

Chapter 1

Electric Energy Systems. An Overview

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1.1 A first vision

1.1.1 The energy challenges in modern times

Energy is a fundamental ingredient of modern society and its supply impacts directly in the social and economic development of nations. Economic growth and energy consumption go hand to hand. The development and quality of our life and our work are totally dependent of a continuous, abundant and economic energy supply. This reality is being faced worldwide as basic energy resources become scarce and increasingly costly. While coal remains an abundant resource, oil and natural gas supply face restrictions, concerns arising on declining volumes on the long term. This reliance on energy for economic growth has historically implied dependence on third parties for energy supply, with geopolitical connotations arising, as energy resources have not been generally in places where high consumption has developed, Energy has transformed itself in a new form of international political power, utilized by owners of energy resources (mainly oil and natural gas).

Within that framework, electricity has become a favorite form of energy usage at the consumer end, with coal, oil, gas, uranium, and other basic resources used to generate the electricity. With its versatility and controllability, instant availability and consumer-end cleanliness, electricity has become an indispensable, multi-purpose form of energy. Its domestic use now extends far beyond the initial purpose, to which it owes its colloquial name (“light” or “lights”), and has become virtually irreplaceable in kitchens –for refrigerators, ovens and cookers or ranges and any number of other appliances– and in the rest of the house as well, for air conditioning, radio, television, computers, and the like. But electricity usage is even broader in the commercial and industrial domains: in addition to providing power for lighting and air conditioning, it drives motors with a host of applications: lifts, cranes, mills, pumps, compressors, lathes or other machine tools, and so on and so forth: it’s

nearly impossible to imagine an industrial activity that doesn't use some sort of electricity. Thus, modern societies have become totally dependent on an abundant electricity supply.

1.1.2 Characteristics of electricity

At first glance electricity must appear to be a commodity much like any other on consumers' list of routine expenses. In fact, this may be the point of view that prompted the revolution that has rocked electric energy systems world-wide, as they have been engulfed in the wave of liberalization and de-regulation that has changed so many other sectors of the economy. And yet electricity is defined by a series of properties that distinguish it from other products, an argument often wielded in an attempt to prevent or at least limit the implementation of such changes in the electricity industry. The chief characteristic of electricity as a product that differentiates it from all others is that it is not susceptible, in practice, to being stored or inventoried. Electricity can, of course, be stored in batteries, but price, performance and inconvenience make this impractical for handling the amounts of energy usually needed in the developed world. Therefore, electricity must be generated and transmitted as it is consumed, which means that electric systems are dynamic and highly complex, as well as immense. At any given time, these vast dynamic systems must strike a balance between generation and demand and the disturbance caused by the failure of a single component may be transmitted across the entire system almost instantaneously. This sobering fact plays a decisive role in the structure, operation and planning of electric energy systems, as discussed below.

Another peculiarity of electricity has to do with its transmission: this is not a product that can be shipped in "packages" from origin to destination by the most suitable medium at any given time. Electric power is transmitted over grids in which the pathway cannot be chosen at will, but is determined by Kirchhoff's laws, whereby current distribution depends on impedance in the lines and other elements through which electricity flows. Except in very simple cases, all that can be said is that electric power flows into the system at one point and out of it at another, because ascribing the flow to any given path is extraordinarily complex and somewhat arbitrary. Moreover, according to these laws of physics, the alternative routes that form the grid are highly interdependent, so that any variation in a transmission facility may cause the instantaneous reconfiguration of power flows; and that, in turn, may have a substantial effect on other facilities. All this renders the dynamic balance referred to in the preceding paragraph even more complex.

1.1.3 Electrical energy systems: the biggest industrial system created by mankind

Indeed, for all its apparent grandiloquence, the introductory sentence to this unit may be no exaggeration. The combination of the extreme convenience of use and countless applications of electricity on the one hand and its particularities on the other has engendered these immense and sophisticated industrial systems. Their size has to do with their scope, as they are designed to carry electricity to practically any place inhabited by human beings from electric power stations located wherever a supply of primary energy—in the form of potential energy in moving water or any of several fuels—is most readily available. Carrying

electric power from place of origin to place of consumption calls for transmission grids and distribution grids or networks that interconnect the entire system and enable it to work as an integrated whole. Their sophistication is a result of the complexity of the problem, determined by the characteristics discussed above: the apparently fragile dynamic equilibrium between generation and demand that must be permanently maintained is depicted in the highly regular patterns followed by the characteristic magnitudes involved –the value and frequency of voltage and currents as well as the waveform of these signals. Such regularity is achieved with complicated control systems that, based on the innumerable measurements that continuously monitor system performance, adapt its response to constantly changing conditions. A major share of these control tasks is performed by powerful computers in energy management centers running a host of management applications: some estimate demand at different grid buses several minutes, hours, days or months in advance; other models determine the generation needed to meet this demand; yet other programs compute the flow in system lines and transformers and the voltage at grid buses under a number of assumptions on operating conditions or component failure, and determine the most suitable action to take in each case. Others study the dynamic behavior of the electric power system under various types of disturbance. Some models not only attempt to determine the most suitable control measures to take when a problem arises, but also to anticipate their possible occurrence, modifying system operating conditions to reduce or eliminate its vulnerability to the most likely contingencies.

This, however, is not all: the economic aspect of the problem must also be borne in mind. The actors that make the system work may be private companies that logically attempt to maximize their earnings or public institutions that aim to minimize the cost of the service provided. In either case, the economic implications of the decisions made cannot be ignored, except, of course, where system safety is at stake. The system operates under normal conditions practically always, so there is sufficient time to make decisions that are not only safe, but economically sound. Hence, when demand rises foreseeably during the day, power should be drawn from the facilities with unused capacity that can generate power most efficiently. The objective is to meet daily load curve needs with power generated at the lowest and least variable cost. This new dimension in the operation of electric energy systems is present in all time scales: from the hourly dispatch of generating plant to the choice of which units should start up and stop and when, including decisions on the use of hydroelectric reserve capacity, maintenance programming and investment in new facilities. It should, moreover, be stressed that all these decisions are made in a context of uncertainty: about the future demand to be met, plant availability, the prices of the various parameters involved in the production process –in particular, fuel– and even the regulatory legislation in effect when long-term decisions are to be implemented.

1.1.4 History

Technological aspects

The first electric light systems, installed around 1870, consisted of individual dynamos that fed the electrical system –arc lamps– in place in a single residence. Thomas Edison discovered the incandescent light bulb around 1880 and authored the idea of increasing the

scale of the process by using a single generator to feed many more bulbs. In 1882, Edison's first generator –driven by a steam turbine located on Pearl Street in lower Manhattan– successfully fed a direct current at a voltage of 100 V to around 400 80-W bulbs in office and residential buildings on Wall Street. Shortly thereafter London's 60-kW Holborn Viaduct station was commissioned, which also generated 100-V direct current. This local generation and distribution scheme was quickly adopted, exclusively for lighting, in many urban and rural communities world-wide.

The invention of the transformer in France in 1883-84 revealed –in a process not exempt from controversy– the advantages of alternating current, which made it possible to conveniently raise the voltage to reduce line losses and voltage drops over long transmission distances. Alternating, single phase electric current was first transmitted in 1884, at a voltage of 18 kV. On 24 August 1891, three-phase current was first transmitted from the hydroelectric power station at Lauffen to the International Exposition at Frankfurt, 175 km away. Swiss engineer Charles Brown –who with his colleague and fellow countryman Walter Boveri founded the Brown-Boveri Company that very year– designed the three phase AC generator and the oil-immersed transformer used in the station. In 1990 the Institute of Electrical and Electronic Engineers, IEEE, agreed to take 24 August 1891 as the date marking the beginning of the industrial use and transmission of alternating current.

The transmission capacity of alternating current lines increases in proportion to the square of the voltage, whereas the cost per unit of power transmitted declines in the same proportion. There was, then, an obvious motivation to surmount the technological barriers limiting the use of higher voltages. Voltages of up to 150 kV were in place by 1910 and the first 245-kV line was commissioned in 1922. The maximum voltage for alternating current has continued to climb ever since, as Figure 1.1 shows. And yet direct current has also always been used, since it has advantages over alternating current in certain applications, such as electrical traction and especially electricity transmission –in overhead, underground or submarine lines– when the distances are too long for alternating current. The upward trend in maximum direct current voltage throughout the twentieth century is also depicted in Figure 1.1.

The alternating voltage frequency to be used in these systems was another of the basic design parameters that had to be determined. Higher frequencies can accommodate more compact generating and consumption units, an advantage offset, however, by the steeper voltage drops in transmission and distribution lines that their use involves. Some countries –the USA, Canada, the Central American countries and the northern-most South American countries– adopted a frequency of 60 Hz, whilst countries in the rest of South America, Europe, Asia and Africa adopted a frequency of 50 Hz. The International Electrotechnical Commission was created in 1906 to standardize electrical facilities everywhere as far as possible. It was, however, unable to standardize frequency, which continues to divide countries around the world into two different groups.

The advantages of interconnecting small electric energy systems soon became obvious. The reliability of each system was enhanced by the support received from the others in the event of emergencies. Reserve capacity could also be reduced, since each system would be able to draw from the total grid reserve capacity. With such interconnections it was possible to deploy the generator units able to meet demand most economically at any given time;

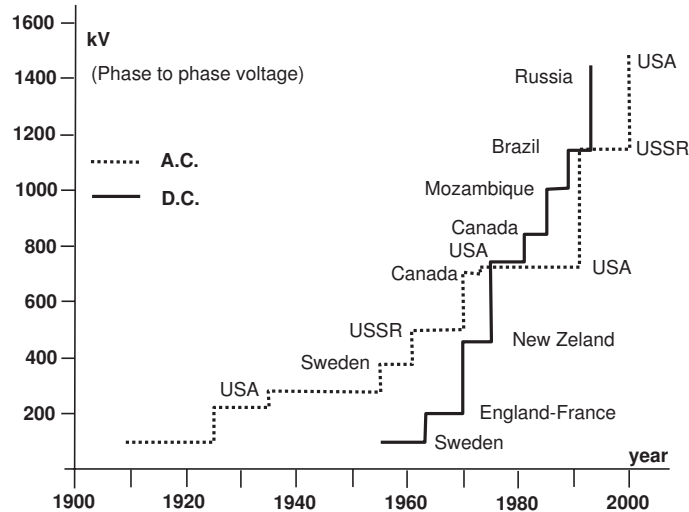


Figure 1.1: Maximum AC and DC rated voltages. [Source: Torá [12]].

the advantage this affords is particularly relevant when peak demand time frames vary from one system to another and when the generation technology mix –hydroelectric and steam, for instance– likewise differs. In 1926 English Parliament created the Central Electricity Board and commissioned it to build a high voltage grid that would interconnect the 500 largest generation stations then in operation.

Organizational aspects

What sort of organizational structure is in place in the sector responsible for planning, operating and maintaining electric energy systems? Who makes the decisions in each case and under what criteria? The reply to these questions has evolved over time, largely to adapt to the conditioning factors imposed by technological development, but also depending on prevailing economic theory. As mentioned above, the first industrial applications of electricity were strictly local, with a generator feeding a series of light bulbs in the surrounding area. Whole hosts of individual systems sprang up under private or public –usually municipal– initiative, primarily to provide urban lighting and, somewhat later, to drive electric motors for many different purposes. The vertically integrated electric utility –which generates, transmits, distributes and supplies electricity– arose naturally and was the predominant model in most countries until very recently. The enormous growth of electricity consumption, the huge economies of scale in electricity generation and the increase in the transmission capacity of high voltage lines drove the development of transmission grids –often under State protection– to interconnect individual systems, giving rise to literally nationwide systems. Technical specialization and the huge volume of resources required to build large power stations led to the co-existence of local distribution companies –with scant or nil production capacity– and large vertically integrated utilities which also sold

wholesale electric power to small distributors.

Because of its special characteristics, electricity, or more appropriately its supply, has long been regarded to be a public service in most countries, an approach that justified State intervention to guarantee reasonable quality and price. In some cases intervention consisted of nationalizing the electricity industry, such as in nearly all European countries until the nineteen nineties. In others electric utilities were subject to the legal provisions typically applied to monopolies, namely the requirement to meet certain minimum quality standards and the imposition of regulated prices to cover the costs incurred, including a reasonable return on the investment made. Until recently, this was the generally accepted model for industry regulation, in which the vertical integration of electric utilities was never questioned.

In the early nineteen nineties, however, a radically different view of the electricity business began to take hold the world over. This approach challenged the vertically integrated structure of electric power suppliers. Densely interconnected transmission grids in most countries and even between countries now enable a generator located at any bus on the grid to compete with other operators to supply electricity virtually anywhere on the grid. It is, therefore, possible to separate strictly monopolistic grid activities from the generation and supply businesses, which can be conducted on a competitive market.

