In particular, subfigure 2 (top-left) shows how the model works for the last week of June 2000. This was the first time in 2000 in which there was high volatility in the Spanish market with prices ranging from 12.37/MWh to 62.20/MWh. It can be observed that even though the model is not able to forecast accurately the first high volatility peak occurred on June 28, it was nevertheless able to reasonably follow the second high volatility peak observed on June 29.

Similarly, subfigures 4 and 5 show the GARCH forecast for the California electricity prices. Subfigure 4 presents the results for the period of the start of the California crisis, May 19–28, 2000. Even though the price was very volatile for that period, the model was still able to follow the trend of the real price mainly after two peaks occurred on the May 22 and 23. Moreover, subfigure 5 shows the results obtained from the model during the height of the California crisis, the last week of June 2000.

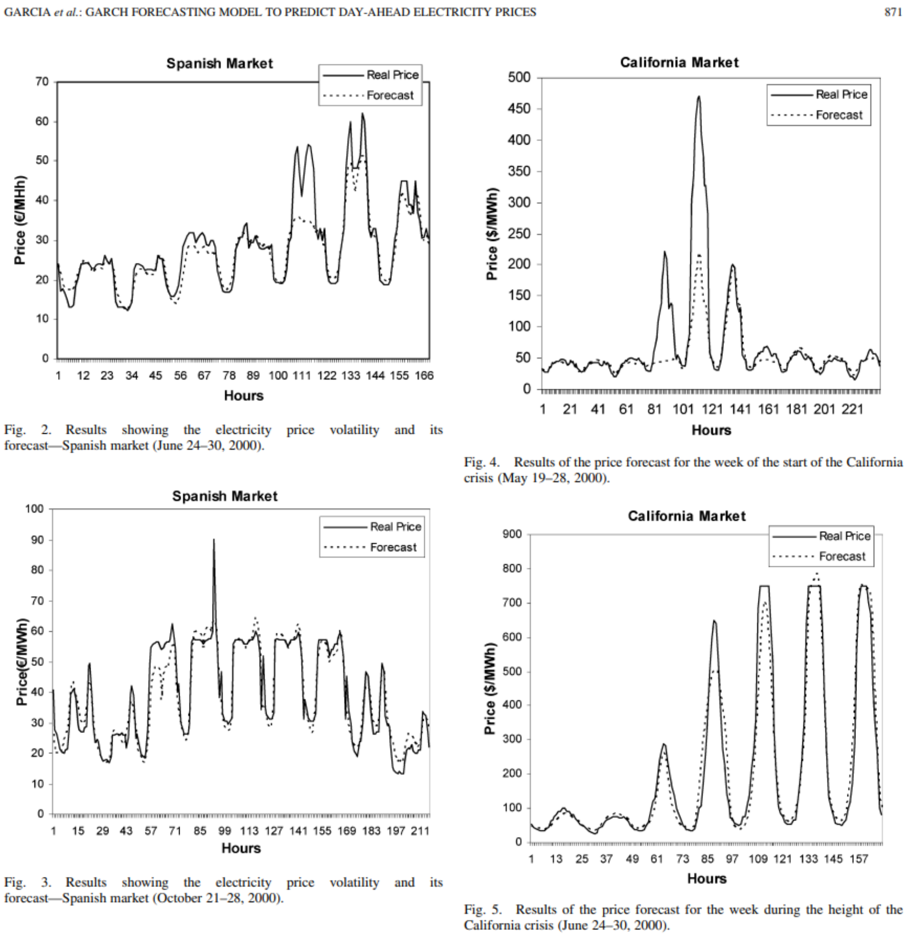

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Fig. 2. Results showing the electricity price volatility and its forecast—Spanish market (June 24–30, 2000).

Fig. 4. Results of the price forecast for the week of the start of the California crisis (May 19–28, 2000).

Fig. 3. Results showing the electricity price volatility and its forecast—Spanish market (October 21–28, 2000).

Fig. 5. Results of the price forecast for the week during the height of the California crisis (June 24–30, 2000).

Figure 24: Forecasts for the Spanish and Californian electricity markets by the GARCH model proposed by [15].