Under this new approach to the electricity business, electric power system operation and planning acquire a whole new dimension. Each generator decides individually when and how much to produce, how to manage the water in their dams and how to plan and implement their plant maintenance programmes. Decisions on investment in new power plants are not made centrally by any body or company responsible for guaranteeing supply, but by private investors seeking a return on their investment, who are not responsible for overall security of supply. The distribution business has not been significantly impacted by this new regulatory framework, except that it must be unbundled from supply, which is now competitive. Transmission, on the contrary, has been the object of a major overhaul, for its crucial importance in determining the competitive conditions under which wholesale market actors must operate.

Although technological and economic factors are ever present, the role played by regulation grows in importance with the geographic and political scope of electrical systems, particularly under competitive market conditions. In regional or supranational electric energy systems, for instance, rules have had to be established in the virtual absence of regulatory provisions for the operation of international markets. The European Union's Internal Electricity Market is paradigmatic in this regard: it covers 27 countries, 25 in the European Union plus Norway and Switzerland. Other regional markets, in different stages of implementation, include the Australian national market, which encompasses several states in that country; Mercosur, servicing Argentina, Brazil, Paraguay and Uruguay; the Central American Electricity Market; and the Regional Transmission Organizations in the United States that link several different but centrally managed electric utilities.

The motivation for establishing these regional markets is essentially economic: lower costs to maintain system safety and the advantage of mutually beneficial transactions among the different systems. Interconnecting whole electric energy systems poses interesting technological problems –such as co-operation to maintain a common frequency across the entire

system, abiding by trade arrangements stipulated between the various countries, support in emergency situations, global analysis and control of certain grid stability phenomena, or management of grid restrictions deriving from international trade— that had been essentially solved or kept under control in the context of vertically integrated electric utilities, via well-established rules for support in emergencies in a climate of co-operation, scant competition and limited trade.

These technical problems have become more acute and their complexity has grown with the need to accommodate economic and regulatory considerations in the recent context of open competition. The proliferation of international transactions conducted in a completely decentralized manner by individual players—buyers and sellers entitled to access the regional grid as a whole— has complicated matters even further. In addition to these technological problems, other issues must also be addressed, such as harmonizing different national regulations, organizing and designing operating rules for regional markets, determining the transmission tolls to be applied in international transactions, pursuing economic efficiency in the allocation of limited grid capacity and solving technical restrictions or proposing suitable regulatory mechanisms to ensure efficient transmission grid expansion.

1.1.5 Environmental impact

In addition to ongoing technological development and the winds of change blowing in the global economy, a factor of increasing weight in the electricity industry, as in all other human activities, is the growing awareness of the importance of the natural environment. There is widespread belief that one of the major challenges facing humanity today is the design of a model for sustainable development, defined to be development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Besides such weighty issues as the enormous social and economic inequalities between peoples or the existence of a growth model that can hardly be extended to the entire world population, other questions, such as the intense use of the known energy resources and their adverse impact on the environment, problems that relate directly to electric energy systems, also come under the umbrella of sustainable development. For these reasons environmental impact is a factor of increasing relevance and importance that conditions the present operation and development of these systems and will indisputably have an even more intense effect on the industry in the future.

Generation is arguably the line of business in electric energy systems that produces the greatest environmental impact, in particular with regard to steam plant emissions and the production of moderately and highly radioactive waste. As far as combustion is concerned, coal- and oil-fired steam plants vie with the transport industry for first place in the emission of both carbon dioxide (CO₂)—associated with greenhouse gas-induced climate change—, nitrous oxides (NO_x) and sulphur dioxide (SO₂)—the former related to the formation of tropospheric ozone and both responsible for acid rain. Carbon dioxide is an inevitable by-product of the combustion of organic material, NO_x comes from the nitrogen in the air and SO₂ from the sulphur in coal and oil. Other environmental effects of conventional steam power stations include the emission of particles and heavy metals, the generation of solid waste such as fly ash and slag, the heating of river, reservoir or sea water to cover

refrigeration needs and, indirectly, the impact of mining. With respect to nuclear power stations, in turn, even assuming that the strict safety measures in place suffice to rule out the likelihood of an accidental catastrophe, the inevitable accumulation of radioactive waste is, irrefutably, an unsolved problem that conditions coming generations so severely that nuclear power as it is known today cannot be regarded to be a sustainable source of energy.

In any event, it must be borne in mind that even generation facilities that use renewable energy and are considered to be the most environment-friendly technologies, have an adverse impact. The most numerous, namely hydroelectric power plants, which have existed ever since electric power was first industrialized, change the surroundings radically: alteration of hydrology, disturbance of habitats or even transformation of the microclimate, not to mention the risk of accidents that can spell vast ecological and human disaster. Other more recent technologies also have adverse consequences: wind, the disturbance of natural habitats and noise; solar, land occupancy and the pollution inherent in the manufacture of the components required for the cells, and more specifically the heavy metals present in their waste products; the use of biomass has the same drawbacks as conventional steam plants, although the effect is less intense, no SO₂ is emitted and, if properly managed, it is neutral with respect to CO₂ emissions. In fact, all electricity generation activities have one feature in common, namely the occupation of land and visual impact, but the area involved and the (not necessarily proportional) extent of social rejection vary considerably with technology and specific local conditions.

In a similar vein, the huge overhead lines that carry electric power across plains, mountain ranges, valleys, and coasts and circle large cities have at least a visual impact on the environment, which is being taken more and more seriously. Less visible but indubitably present are the electromagnetic fields that go hand-in-hand with the physics of electricity, although their potential effects on people, fauna and flora are still under examination. Such considerations have important consequences, since environmental permits and rights of way constitute strong constraints on the expansion of the transmission grid. As a result, the grid is operating closer and closer to its maximum capacity, occasioning new technical problems –relating to its dynamic behavior, for instance– which logically have economic consequences. In some cases alternative solutions are available, albeit at a higher cost, such as running underground lines in densely populated areas.

But the question is not solely one of establishing the magnitude of the environmental impact of the electricity industry or of the awareness that minimizing this impact generally entails increased system costs. The question, rather, is whether or not this impact should be considered when deciding how to best allocate society's scant resources. In a free market, the tool for resource allocation is product price –in this case, of the various power options. Nonetheless, the general opinion, among both the public at large and governmental authorities at the various levels, is that energy prices do not cover all the types of impact discussed above. This is what is known as a market failure or externality, defined to be the consequences of some productive or consumption processes for other economic agents that are not fully accounted for by production or consumption costs. The existence of such externalities –also called external costs– therefore leads to an undue allocation of resources in the economy, preventing the market from properly and efficiently allocating resources on

the grounds of their price. Indeed, since account is not taken of these external costs, the price of energy is lower –and therefore consumption and environmental impact are higher– than they would be if total power costs were efficiently allocated. The existence of externalities, if not taken into consideration, also leads to the choice of more highly polluting power technologies than if allocation were optimum. In order to correct this market failure and reach optimum allocation, such costs must be internalized, building them into the price in a way that the economic agents can include them in their decision-making and ensure an optimum outcome for society as a whole.

1.2 The technological environment

1.2.1 Electric power system structure

Electric energy systems have developed along more or less the same lines in all countries, converging towards a very similar structure and configuration. This is hardly surprising, account taken of the very specific characteristics of the product they sell. As mentioned earlier, electricity generation, transmission, distribution and supply are inevitably conditioned by the fact that generation and demand must be in instantaneous and permanent balance. The relevance of technical factors in maintaining such large-scale systems in dynamic equilibrium cannot be overlooked. A disturbance anywhere on the system may endanger the overall dynamic balance, with adverse consequences for the supply of electricity across vast areas, even whole regions of a country or an entire country. It is perhaps for this reason that the existence of sophisticated real-time control, supervision and monitoring systems, together with the protection facilities is what, from the technical standpoint, chiefly differentiates the configuration and structure of electric energy systems from other industrial activities. The functions typical of any industry, such as production, shipping, planning and organization, are also highly specialized in the electricity industry.

The organization of the electricity industry, like any other, is divided into production centers –generating plant–; transmission (equivalent to transport or shipping in other industries) –the high voltage grid–; distribution –the low voltage grid or network–; and consumption (also termed supply in some contexts), in addition to the associated protection and control systems. More formally, system configuration and structure are as depicted in Figure 1.2. Production centers generate electricity at voltages of several kilovolts –typically from 6 to 20 kV– and immediately transform this power to voltages of hundred of kilovolts –132, 220, 400, 500 and 700 kV are relatively common values– to optimize long-distance transmission over electric lines to the areas where consumption is most intense. Raising the voltage makes it possible to transmit large amounts of electric power –the entire output from a nuclear powered generator, for instance– over long distances using reasonably inexpensive cable technology with minimum line losses. The transmission grid interconnects all the major production and consumption centers, generally forming a very dense web to guarantee high reliability, with alternative pathways for the supply of electric power in the event of failure in a few of the lines. These electric power transmission highways are interconnected at communication nodes known as electric substations; the regional grids are spun out from the stations at a somewhat lower voltage –132, 66 or 45 kV in Spain, for instance– and in

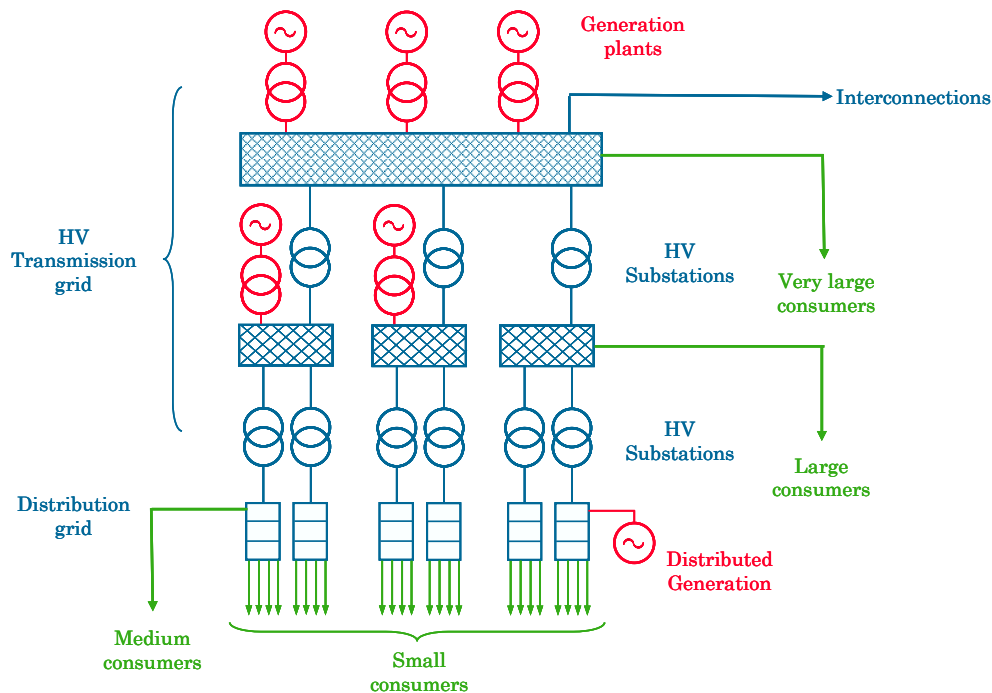


Figure 1.2: Electric power system configuration and structure.

turn feed local distribution networks, which bring electric power to consumers at less hazardous voltages, adapted to consumer needs –20 000, 15 000, 6 600, 380 or 220 V. Successive substations step the working voltage down in several phases and centralize the measuring and protection devices for the entire transmission grid. The configuration of these grids is usually radial, with tentacles stretching out to even the most remote consumption points. As the lines are split up at each step, the grids carry less and less power and consequently can operate at lower voltages. Consumers connect to the voltage level best suited to their power needs, in accordance with the basic principle that the lower the voltage, the smaller the power capacity. This means that highly energy-intensive businesses –iron and steel plants and mills, aluminium plants, railways, and the like– connect directly to the high voltage grid; other major consumers –large factories– receive power at a somewhat lower voltage and small consumers –households, retailers, small factories– are connected to the low voltage network. Based on a more or less reciprocal principle, generating stations with a very small output feed their electric power directly into the distribution network, instead of connecting to the high voltage grid. Such generators, which usually run small hydroelectric,

Region	1980	1983	1986	1989	1992	1995	1998	2001	2004
North America	9,792	9,863	10,677	12,035	12,115	12,716	13,258	13,392	13,715
Latin America	796	860	1,005	1,048	1,090	1,209	1,331	1,356	1,495
Europe	4,111	4,240	4,711	5,005	4,983	5,192	5,520	5,854	6,138
Former Soviet Union	4,584	4,881	5,045	5,351	4,848	3,989	3,777	4,003	4,266
Asia & Oceania	476	514	587	697	793	926	1,009	1,112	1,329
Middle East	599	807	929	1,064	1,137	1,364	1,563	1,744	2,027
Africa	375	392	443	457	450	467	477	496	542
World	1,663	1,698	1,827	1,980	1,986	2,062	2,150	2,242	2,421

Table 1.1: Electricity consumption per capita (kWh), 1980-2004 [Source: Energy Information Administration, U.S. Government]

photovoltaic, wind, CHP or other types of modular power stations engaging in distributed generation, are sometimes grouped under a single category for regulatory purposes; an example would be Spain's Electricity Act, which deals with them collectively under the term "special regime generators". The points below focus on these chief components of electric energy systems: consumption, production, transmission, distribution and protection and control.

1.2.2 Consumption

Demand growth

Electricity demand has undergone high, sustained growth since the outset. The creation of standards for the electricity "product" –voltage, frequency, current– paved the way for the enormous boom in electricity consumption. This in turn laid the grounds for the standardization of electrically powered fixtures and facilities –from light bulbs and motors to PCs–, dramatically lowering manufacturing costs and enhancing product versatility, making it possible to use a given electrically-powered item virtually anywhere. Electric power consumption is one of the clearest indicators of a country's industrial development, and closely parallels GDP growth. As noted earlier, there are scarcely any production processes or sectors involved in creating wealth that do not require electricity. But electric power consumption has also been used as a measure of social development. Electricity consumption per capita and especially the degree of electrification in a country –i.e., the percentage of the population living in electrified homes– provide a clear indication of the standard of living. This is not surprising, since such basics as lighting, a supply of potable water, refrigerators and other household appliances depend on access to electricity. The curves in the figures shown below relate the growth in electricity consumption to other basic indicators, such as gross domestic product, population or energy consumption. The growth rate is obviously higher in countries with low baseline levels of electric power consumption and high economic growth.

Electrification rates and electricity consumption per capita vary widely from one area of the world to another, as Table 1 below eloquently illustrates [13]. One third of the Earth's six million inhabitants have no electricity.

But the growth in electricity consumption is not limited to developing countries: it has definitely steadied, but is certainly not flat in developed countries. Whilst the industrial world's consumer mentality may partly be driving such growth, it is nonetheless true that

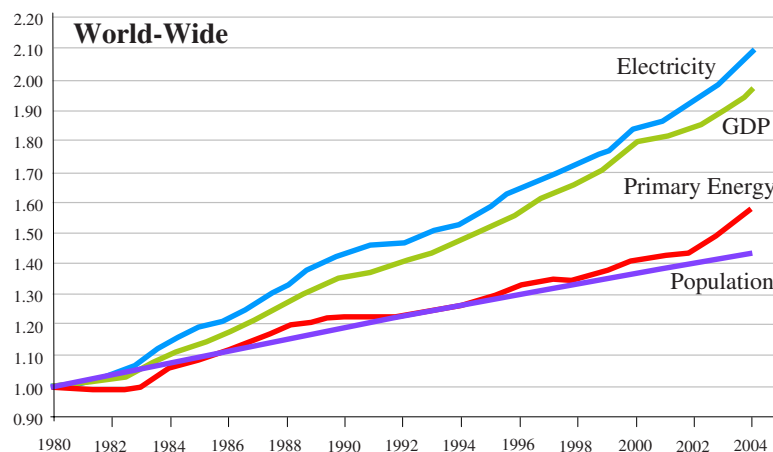


Figure 1.3: World Growth Rate referred to 1980 value [Source: Energy Information Administration, U.S. Government; U.S. Department of Agriculture].

new uses are continuously found for electric power. The generalized use of air conditioning in these countries is an obvious example and one that has brought a radical change in seasonal consumption curves, as explained below.

In addition, sustained electricity consumption growth exists despite substantial improvement in the efficiency of most equipment and processes using electric power, which reduces the input power in kWh needed to attain a given result. More and more voices are being raised in defence of the need to rationalize the consumption of electricity and all other forms of energy. Aware of the environmental impact of such consumption and the vast amount of natural resources that are literally going up in smoke, such voices rightly call for intergenerational solidarity to be able to bequeath to coming generations an ecologically acceptable planet whose energy resources have not been depleted. Hence the importance of demand side management (DSM), a term coined in the United States to mean all the techniques and actions geared to rationalizing the consumption of electric power. The aim, on one hand, is more efficient use of existing consumption to reduce the enormous investment involved in the construction of new stations and the substantial cost of producing electricity and, on the other hand, just energy savings by cutting down certain consumptions, with the same beneficial implications. Demand side management should, therefore, be an active component of future electric energy systems, reflecting the attempt to internalize environmental costs, for instance, which are so often ignored. The role and suitable regulation of this business is one of the challenges facing the new structure and regulation of a liberalized electricity industry.

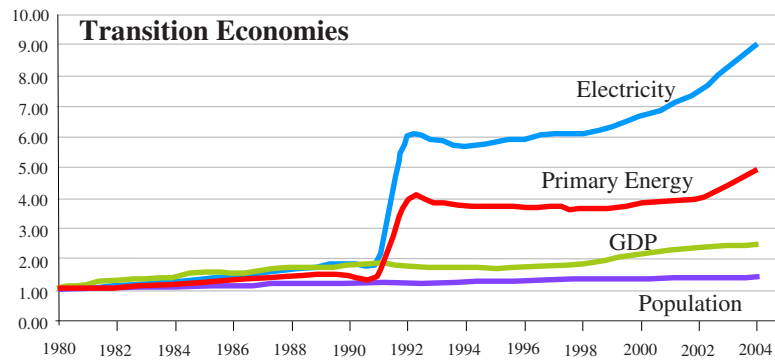


Figure 1.4: Transition Economies Growth Rate referred to 1980 value [Source: Energy Information Administration, U.S. Government; U.S. Department of Agriculture].

It may be important in this regard for consumers, the final and key link in the electricity chain, to receive the sophisticated economic signals that deregulation is sending out to the various other players involved –producers, transmitters, distributors and suppliers. Pricing should be designed to make consumers aware of the real –economic and environmental–cost of meeting their power needs, taking account of their consumption patterns in terms of hourly profile and total load. In the medium term, this should accustom domestic, commercial and industrial users to monitor and actively control electric consumption, in much the same way that discriminatory hourly telephone rates encourage customers to make non-urgent long-distance calls at off-peak times. Similarly, customers will voluntarily reduce electricity consumption by foregoing the most superfluous applications at times when higher prices signal that expensive resources are being deployed or that the margin between the demand and supply of electric power is narrow. The capacity of demand to respond to pricing is generally characterized by a parameter termed price elasticity of demand. This is defined to be the percentage variation in consumption of electricity or any other product in response to a unit variation in the price. Electricity demand is characterized, generally speaking, by scant short-term elasticity; in other words, the reaction to changes in price are small, although this assertion is more accurate for some types of consumer than others. Such limited elasticity is arguably due to the mentality prevailing until very recently in the electricity industry: continuity of supply was regarded to be a nearly sacred duty, to be fulfilled at any price. Consumers –who were identified, indeed, as subscribers rather than customers– were merely passive recipients of the service provided. Advances in

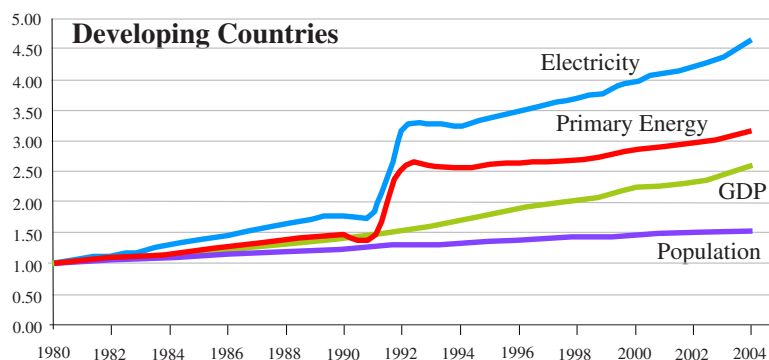


Figure 1.5: Developing Countries Growth Rate referred to 1980 value [Source: Energy Information Administration, U.S. Government; U.S. Department of Agriculture].

communications technology, in conjunction with the liberalization of the electric and energy industries in much of the world, are going to change consumers' role radically. Demand side mentality overall will not change readily or quickly. Nonetheless, the years to come will very likely witness the maturing and accentuation of the role played by demand in the electricity industry, which will become as relevant as other areas, such as generation. Elasticity will grow, although much of the demand will foreseeably remain impervious to price.

Demand profiles

Consumption is characterized by a variety of items, from the technical standpoint. The two most important are power and energy. Power, measured in watts (W) is the energy (Wh) required per unit of time. Power, therefore, is the instantaneous energy consumed. Since electric power is not stored, electric facilities must be designed to withstand the maximum instantaneous energy consumed, in other words, to withstand the maximum power load in the system throughout the consumption cycle. Therefore, not only the total electric capacity needed, but the demand profile over time is especially relevant to characterize consumption. Such profiles, known as load curves, represent power consumed as a function of time. It may be readily deduced that a given value of energy consumed may have a number of related load profiles. Some may be flat, indicating very constant electricity consumption over time, while others may have one or several very steep valleys or peaks, denoting very variable demand. An aluminium plant working around the clock 365 days a year and a factory operating at full capacity only during the daytime on weekdays would exemplify these two

types of profiles. Load profiles commonly generate repetitive patterns over time. Thus, for instance, weekday demand is normally very uniform, as is the weekly load during a given season. Therefore, depending on the time scale considered, the load profile to be used may be daily, weekly, monthly, seasonal, yearly or even multi-yearly. Load profiles also have economic relevance, as will be seen in the discussion below: for any given demand level, it is less expensive to cover a flat than a spiked load profile. For this reason, load curves constitute one of the most relevant parameters considered in the methods used to set tariffs.

Summing all the individual consumption curves for an electric power system yields the total daily, weekly, monthly, seasonal, yearly and multi-yearly load curves, each with a characteristic and highly significant power profile. The figures below show load curves for a South American electric energy system, specifically central Chile [source: www.cdec-sic.cl], with indication of energy supplied by run of river hydro (pass), reservoir hydro (dam) and thermal generation. There are very clear peaks and valleys in each, denoting cyclical maximum and minimum demand. Demand forecasting is an essential problem to solve in foreseeing the conditions under which the system will be operating in the short, medium and long term. Normal procedure is to base the prediction on historical data adjusted to take account of factors affecting the expected load. The most important of these factors include temperature, since many electrical devices are used for space heating or cooling; number of working days, to account for the difference in consumption on business days and holidays; and economic growth, in view of the above-mentioned close relationship between economic activity and electricity consumption. Therefore, consumption at any given time can be reasonably well predicted from time series data corrected for foreseeable variations in growth, working days and temperature, and taking account as well of special events that may have a substantial effect on demand.

Aggregate electricity consumption can also be represented as a monotonic load curve, which is particularly useful in certain applications and studies. Such curves represent the length of time that demand exceeds a given load. The thick line in Figure 1.9 is the approximate monotonic load curve for for a Canadian utility, which generates with hydro energy [Source: www.gcpud.org]: the abscissa values represent time in hours and the ordinate values demand in megawatts. Therefore, each point on the curve indicates the total hours during the year that demand exceeded a given value. In the example, the load was in excess of 15,000 MW for a total of 1,200 hours in 2005. The load monotone can be plotted directly from the chronological load curve by ranking demand in descending order. The integral of the load monotone represents the energy consumed in the time frame considered. It will be noted, however, that whereas a given load curve can have only one load monotone, the opposite is not true. Although the chronological information contained in load curves is lost in monotonic curves, the latter are widely used for their simplicity. Probabilistic monotone curves are commonly used in prospective studies, which are based on demand forecasts subject to some degree of uncertainty; in this case the x-axis values represent the likelihood that demand will exceed a given value. As in the case of chronological demand profiles, monotonic load curves can be plotted for daily, weekly, monthly, seasonal, yearly or multi-yearly consumption.