A Example of loads sensitive to grid instability

We report here a non-exhaustive list of possible damages caused by a non-equilibrated grid taken from *CEI 0-21, 2019/04* [12].

Tabella 1 – Carichi sensibili

	FENOMENO CONSIDERATO	Carico SENSIBILE	CONSEGUENZE
(a)	Buchi di tensione: $\Delta V \leq 30\ \%\ U_N$ $\Delta t \leq 60 \div 100$ ms	Apparati elettronici digitali di controllo di processo o macchinari calcolatori in genere	Arresti e/o anomalie dei processi/macchinari
		Azionamenti a velocità variabile (elettronica di potenza)	Interventi delle protezioni dell'elettronica di potenza
	Buchi di tensione: $\Delta V \geq 30\ \%\ U_N$ $\Delta t \leq 60 \div 100$ ms	In aggiunta a quanto sopra, dispositivi elettromeccanici (relè ausiliari, teleruttori)	Arresto quasi globale di tutte le utenze
(b)	Sovratensioni non impulsive (lunga durata)	Motori e macchine elettriche Bobine di contattori Lampade a incandescenza	Riduzione di vita degli isolamenti
	Variazioni lente di tensione $\Delta V = \pm 10\ \%\ V_N$	Impianti di illuminazione Gli stessi apparecchi di (a) e (b)	In caso di riduzione, rallentamento o arresto di motori elettrici: le stesse conseguenze di (a) e (b)
	Sovratensioni impulsive	Componenti elettronici sia di controllo che di potenza.	Perforazione isolamenti
		Motori, cavi e macchinario elettrico in genere	Danneggiamento ai circuiti elettronici
	Transitori di commutazione (ponti convertitori, tecniche chopper)	Linee trasmissione dati e segnali a basso livello di potenza. Apparecchi elettronici di controllo	Malfunzionamento dei sistemi di controllo e di elaborazione dati.
	Armoniche	Condensatori	Sovra riscaldamento e danneggiamento condensatori
		Relè di protezione	Interventi intempestivi relè di protezione
		Collegamenti a basso livello di potenza	Malfunzionamento sistemi di controllo e trasmissione dati
		Motori e macchine rotanti	Incremento delle perdite di motori, trasformatori e cavi e conseguente. Sovra riscaldamento
		Trasformatori	
		Cavi elettrici	
	Dissimmetrie e squilibri	Motori elettrici e macchine rotanti in genere	Sovra riscaldamento

Figure 25: Here are listed some consequences on sensitive loads (appliances, motors, lightning) caused by phenomena associated with a poor grid quality.

B Sketch of the Italian EE bill

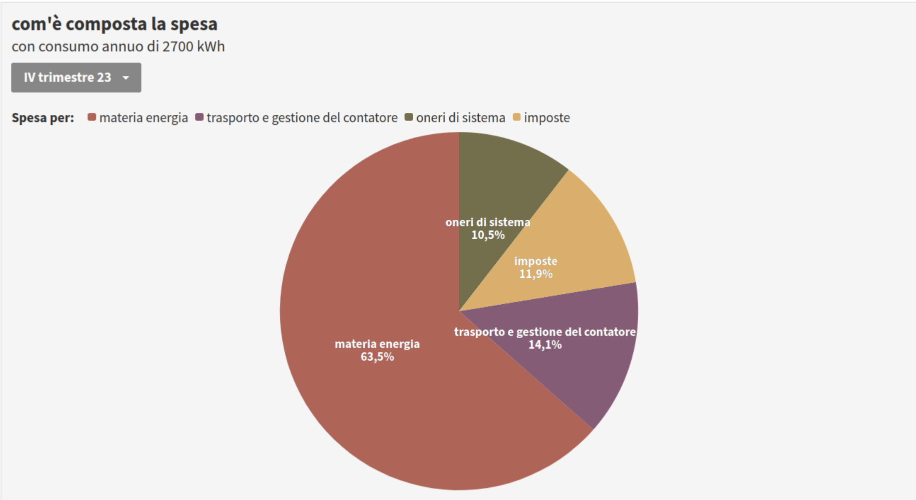

Figure 26: Example of an Italian bill subdivision from the fourth quarter in 2023 (source: ARERA).

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