In addition to the power/energy properties discussed at length in the foregoing paragraphs, consumption is characterized by other technical factors. Account must be taken,

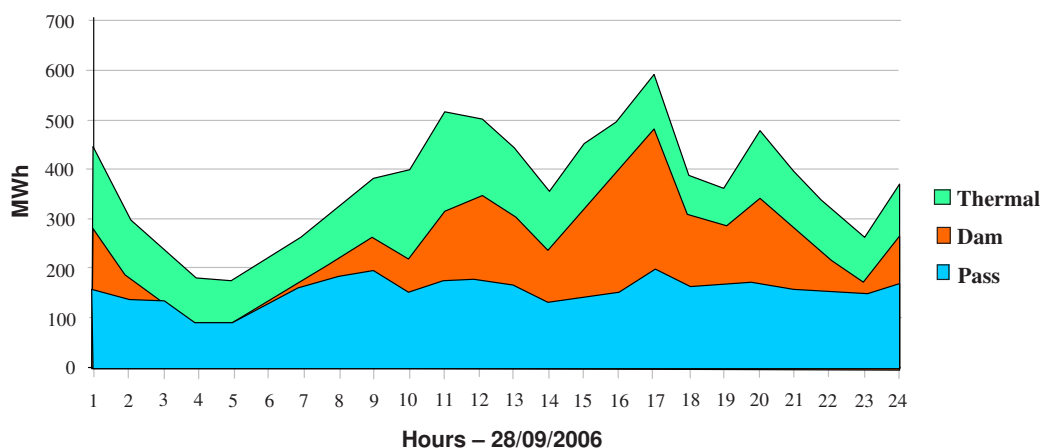


Figure 1.6: Hourly Power Load for a South American system.

for instance, of the fact that while real power and energy are consumed in the system, reactive power is also either generated or consumed –usually the latter, since inductive motors, which consume reactive power, generally predominate. This gives rise to a power factor less than unity, which penalizes consumption as far as the tariff charged is concerned, because it entails the circulation of unproductive current and with it ohmic dissipation and line capacity saturation. Moreover, consumption may depend on supply conditions –voltage, frequency–, be static or dynamic, or vary with connection time due to heating or other effects. All of this must be taken into account in load modeling.

Service quality

Electric power consumption may be very sensitive to the technical properties of the supply of electricity. Many devices malfunction or simply do not operate at all unless the voltage wave is perfectly sinusoidal and its frequency and magnitude are constant and stable over time. The precision, quality, features and performance of electrical devices depend on the quality of the current that powers them. Problems may also arise in almost any type of electrical device when the supply voltage is too low or too high (overvoltage). Computer,

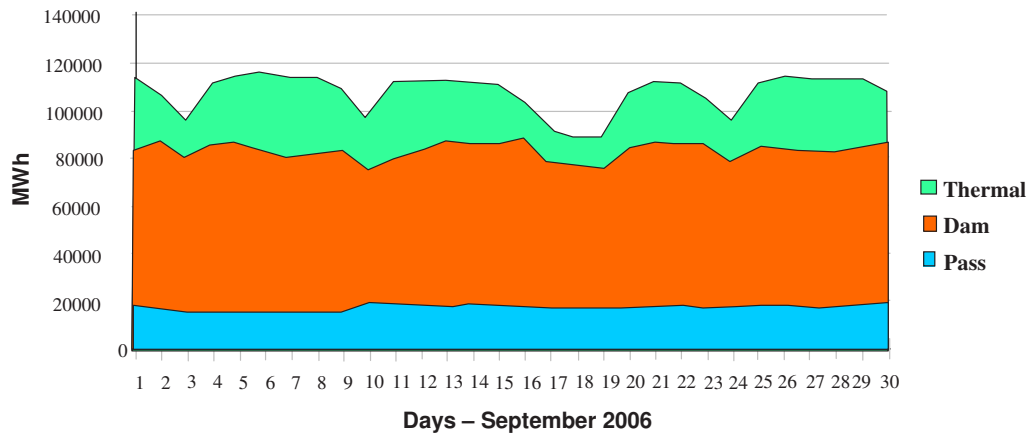


Figure 1.7: Monthly Power Load for a South American system.

motor and household appliance performance may suffer or these devices may even fail altogether when the supply voltage swings up or down. Most electrically powered equipment, especially particularly expensive equipment or any regarded to be vital for the proper and safe operation of all kinds of processes, is fitted with protection systems –fuses, circuit breakers and switches, protection relays– to prevent damage caused by voltage fluctuations outside an acceptable range. Thus, for instance, the motors that drive the cooling pumps in nuclear power plants are fitted with under- and over-voltage protection that may even trip systems that cause plant shutdown, given the vital role of these motors in safe plant operation. Finally, outages whether short or long are clearly detrimental to service quality. Who hasn't lost unstored information representing hours of work on a PC because of an untimely power outage? But power failures can cause even greater harm in industries such as foundries or in chemical or mechanical processes whose interruption may entail huge losses.

In developed countries, where the universal supply of electricity is guaranteed, attention increasingly focuses on quality, as in any other commercial product. Consumption and consumers have become more demanding in this regard and electricity industry regulation authorities assiduously include quality standards in laws and regulations. Designing the

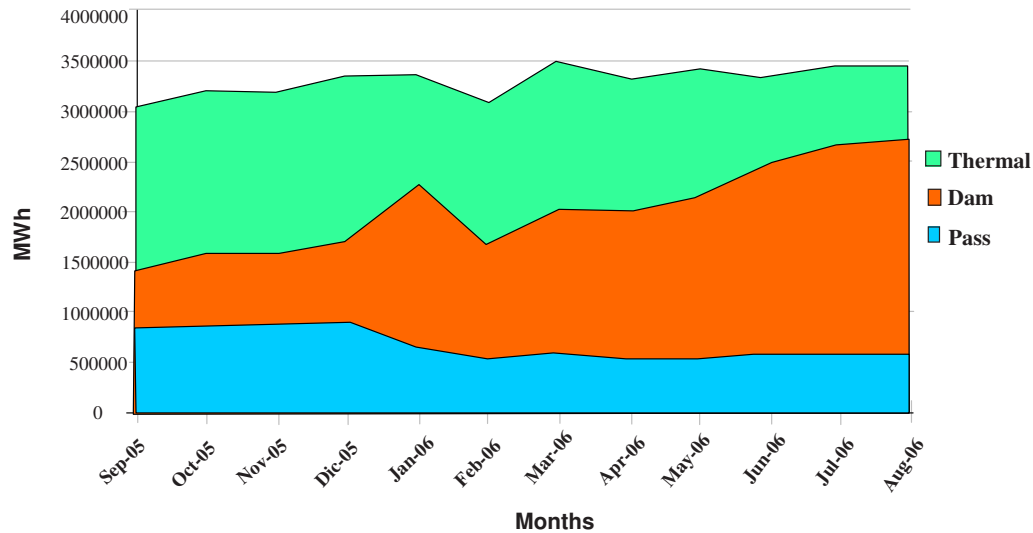


Figure 1.8: Yearly Power Load for a South American system.

proper signals to suitably combine efficiency with high quality service is one of the major challenges facing the new regulatory system.

The factors that basically characterize quality of electricity service are set out briefly below:

- **Supply outages:** Supply interruptions may have serious consequences for consumers. The duration of such interruptions may be very short –in which case they are called micro-outages, often caused by the re-connection of switches after a short-circuit– or long. Normally, the harm caused increases non-linearly with the duration of the outage.
- **Voltage drops:** Momentary dip in supply voltage caused by system short-circuits or failures, lasting only until the fault is cleared, or due to the start-up of nearby motors with high input demand when first switched on, occasioning voltage drops in the supply network. Some devices are particularly sensitive to these drops, particularly motors whose electromagnetic torque varies with the square of the supply voltage.
- **Voltage wave harmonics:** deviations from the fundamental frequency of the voltage

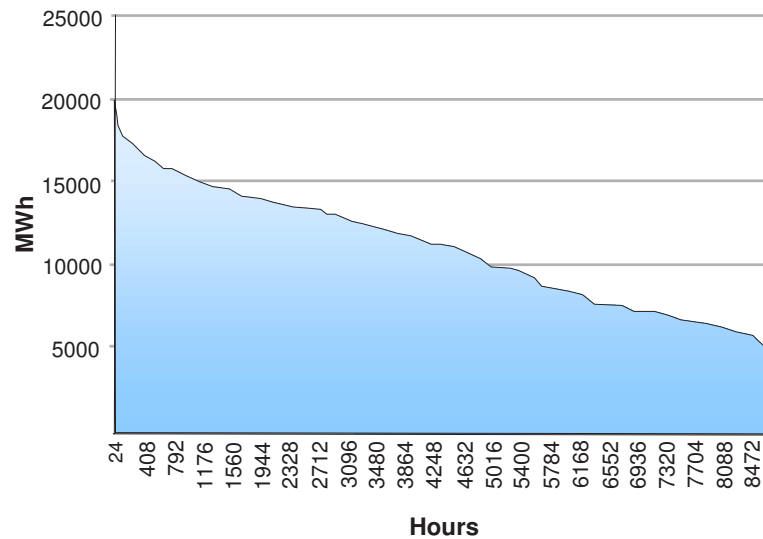


Figure 1.9: Monotonic load curve for a Canadian Utility. [Source: Grant County PUD, <http://www.gcpud.org/energy.htm>].

sine wave due to the saturation of ferromagnetic materials –in system transformers or generators, for instance– or to the loads themselves; these deviations may also have adverse effects on consumer appliances.

- Flicker: Low frequency fluctuations in voltage amplitude normally due to certain types of loads. Arc furnaces and electronic devices with thyristors usually cause flicker, which is detrimental to the proper operation of devices connected to the network. The solution to this problem is complex, since it depends not on the supplier but on system loads.
- Overvoltage: Voltage increases caused by short-circuits, faults, lightning or any other event, potentially causing severe damage to consumer appliances.

Finally, it should be added that electric power consumption may vary broadly with temperature or contingencies. What must be borne in mind in this regard is, as mentioned earlier, that this demand must be met instantaneously and therefore the electric power supply system –power stations, transmission, distribution– must be designed to be able to detect and respond immediately to such variations. The system must be fitted with sophisticated measurement, control and supervisory equipment and must have reserve generating capacity ready to go into production at all times. And yet most users flipping switches in their homes or workplaces to turn on the lights or start up an appliance or tool are blithely unaware of the host of systems, services and processes needed to provide that service.

1.2.3 Generation

Different generation technologies

The electricity required to meet these consumption needs is generated in production centers commonly called power plants or stations, where a source of primary energy is converted into electric power with clearly defined characteristics. Specifically, these facilities generate a three-phase, sinusoidal voltage system, with a strictly standardized and controlled wave frequency and amplitude. There are many generation technologies, usually associated with the fuel used. Conventional power stations are divided into hydroelectric, steam and nuclear plants, as described below.

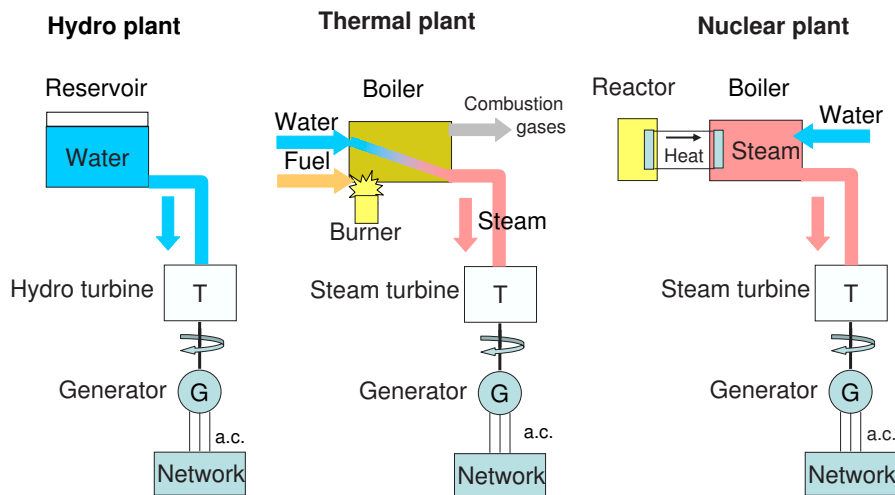


Figure 1.10: Hydroelectric, thermal and nuclear plants.

The primary source of energy used in hydroelectric stations is water, which is expressed, energetically speaking, in terms of flow rate and height –or “head”. Hydroelectric energy is converted by a hydraulic turbine into mechanical energy, characterized by the torque and speed of the shaft coupled to the electric generator. In other words, hydraulic energy is converted into electrical energy in the generator, producing voltage and current in the machine terminals. Because of the source of primary energy used, hydroelectric stations produce less atmospheric pollution than other conventional generation technologies. Another advantage to this type of stations, in addition to the cost of the fuel and lack of pollution, is their connection and disconnection flexibility, making them highly suitable regulating stations to adjust production to demand needs. Nonetheless, they are costly to build, and ensuring a

steady supply of water normally involves flooding vast areas. And finally, their operation is contingent upon a highly random factor –rainfall in the area where they are sited.

The many types of hydroelectric stations can be grouped under three main categories, which are distinguished in system operation:

- Conventional hydroelectric stations such as depicted in Figure 1.10 are the most common type; their characteristics are as described in the preceding paragraph.
- Run-of-the-river plants have no storage capacity and consequently cannot be deployed to use water resources for opportunistic generation; for this reason they are not used as regulating stations;
- Pumping power stations have a raised reservoir to which they can pump water when electric power is cheaper, and then dump it on to a turbine when it is more cost-effective to do so. They can be regarded to be an efficient means of storing energy, but not electricity per se.

Steam or thermal power stations –such as depicted in Figure 1.10–, in which the primary energy is provided by a fossil fuel (coal, fuel-oil or gas), are respectively termed coal-fired oil-fired or gas-fired stations. The operating principle behind these stations is basically as follows:

1. the fuel is burned in a boiler to produce high pressure steam;
2. high-pressure steam is converted in the steam turbine into mechanical energy;
3. mechanical energy, as in hydroelectric plants, is converted into electric power by the generator.

The thermal efficiency of steam power stations, which convert thermal to mechanical to electrical energy, depends primarily on the calorific value of the fuel used. In any event, the highest efficiency reached is never over 45%. Due to the heat inertia of the boiler, around seven hours, these stations cannot be readily connected and disconnected, i.e., they are less flexible in this respect than hydroelectric plants. In light of this, start/stop studies are conducted on steam power plants to establish operating orders and they are sometimes placed in standby operation, without generating any power whatsoever. Although fuel may be subject to variations in price, in most countries a constant supply is regarded to be routinely available. Therefore, such stations can be used for regulation, subject only to their connection inertia.

There are two types of steam plant technologies that use gas as a fuel, as shown in Figure 1.11. On the one hand, there are gas turbine plants where, like in jet engines, gas combustion in high pressure air feeds a turbine that produces mechanical energy, in turn absorbed by an AC generator. And on the other there are combined cycle or CCGT (combined cycle gas turbine) plants, which, as today's technology of choice, merit further comment. The operation of these stations –as may be inferred from their name– involves two types of cycles. In the primary cycle a compressor attached to the shaft of a gas turbine

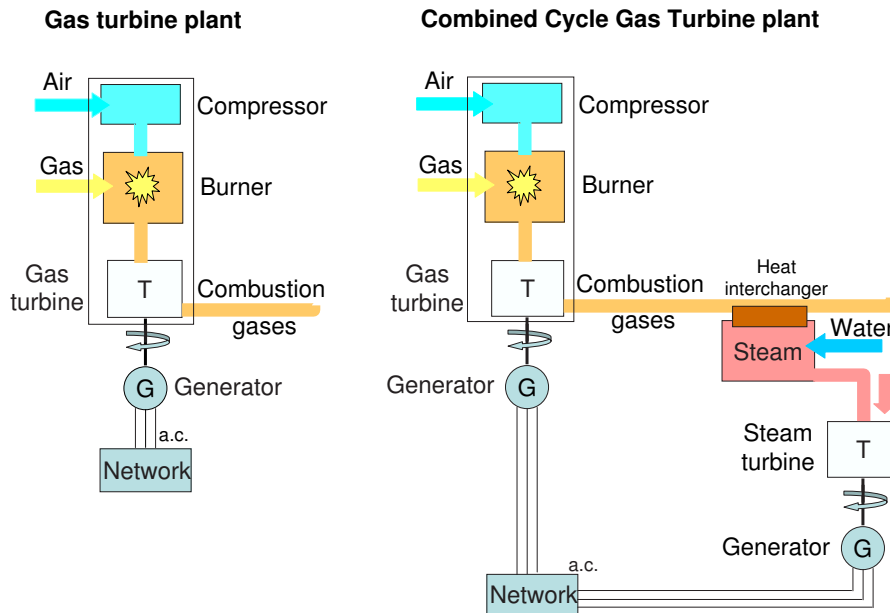


Figure 1.11: Gas turbine and CCGT power plants.

absorbs air at atmospheric pressure, compresses it and guides it to a combustion chamber where the gas that triggers combustion is likewise injected. The resulting gas expands in the turbine blades to produce mechanical energy. The gas expelled from the turbine, which is still at a high temperature, is used to heat a water vapor circuit where the latent heat in the gas is converted into mechanical energy in a steam turbine. Finally, electricity is generated by one or two AC generators connected to a single common shaft or two separate shafts, one for each cycle. Thanks to the latest advances in ceramics –the materials used to protect the blades from high temperatures–, performance in these cycles is substantially higher than in open gas or conventional steam turbine cycles, with thermal efficiency values of up to 60% in some facilities. This, together with a considerable reduction in polluting emissions, a high degree of modularity and reasonable investment costs, make CCGT one of the most competitive generation technologies available.

Nuclear power plants (see Figure 1.10), also known as atomic power plants, consist essentially of a nuclear reactor that produces vast amounts of heat with the atomic fission of the uranium. This heat is transferred to a fluid –carbon dioxide, liquid sodium or water– and carried to a heat exchanger where it is transferred to a water circuit. Like in steam stations, the rest of the process involves transforming the steam produced into mechanical energy in a steam turbine and then into electric power with an AC generator. Figure 1.12 shows a drawing of a nuclear power station. There are two drawbacks to the use of nuclear power plants which are difficult to solve, and which have made them socially unacceptable in some countries: the magnitude of the catastrophe in the event of an accident –no matter how

low the risk— and the problem of eliminating radioactive waste. In light of these difficulties, some countries have imposed a moratorium on the construction of nuclear power plants. From the standpoint of system operation, nuclear power stations are always base plants, rarely used for regulation because of the inherent hazards in changing the cooling conditions in the nuclear reactor.

In electric power grids, most production presently takes place in the so-called conventional stations, i.e., the sort described in the foregoing discussion. There are, however, other types of power stations that are gradually acquiring significance in some areas and countries. These are often called alternative plants, characterized by their limited environmental impact and the use of renewable sources of energy: wind, solar, biomass and CHP (combined heat and power or “co-generation”) plants, depicted in Figures 1.12 and 1.13.

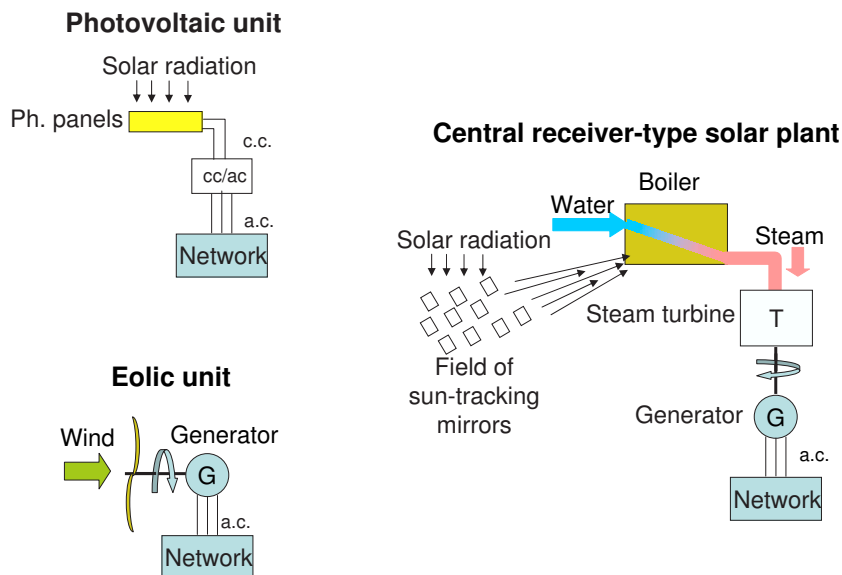


Figure 1.12: Solar and wind power stations.

Of all these technologies, the one that has undergone most spectacular growth in recent years is wind energy: in fact, CCGT and wind technologies account for very nearly all the new medium- or short-term generation plant. Wind farms may be fitted with synchronous AC generators—such as the ones used in other types of power stations— or asynchronous facilities, which accommodate small variations in speed when the torque fluctuates, to reduce equipment wear due to variations in wind speed. In asynchronous stations, capacitors are needed to generate the reactive power consumed by the induction machinery. These stations may be connected to the grid directly or indirectly, through a rectifier, inverter and filter. Whilst the generation of direct current makes it possible to work at variable speeds, this comes at a cost, in addition to line loss and reliability issues, although the reactive power

generated can be controlled by power electronics.

The source of solar energy is abundant but the technology is still scantily developed. Some growth has been recorded, however, in the installation of photovoltaic cells, which convert solar energy directly to DC current for storage in batteries. But these are usually self-generation facilities, typically deployed in remote areas with no other source of primary energy, or in hybrid systems. In any event, photovoltaic cells are still quite expensive. Very few solar steam power stations in which solar radiation is used to heat a fluid and generate electricity thermodynamically have been commissioned for commercial operation. Even so, there is a variety of alternative solar thermal technologies in place:

- Parabolic trough stations use parabolic collectors to focus radiation on pipes and heat the oil they carry. This oil then releases heat in a steam turbine cycle in stations using solar energy alone, or in a variety of cycles in hybrid plants;
- Central receiver or solar power tower stations, such as shown in Figure 1.12, have a field of heliostats –sun-tracking mirrors– that focus radiation on any of a number of types of receivers, normally located in a tower where heat is accumulated for subsequent use in any kind of power cycle;
- Solar dish generation is similar to the central receiver design but on a smaller scale, in which each module has its own “dishes” or parabolic disks and its own receiver. They generally use Stirling or gas turbine cycles; the principal advantage is their modularity.

Biomass generation (see Figure 1.13), which means obtaining energy from biological resources –energy crops (also called biomass feedstocks), livestock waste or forestry residue, and so on– uses a resource available in nearly any habitat and perhaps for that reason is gaining popularity in developing countries such as India. The two basic approaches taken in this technology are:

- Direct combustion in specific furnaces to produce steam subsequently used in a turbine cycle, like in conventional steam power stations;
- Gasification of the organic matter to obtain a combustible gas, usually with a high methane content, generally used to feed an internal combustion engine or gas turbine coupled to an electric generator. Matter can be gasified with physical-chemical or anaerobic biological processes.

Finally, CHP (combined heat and power) or co-generation technology, see Figure 1.13, is based on the fact that many industrial plants have process heating requirements: the basic principle is to make industrial use of the surplus heat produced by some type of steam generation system instead of wasting it by cooling the return fluid.

The why’s and wherefore’s of a generation mix

The existence of such a wide variety of technologies in most countries can be justified in a number of ways. Firstly, there is a purely economic justification deriving from the load

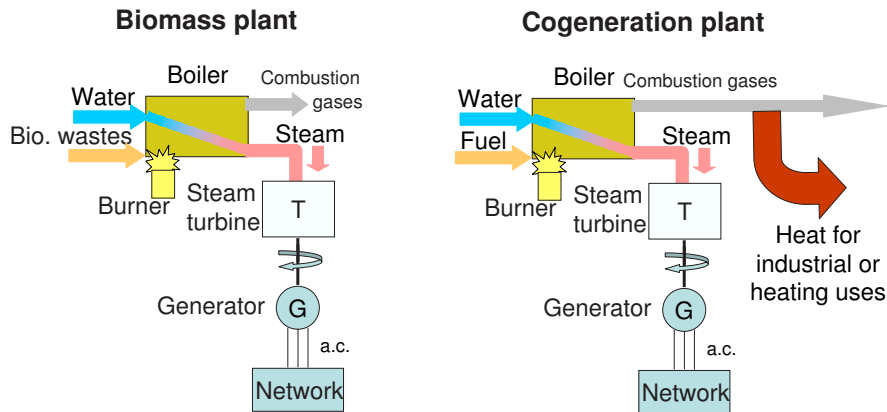


Figure 1.13: CHP and biomass power plants.

curve. The range of fixed investment costs to build a station and the operating costs to generate electricity vary widely from one technology to another. Nuclear power plants, for instance, call for very high investment, but have comparatively low operating costs—due to the price of the fuel, in this case uranium, and the efficiency of the energy conversion process—making nuclear power an attractive technology from the standpoint discussed here for the arm of the demand curve that covers the 8,760 hours in the year. The other extreme is gas turbine technology, which has the highest operating but the lowest investment costs, making it a very attractive type of generation to cover demand peaks, i.e., a relatively small number of hours per year. Conventional steam stations fall in between these two extremes. Obviously, the assumptions on which economic analyses are based and which justify the co-existence of different technologies always involve some degree of uncertainty in connection with the shape of the future demand curve, fuel costs, specific operation of each generating station, capital costs, regulatory decisions, market prices (as appropriate), and so on.

Not only economic arguments, but political and environmental strategy weigh heavily in the reasons for deploying a technology mix in electricity generation. Ensuring a supply of fuel as independent as possible of political and economic crises—be they international, such as the oil price crisis, or domestic, such as a miners' strike—entails the implementation of a diversification strategy. Moreover, the internalization of environmental costs and medium- and long-term environmental sustainability go hand-in-hand with regulatory measures to encourage the use of production technologies with lesser environmental impact.

Today, most electricity generation takes place in large production centers scattered

across a country, often at long distances from the major consumption centers. It seems natural to build stations close to the source of fuel –mines and ports for coal, refineries for fuel-oil, regasifiers and pipelines for gas-fired stations, rivers with a heavy flow or head for hydroelectric stations– as well as the coast or rivers, since water is a vital coolant in large steam plants. Attempts are usually made to site large power stations at a substantial distance from densely populated areas, due to issues such as pollution and the adverse social reaction to nuclear power plants. The transmission grid is responsible for carrying the electricity generated to the consumption centers. The enormous size of modern electric power plants is a result of the lower unit costs obtained by increasing their size to the present dimensions. This effect, known as economies of scale, has weighed, for instance, in the decision to build nuclear plants with an installed capacity of up to 1000 MW, or 500-MW or even larger coal- or oil-fired steam stations, since they are more competitive than smaller plants using the same technologies. The appearance of CCGT technology has reversed this trend since, as such plants are much more modular, they can be much smaller and still be competitive. The next few decades may see a dramatic rise in distributed generation, with power stations located much closer to consumers, supported by regulatory measures encouraging diversification, energy savings –such as in CHP– and reduction of environmental impact. The generation of electric power in large plants is characterized, economically, by very heavy investments, amortized in the very long term (25 or 30 years), after several years of construction (five, ten or even more in the case of nuclear plants or large-scale hydroelectric stations). The high financial risk that this entails can be assumed by State-owned entities or private initiative if there is a sufficient governmental guarantee to ensure the recovery of investment and operating costs through regulated tariffs. The appearance of CCGT technology has changed the economic context substantially by significantly reducing risk: these stations are more flexible, modular and competitive, smaller and therefore quicker to build. All the foregoing has greatly facilitated private investment, in the wake of the recent regulatory changes to introduce free competition in the electricity industry.

1.2.4 Transmission

The transmission grid connects large and geographically scattered production centers to demand hubs, generally located near cities and industrial areas, maintaining the electric power system fully interconnected and in synchronic operation. The long-distance transmission of huge amounts of power necessitates operating at high voltages to reduce circulating current intensity and, therefore, line loss. The transmission grid is the backbone of the electric power system, interconnecting all its neuralgic centers. Its key role in the dynamic equilibrium between production and consumption determines its typically web-like structure, in which every station on the grid is backed up by all the others to avert the consequences of possible failures. Ideally the system should operate as though all generation and all demand were connected to a single bus. It is fitted with sophisticated measurement, protection and control equipment so overall system operation is not compromised by faults, i.e., short-circuits, lightning, dispatch errors or equipment failure. The transmission grid has acquired particular relevance in the new regulatory context that encourages competition, since it is the wholesale market facilitator, the meeting point for market players, as discussed below.

The growth of transmission grid capacity, together with the development of connectivity between transmission grids, both within and across national boundaries, have paved the way for regional or international scale electricity markets.

Power lines

Transmission grid lines consist of aluminium cables with a steel core that rest on towers. Line design is based both on mechanical and electrical considerations. The towers must be sturdy enough to bear the weight of and withstand the voltage in the cables while maintaining the minimum safety distance between cables, between the cables and the towers and between the cables and the ground. A very visible assembly of insulators attaches the cables to the towers. Since each insulator can accommodate voltage of from 12 to 18 kV, 400-kV lines need on the order of 20 to 25 such links in the insulation chain. Sometimes two lines run along a parallel route, sharing the same towers: this is known as a double circuit, an example of which is illustrated in Figure 1.14.

Electrically, the section of the cables determines the maximum current intensity they can transmit and therefore the line transmission capacity. The greater the intensity, the greater the line losses due to the Joule effect, higher conductor temperature and greater cable expansion and lengthening –with the concomitant shorter distance to the ground and greater risk of discharge. To reduce so-called corona discharge –rupture of the insulation capacity of the air around the cables due to high electrical fields, occasioning line losses and electromagnetic disturbance that may cause interference in communications systems– each phase of the line is generally divided into two, three or more cables, giving rise to duplex or triplex cables. One of the most important line parameters, inductance, depends largely on the relative geometric position of the three phases on the tower. Moreover, the lines provoke a capacitive effect with the earth that fixes the value of their capacitance to ground. Consequently, the inductive effect predominates in lines that carry power close to their capacity limit, which consume reactive energy, whereas the capacitive effect prevails and the lines generate reactive energy when they carry small amounts of power, typically at night. Some transmission lines run underground, mostly in urban grids where the operating voltage is lower and only very rarely in the case of very high voltage circuits. High voltage underground systems involve the deployment of rather expensive technology, since the very short distance between the line and the ground necessitates the installation of very heavy duty insulators. These lines have a much more pronounced capacitive effect than overhead lines.

In a meshed system such as the transmission grid, energy flows are distributed across the lines depending on their impedance, in accordance with Kirchhoff's laws. The long distances and large scale of the power transmitted may reduce the grid's ability to maintain system operation, favoring the appearance of instability detrimental to the dynamic equilibrium between generation and demand. This may reduce line transmission capacity to less than its natural thermal limit.

As noted above, for reasons of environmental impact it is increasingly difficult to expand and reinforce the transmission system, translating into a growing need to make optimum use of existing facilities. This represents an important challenge, since it entails narrowing safety

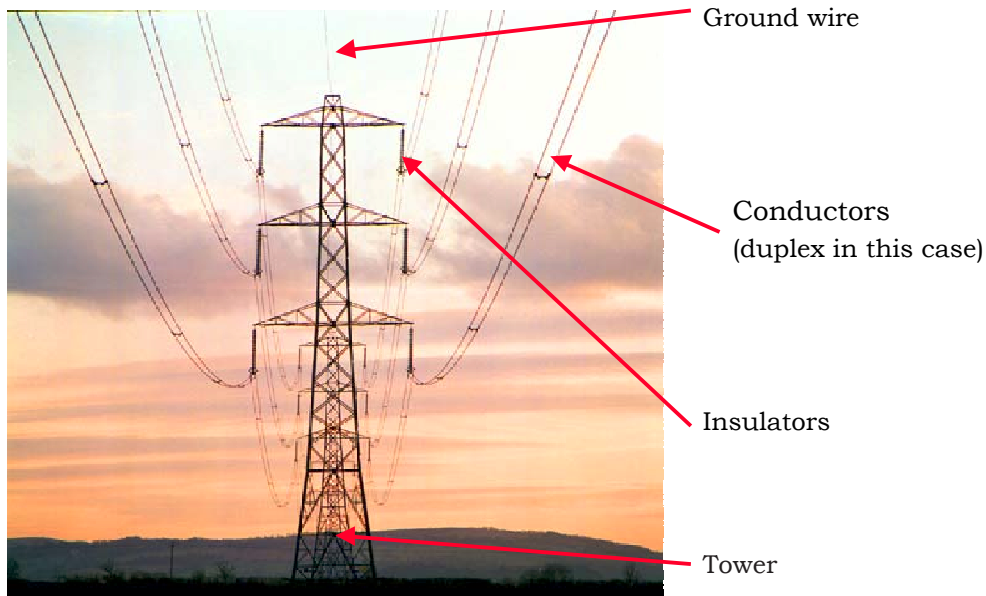


Figure 1.14: 400-kV double circuit line.

margins and perfecting protection, measurement and control logic. With the development of power electronics new devices have become available that attempt to increase actual line capacity and steer current flow towards the lines with the smallest loads. Such devices are known as flexible alternating current transmission systems or FACTS.

Substations

Substations constitute the second fundamental component of the transmission grid. They have three chief functions: they are the interconnection buses for lines, the transformation nodes that feed the distribution networks that reach consumers, and the centers where system measurement, protection, interruption and dispatch equipment is sited. Typically, several high voltage lines feed into the substation, which steps the voltage down and sends the resulting current over the outgoing (lower voltage) transmission or distribution lines. Materially, the substation is structured around thick bars to which the various lines connect. Circuit opening and closing facilities ensure the connection and disconnection operations needed for dispatch, configuration changes or the isolation of failed lines or other elements. There is a wide variety of substation configurations. Busbar numbers and arrangement – single, split, double or triple bar substations, with or without transfer bars, or ring-shaped – and the number of circuit breaker and dispatch devices per outgoing or incoming line determine the configuration type. Increasing the number of such devices increases substation costs but enhances safety, preventing such anomalies as momentary downstream outages due to simple dispatching operations.

The most representative technological facility in substations is the transformer, which



Figure 1.15: Substation power transformers.

raises or lowers voltage. Transformation is performed electromagnetically with two sets of (high and low voltage) coils wound around a ferromagnetic core. The entire assembly is immersed in a vat of oil to ensure optimum conductor insulation. These are very large-scale, expensive, heavy, high-performance facilities, with a very low failure rate. Many transformers are involved in system voltage control: in these, the windings are fitted with taps that allow for slight modifications in the turns ratio –and therefore voltage step-up or step-down. In some transformers regulation can be performed when charged, whilst in others it may not. Figure 1.15 shows several substation transformers. Other substation components include line breaker and switching devices. As noted earlier, substations are the interconnection buses on the grid, where the connections between the various elements are made or severed. This function, which is natural and foreseeable in normal operation, is crucial in the event of failure. Indeed, system must absolutely be protected from the short-circuits occurring in lines or substation bars, since they trigger the circulation of very strong currents that could damage cables and equipment. A fault must then be cleared –i.e., the overcurrent canceled– as soon as possible and isolated to repair the damaged component; otherwise, the system as a whole may be endangered. The most sophisticated line breakers are automatic circuit breakers, which are able to open a circuit when overcurrents occur. The protection devices detect overcurrents and, applying appropriate logic, decide which lines must be opened to clear the fault. Constructively speaking, there are many types of such breakers, ranging from compressed air (or pneumatic) or magnetic blowout breakers for small power and voltage to circuit breakers immersed in oil or sulphuric hexafluoride devices for systems with very high voltage and capacity. One special feature of these mechanisms is their ability to open twice in immediate succession. Since many faults have a very short duration because the cause of the outage disappears spontaneously –if due to a false contact or one that is burnt out by the current flow for instance–, the system usually attempts to

reconnect the circuit breaker automatically, in case the cause of the fault has in fact been eliminated. If not, the breaker will re-open. It should be noted here that due to breaker construction design, it is not usually possible to ascertain from plain sight whether a breaker is open (=off) or closed.

Once the fault is cleared and identified, the damaged area must be electrically isolated to reconnect the rest of the elements initially shut down by the circuit breaker. This is done with local disconnectors, used to open or close a line when the current is negligible. Their function, therefore, is not to cut off the current, but simply to visibly isolate a section of line or a device, machine, substation bar or any other element so it can be handled for repair or maintenance in the total assurance that it is not charged. The operator closes the circuit manually after confirming that the circuit breaker has worked properly and removed voltage from the entire area in question. There are several different types of disconnectors: rotary, sliding, column rotary and pantographic.

Finally, the line breakers used in grid dispatching have a break capacity on the order of the nominal intensity of the current in the circuit or line they are designed to open or close. Consequently, they do not open in the event of short-circuiting. Air-break switches, automatic air switches, automatic gas circuit breakers, magnetic blow-out switches and oil or hexafluoride switches are some of the protection devices used for this purpose.

Today some substations are entirely immersed in hexafluoride. Although more expensive, this arrangement makes it possible to considerably shorten the distance between bars, conductors and cables, and is particularly attractive for urban environments where square footage is costly. Such substations are, moreover, extremely safe.

1.2.5 Distribution

Lower voltage networks branch off the high voltage grid from the substations in multiple directions to carry electric power to even the most secluded areas. The structure of this network, generically called the distribution grid or network, is very different from transmission grid structure. The upper or regional level, which actually forms a part of the transmission grid, has an open web or loop configuration and operates at somewhat lower but still very high voltages, typically 132, 66 and 45 kV. The substations fed by this part of the grid step the voltage down to 20, 15 or 6.6 kV, splitting power off into the distribution network per se, which is the part of the system that supplies power to the final consumer. The structure of this network may vary, but its operation is always radial. The substations normally house circuit-breakers that protect the feeders, i.e., lines running to other transformer stations where the voltage is stepped down again to supply low voltage power, which may be 380, 220, 127 or 110 V, depending on the country, to residential customers, wholesalers and retailers and the like. Consumers connect into the system at the voltage level best suited to the scale of consumption. In rural areas, the distribution networks are generally radial and consist of less expensive overhead lines because load density is not very high, the reliability required is lower due the smaller number of users and space is not an issue. One problem encountered is that reliability declines as the distance from the substation grows. For this reason the network is sometimes designed to provide downstream emergency supply in the event of failures. The voltage drop problems that also arise in these networks are solved by

placing taps on the transformers and capacitor banks that supply reactive power.

Distribution networks in urban areas, which are characterized by high load densities concentrated in small areas, generally run underground. Due to the larger number of users, reliability requirements are stricter. Whilst it is more costly to lay and repair underground lines, the distances involved are much shorter than in rural networks. Urban system structure is usually meshed for greater reliability, but by and large these networks operate radially –with circuit-breakers normally open– for reasons of cost and ease of operation. Distribution networks, which comprise thousands of kilometers of wiring, are subject to more frequent failure than the transmission grid and their structure is less redundant; this means that most of the supply outages that affect the final consumer originate in the distribution network. In terms of investment, they account for a large share of total system costs and normally call for an investment several times higher than the transmission grid.

1.2.6 Control and protection

This review of the chief technological aspects of electric energy systems concludes with a brief description of control and protection systems and equipment. The role and importance of these elements in sustaining system operations have been stressed repeatedly in the foregoing. In view of the wide variety of such systems, the following discussion will be limited to a mere enumeration of the devices involved. They are organized by levels or layers.

On the first level, the elements that comprise the system backbone –generating stations, high voltage grids, large substations– are centrally monitored and controlled from a control centre that supervises the system status in real time –generating plant, line flows, voltage levels, voltage wave frequency and the like– by remotely transmitted and duly processed measurements. This supervisory and control system goes by the name of SCADA, acronym for supervisory control and data acquisition. These control centres –there may be one for the entire country, or several, scaled by order of importance and coordinated– strive to ensure system safety and may transmit instructions to generating stations to produce real or reactive power, order grid dispatching operations, change transformer taps or connect capacitor banks. Such instructions are based on system data, interpreted by operators on the grounds of their experience or with the support of sophisticated models that analyze operating conditions and determine line flows or bus voltages under different hypothetical contingencies.

The control systems installed in production plants constitute the second level of operation. The two most important such systems are speed and voltage regulators. Speed regulators maintain the instantaneous balance between generation and consumption in the system as a whole. Generating plant must respond immediately to any increase or decrease in demand. Similarly, the chance tripping of a unit in operation at any given time –where nuclear power is involved, this may mean up to 1000 MW– occasions an instantaneous imbalance between power generated and consumed that must be compensated for by immediately replacing the failed unit. When the power generated differs from system load, the surplus power or power shortage is stored or withdrawn, respectively, from the kinetic energy stored in rotating machines. Speeding up or slowing down these facilities provokes a

change in revolutions per minute in the AC generators or the frequency of the wavelength generated. Such parameter changes automatically activate the respective steam, water or gas-driven valve to modify plant generation accordingly. This is called primary regulation of load-frequency control.

A power shortage caused by a power station failure, for instance, prompts a joint response across the entire inter-connected system –all the countries synchronously connected to the country where the shortage occurred are involved– which prevents system frequency from falling further, but is unable to re-establish it exactly to the nominal value. Nor do the power exchanges with neighboring systems sustain their predetermined values, due to the flows required to maintain the frequency. A second control loop –known as AGC or automatic generation control– re-establishes frequency to the nominal value and the exchange operations to their initial values. This constitutes what is known as secondary regulation, which is also usually automatic, and does not involve all generators, in particular none located on neighboring systems. The extra generation required is redistributed among the stations chosen for this purpose. This also regenerates the primary reserve capacity, to ensure continued operation and prevent system standstill resulting from units reaching their limit capacity. Finally, tertiary regulation may also be implemented. At this level, in which supervision is not automatic, the control centre may change long-term dispatching instructions to enhance economic efficiency and restore the so-called secondary reserve capacity, in much the same way that secondary control restores the primary reserve capacity. It will be noted that secondary and tertiary regulation form a part of the higher control level referred to above, but they have been described here for greater clarity.

Power stations are fitted with a second control loop related to system voltage. System voltage must be kept within certain allowable margins to ensure system safety and guarantee that the power delivered is of a reasonable quality. The voltage level of an electric power system is closely related to the balance of reactive power. High reactive consumption, either by charged lines or inductive motors, tends to depress system voltage, whereas a supply of reactive power, from uncharged lines or capacitor banks for instance, tends to raise system voltage. For these reasons power stations, which are able to produce or consume reactive power at will with their (synchronous) AC generators, are ideal candidates to monitor and correct dangerous voltage fluctuations. The voltage regulator measures voltages at generator terminals or selected points of the system, compares the measurement with a reference value and adjusts the AC generator excitation current accordingly, which controls the reactive energy supplied or absorbed by the unit.

Power stations, naturally, are fitted with protection systems that prevent potential damage. The AC generator, pumps, turbines and any other vital component are equipped with the respective measuring systems, tripping relays and alarms. The approach is as discussed above for substations: the protection relays must detect and locate faults, the automatic circuit-breakers clear them and the disconnectors isolate the failure to be able to re-establish service in the rest of the system while the fault is repaired. Protection relays must be sensitive enough to detect the fault, selective to minimize the impact of clearance, able to respond quickly for protection to be effective, and reliable, i.e., neither tripping operations unnecessarily nor failing to act in critical situations. They must also be robust, since they operate under widely varying adverse circumstances, and able to operate independently and

automatically, even in the absence of electricity.

1.3 The economic environment

1.3.1 The electric sector and economic activity

The economic end of electric power system management is extremely complex due, among others, to the breadth of the task, which covers financial, pricing, social, business and environmental factors, not to mention investment planning and system operation, this last closely related to the technological aspects of such systems. And all of these issues must be handled within the regulatory and legal context prevailing in each country. This, naturally, significantly conditions not only the approach and the margins within which each of these activities may be conducted, but also determines exactly who the decision-makers are. With the profound regulatory change underway in the industry in many areas of the world, any attempt at describing the economic environment should address both the traditional setting, still in place in many countries, as well as more liberalized situations. Instead of comparing the two approaches subject by subject, the following discussion first provides an overview of the well-established expansion planning and system operation functions in the traditional scenario, to then highlight the philosophy and changes introduced by the new regulations.

The planning and actual operation of an electric power system are the result of a complex chain of decisions. The first link comprises long-term provisions –capacity expansion, fuel contracts; the second medium-term planning– hydroelectric management, facility maintenance programmes; the third short-term specifications –generating unit connection, operating capacity in reserve; and the fourth actual system operation –generating unit dispatching, frequency regulation, response to possible emergency situations. Decision-making is supported by computing models fed by highly sophisticated data acquisition and communications systems. Today’s resources make it possible, for instance, to precisely calculate the marginal cost of meeting demand (i.e., the cost of one additional kWh) at any given point on the system at a given time, taking account of the entire chain of decisions referred above.

Decisions affecting electric power system expansion and operation should be guided by criteria of economic efficiency to minimize the cost of delivering an acceptable quality of supply to consumers or customers. Nonetheless, constant account must be taken of technical considerations to ensure the material feasibility of supplying electric power –arguably an issue much more vital in this than any other industry, given its specific characteristics. As discussed below, the importance of such considerations grows as the time lapsing between decision-making and implementation narrows down to real time, when the distinction between economic and technical factors blurs and no sharp line can be drawn between them. Given the size, dimension and complexity of the problem, the entire decision chain must be rationalized and organized. This is achieved by ranking the expansion and operating functions chronologically. In longer term decisions, for instance, where future uncertainty and economic criteria carry considerable weight, a rough approximation of system technological behavior suffices. Such decisions successively guide shorter term decision-making in which technical specifics are much more relevant, culminating in real-time operation, where

system dynamics must be analyzed in full detail, millisecond by millisecond.

1.3.2 Expansion and operation in the traditional context

In this context, a government-controlled centralized co-ordinator is responsible for overall electric power system operation decisions, control and monitoring. This body is likewise entrusted with the formulation of plans for system expansion, as regards the installation of both new generating capacity and transmission grid lines or facilities. It is also often responsible for implementing such plans if the grid is publicly owned.

The underlying criterion for the entire decision-making processes is maximization of social utility in the production and consumption of electric power. This involves two fundamental concerns. The first is to attempt to minimize the entire chain of costs incurred to provide service, including both investment and operating costs. Nonetheless, the attainment of an inexpensive service is not the only factor used to measure social utility. The quality of supply must also be satisfactory. Utility is low for both industrial and residential consumers where service is cheap but plagued by constant outages. A number of uncertainties –rainfall, real demand growth, generating, transmission and distribution equipment failure– make it impossible to guarantee outage-free service in future scenarios. In other words, there will always be some likelihood of inability to service all the demand at all times, which is a measure of system reliability. It is equally clear, however, that such likelihood of failure can be minimized by investing in more facilities and operating more conservatively. Increased reliability entails higher costs. For this reason, the first criterion referred to above, cost minimization, must be qualified to accommodate the second criterion, which reflects system reliability. This can be built into the decision-making process in a variety of ways. One is to set a minimum reliability threshold based on past experience and social perception of the concept, measured in terms of the likelihood of an interruption of supply of electric power or some other similar indicator. A more soundly based method consists of attempting to quantify the financial harm caused by an interruption of service on the basis of its utility to consumers. Building this factor into the cost minimization process as one more expense to be taken into account is actually a way of maximizing the social utility of the service. The inherent difficulty in this second approach lies in quantifying “utility”, which may vary from one consumer or individual to another, and which there is no clear way to measure, although attempts have been made in this respect by conducting systematic surveys of consumers, specifically designed for this purpose.

Reliability is a factor that involves the entire decision-making process, from long- to short-term. Service interruption may be due to investment-related issues: if system installed capacity is insufficient to cover demand, perhaps because demand growth has been unexpectedly steep, hydrological conditions particularly adverse, transmission capacity lacking or the implementation of new investment delayed; to operating problems: poor reservoir management, lack of immediate response to failures in units or lines due to a shortage of reserve capacity; or real-time system stability problems. In light of this, in nearly all the decision-making scenarios reviewed below, cost and reliability factors must be brought into balance in the decision reached. The term adequacy is generally used to describe long-term reliability and safety to refer to short-term operations.

There is no standard way to organize electric power system planning and operation. The solution to such a complex problem nearly always involves breaking it down into simpler problems and all the approaches taken to date involve, in one way or another, time-scaled hierarchical decomposition. Decision-making is ranked by time frame and the respective functions are scaled accordingly. The highest level comprises the longest term decisions, which tend to address strategic problems. The solutions adopted are then passed on to the lower levels, delimiting their scope of action. At successively lower levels of the scale, as functions approach real time, they must seek the optimum solution within the restrictions imposed by the problem posed as well as by the guidelines received from the higher levels. This structure, abstractly defined in this section, is described more specifically in the items below.

Long term

First level decision-making takes a long-term approach, projecting anywhere from 2 or 3 to 10, 15 or more years into the future, to define generating plant and transmission/distribution grid investments. The process involves determining the type, dimensions and timing of new generation and transmission facilities to be installed based on several parameters, namely demand growth forecasts, technological alternatives and costs, estimated fuel availability and price trends, reliability criteria adopted, environmental impact restrictions, diversification policies and objectives relating to dependence on the foreign sector. Such distant horizons are necessary because the (very large) investments involved are justified on the grounds of the earnings over the service life of such facilities, which may be from 25 to 30 years in the case of steam power stations and much longer for hydroelectric plants.

With such distant horizons, uncertainty is obviously a key determining factor. A whole suite of scenarios must be addressed, the respective probabilistic assessments conducted and the most suitable criteria adopted, such as: minimization of expected average costs, minimization of regret or minimization of risk, taken as the variance of cost distribution.

For the same reason, it makes no sense in this type of studies to evaluate the technical behavior of system operation in detail, since it is neither feasible nor sensible to seek accuracy in the evaluation of operating costs when the process involves much greater levels of financial uncertainty.

One of the chief requisites to the process is a good database, which must contain information such as updated data on technologies as well as historical series on demand, hydrology (rainfall), equipment failure rates and so on. The long-term demand forecast built from these data assumes the form of a probability curve that determines system expansion needs. As indicated above, the hourly demand profile is as important as total demand in this regard, since the choice of technologies largely depends on this information. The next step is to determine the generating plant expansion required to meet demand under terms which, while respecting the different strategic criteria mentioned above, seek the option that minimizes the anticipated costs over the entire period considered. Such costs include the fixed costs of the investment chosen plus operating costs throughout the entire period, which will, obviously, depend on the type of investments made. The support of simulation and optimization models is often enlisted for such estimates. Because of the scale of the

problem posed, decomposition analysis techniques are generally used that run iteratively and alternatively between two modules, one specializing in expansion cost calculations and the other in operating costs, exchanging information between the two as necessary until the results converge.

Decisions to enlarge the transmission grid have traditionally depended on new generation plant investment needs and demand center growth. This is because considerably less investment and time were needed to build grid facilities than generating stations, although in countries where geography and distance call for very large-scale and costly transmission systems, this may not be wholly true. Once the new plants are sited and consumption and production growth rates are estimated, grid expansion is determined, comparing the necessary investment costs with the benefits afforded the system: lower operating costs, smaller system losses, greater reliability in demand coverage. The decision process is also impacted by safety criteria that ensure that supply will not be subject to interruptions due to grid reinforcements or other technical aspects, such as voltage or stability issues.

Expansion decisions are, naturally, dynamic over time, inasmuch as they must be periodically adjusted when real data on demand growth, technological innovations or fuel purchase terms modify the assumptions underlying the initial expansion plans.

Medium term

Once future investment is defined, medium/long term facility operating plans must be laid. For a one- to three-year horizon, depending on the system in question, such planning involves determining the best unit and grid maintenance cycle programme, the most beneficial fuel purchase policy and the most efficient use of power plants subject to primary energy limitations –hydroelectric stations in particular– or to yearly production restrictions for environmental reasons. Electricity generating plants are sophisticated systems with thousands of components that must be revised periodically to prevent major and sometimes hazardous failure and assure plant efficiency, from the technical standpoint. Operation of conventional steam plants is usually interrupted around twenty days a year for these purposes. Nuclear plants need to recharge their fuel (uranium bars) once every 18 months, so maintenance tasks are programmed to concur with such plant shut-downs. Electric power lines and the components of the transmission and distribution grids located in substations also need upkeep, such as the replacement of faulty insulators or their cleaning to prevent loss of insulation power. Although technology to perform these tasks on live lines is more and more commonly available, most of these operations are conducted on de-energized facilities for obvious safety reasons, which involves disconnecting certain lines or parts of substations. This, in turn, requires careful maintenance programme planning to interfere as little as possible with system operation.

Fuel management also calls for careful planning, sometimes far in advance. Once input needs are defined, fuel purchases must be planned, often on international markets, to buy at the most advantageous price, make shipping and storage arrangements and take all other necessary logistical measures to ensure that stations do not run out of fuel. Finally, the use of water resources in hydroelectric plants must also be planned, as if it, too, were a fuel. In fact, water can be seen as a cost-free fuel in limited supply. Therefore its use must be scheduled

in the manner most beneficial to the system. Run-of-the-river stations require no planning, but decisions are imperative where there is an option to either generate energy or store water for production at a later time. Depending on the size of the reservoir, such decisions may cover time frames ranging anywhere from a single day to several weeks, months or even years for the largest reservoirs –the so-called carry-over storage reservoirs. Stations whose management and regulation extend over several months should be planned on a yearly or multi-yearly basis. Since the logical aim of such planning is to attempt to replace the most expensive thermal production, this type of planning is usually termed hydrothermal co-ordination. A similar approach is taken for any other technology subject to restrictions on use that limit accumulated production in a given time frame, typically seasonal or annual. One example would be the existence of mandatory national fuel consumption quotas or yearly pollution limits.

Short term

Short-term decision-making is referred to a weekly scale –i.e., from a few days up to one month. It involves determining the production plan for hydroelectric and steam power stations on an hourly basis for each day of the week or month. This plan must abide, moreover, by the instructions received from the immediately higher decision level described in the preceding section in connection with maintenance action, weekly or monthly hydroelectric management, emissions plan, management of fuel quotas, and so on.

At this level, system details are extremely relevant, and account must be taken of aspects such as steam plant generating unit start-up and shut-down processes and costs, the hydrological restrictions in place in river basins, stations in tandem arrangement, demand chronology profiles, which call for accurate production monitoring, generating capacity to be held in reserve to respond immediately to fortuitous equipment failure and so on.

The possibility of varying steam power station output is limited by the technical characteristics of their generating units. It takes an inactive station a certain minimum amount of time to recover operational status, which is primarily determined by the time needed to heat the boiler to a suitable temperature. This minimum lead time depends therefore on the cooling state of the boiler: in other words, the amount of time it has been off. The most conventional steam power plants may need from eight to ten hours if the boiler is completely cold. Gas and CCGT plants are more flexible, with lead times of from one to two hours or even only a few minutes for simple gas turbines. As a result, the cost of starting up a steam power station is significant and can be quantified as the price of the fuel that must be unproductively burnt to heat the boiler to the appropriate temperature. For this reason, even if demand declines substantially, it may not be cost-effective to disconnect certain steam stations at night, but rather to maintain a minimum production level. This level, known as the plant's minimum load, is relatively high, generally speaking –on the order of 30 to 40 per cent of the station's maximum output– due to boiler combustion stability requirements. Depending on the findings of cost-effectiveness studies, then, a decision must be made on whether it is more economically sound to start and stop the station every day –daily start-up cycle– or shut down on the weekends only –weekly cycle– or simply not shut down ever, as in the case of nuclear stations. Sometimes it may be more efficient to keep the

boiler hot without producing anything. Boiler thermal constants and their limits likewise impose constraints on how quickly steam plant output rates can be modified, which are known as upward or downward ramp constraints. All of this calls for careful planning of unit start-ups and shut-downs, a problem known as unit commitment.

This decision is also strongly influenced by weekly or monthly hydroelectric management, as well as system reserve capacity requirements. Hydroelectric stations are much more flexible in this respect, with practically zero lead time, no significant start-up costs and virtually no real limits to modulating generating capacity. The optimal scheduling of hydroelectric production to cover seasonal variations in demand takes account of a number of considerations: higher level decisions on the amount of water resources to be used in the week or month, the most cost-effective hourly distribution –hydrothermal co-ordination during the month or week– and the technical constraints on steam plant units. Hydroelectric generation and the respective use of water in reservoirs must likewise abide by possible restrictions imposed by water management for other purposes –irrigation, fauna, minimum reservoir and river flow levels and so on– as well as other conditioning factors characteristic of water works and their configuration: canals, reservoir limits, reservoirs in tandem or pipelines.

Here also, reliability criteria play a role in decision-making. Provision must be made for the immediate replacement of any plant in the system that may reasonably be expected to fail or for the ability to respond to transmission grid incidents. This translates into the start-up and connection of new units which, although unnecessary under normal conditions, would not otherwise be able to generate power for several hours if needed to cover emergencies.

Real time

Real time operating functions are based essentially on safety criteria rather than on financial considerations. The economic component of the process is defined by higher level decisions, although sight should never be lost, as noted earlier, of the economic aspects of reliability. Supervision, control and monitoring ensure the technical viability of the immense and dynamic electric power system, as described in the foregoing.

1.3.3 Expansion and operation in the new regulatory context

The new electricity industry regulatory environment is bringing profound change to electric power system operating and planning habits. Industry liberalization has gone hand-in-hand with dramatic decentralization of planning and operating functions. System expansion – now focused on investment– and operation are the result of individual company decisions based on the maximization of business earnings, either under organized tendering or through private electric power supply contracts. Economic and financial risk and anticipated returns on investment, instead of the traditional cost minimization criteria, drive decision-making. The challenge for administrative and regulatory authorities is to design liberalized market rules that ensure that the strictly entrepreneurial behavior of each market player leads to overall minimization of system costs, reflected in the tariff charged to final consumers.

Real time system operation, however, continues to be a centralized task. A central operator, usually called the System Operator, oversees system safety under a supervision

and control scheme that is essentially the same as described above for the traditional setting. Ensuring the real-time technical viability of the system calls for advanced co-ordination of all the available resources, which in turn requires absolute independence from the various actors' individual interests. Electric power system operation is viewed, therefore, from a wholly different vantage. There are new functions, responsibilities and ways to broach the decision-making process, and changes in the roles played by each of the agents involved. Electric utilities have had to reorganise to assume their new market functions. They are faced with the challenge of adapting to a new environment in which they must change many operating habits and where new duties and tasks are arising. Some of the most novel of these tasks have to do with tendering, landing contracts and formulating yearly budgets—revenues less operating expenses— all within the framework of risk management policy.

Long term

The new environment has completely revolutionized the approach taken to electricity generation planning. The liberalization and decentralization of investment decisions ascribe to each actor the responsibility for assessing the advisability of investing in new generating facilities, based on individual benefit-cost analysis. Hence, new investment is studied from the perspective of estimated revenues over a period of several years, in other words, of the evaluation of future market performance. Such analyses address factors associated with estimated fuel prices, demand levels, new third-party investment, market prices and the like. And financial risk assessment plays a crucial role in such reviews because it is the key to suitable investment financing. Rainfall and demand stochasticity, as well as the possible interplay between price scenarios and third-party expansion decisions, are aspects that have to be considered in this environment. Risk management constitutes one of the chief activities and drivers of the planning and operation of electric energy systems. The formulation of contracts to supply power or obtain financing, along with access to futures markets and options are elements of immense importance in this environment.

Whilst transmission grid planning continues to be centralized, the perspective has changed and today's decisions are subject to much greater uncertainty. The basic planning criterion, namely optimization of the social utility of electricity production and consumption, remains unvaried. But such utility no longer necessarily acquires the form of minimization of production costs, but rather maximization of the earnings of individual actors: utility of electricity consumption less acquisition cost, for consumers, and revenues from the sale of electricity less generating costs, for producers. Moreover, the uncertainty surrounding the planner's decisions has risen dramatically. Traditionally, the grid was planned on the basis of prior decisions on expansion of generating capacity, information which in an environment of free competition is not compiled centrally or a priori, but rather is the result of business decisions made individually by the different players at any given time. Consequently, neither the amount nor the location of new generating plant is known for certain when the grid is being planned. Furthermore, the time that may lapse from when the decision to build a line is made until it becomes operational is growing longer, due in particular to difficulties arising in connection with the environment and territorial organization. As a result, construction lead times are often longer for the transmission grid than

for the power stations themselves.

Medium term

Of the various agents participating in the electricity market, several must try to optimize their medium- and short-term decisions: consumers, suppliers and producers. In the system operation setting, however, producers play the lead role. The three medium-term aims pursued by generators are:

- Formulate medium-term economic forecasts: revenue projections and yearly budgets;
- Provide support for the long-term functions mentioned above: contract management, determination of long-term business strategies and investment assessment;
- Provide support for short-term functions, in particular the formulation of bids on daily markets for electric power and ancillary services: hydroelectric output guidelines, valuation of water reserves and guidelines for steam production subject to provisions on national coal quotas, environmental restrictions or similar.

The new approach for designing models to support these decisions, which seeks optimization of each agent's own market earnings, calls in one way or another for building new theoretical microeconomic- and game theory-based concepts into the model. Markets are regarded to be dynamic elements that stabilize around certain points of equilibrium characterized by the various agents' production structures. Alternatively, they may be viewed as the result of a certain game in which the established rules ultimately impose a strategy to be followed by each agent in response to the reactions of all the others.

Short term

Although there is a variety of ways to organize electricity markets, they all have a series of short-term –typically daily– markets, as well as intradaily markets and ancillary service markets, where the short-term output of generating stations is determined. Of the three, the daily bid market is usually the most important in terms of trading volume. Consequently short-term operation tends to revolve around the preparation of daily bids. This process is governed by higher level strategic decisions. As such, it is informed by the output guidelines deriving from analyses covering longer terms and its role consists of setting market prices on a day to day basis. The estimation of short-term prices –on this time scale the uncertainty associated with rainfall and unit availability is very small– is an important task, since it serves as a guide for decisions on the internalization of steam generating units costs and whether or not to draw on hydroelectric production. As a result of this and enlightened assumptions on the behavior of the competition, companies establish the bids, specifying quantity and price, with which compete on the wholesale market.

Real time

As in the traditional setting, real-time operation is strongly influenced by safety considerations and has a similar structure, although considerable effort is generally made to differentiate and clearly value the various types of so-called ancillary services provided by each agent in this respect. And wherever possible, market mechanisms have been implemented to competitively decide who provides what service and at what price. Such mechanisms are often deployed in connection with operating –secondary or tertiary– capacity in reserve, as well at times with voltage control and even system cold-starts. Primary frequency/output control continues to be a mandatory basic service at the System Operator’s disposal as an element vital to system safety.

In this competitive framework, companies must offer their services taking account of the costs incurred in their power stations to provide them, along with other considerations such as market opportunities.

1.4 The regulatory environment

1.4.1 Traditional regulation and regulation of competitive markets

In a nutshell, regulation can be defined as a “system that allows a government to formalize and institutionalize its commitments to protect consumers and investors” [14]. Depending on the development of the electricity industry in each country –and even in different regions of a country–, the prevailing ideology, specific natural resources and technological change, among other factors, the electric power industry has adopted different organizational and ownership (private or public, at the municipal, provincial or national level) formulas.

Despite this diversity, ever since the electricity industry reached maturity and until very recently, regulation around the world was uniformly of the sort applied to a public service provided under monopoly arrangements: guaranteed franchise for the –typically vertically integrated– electricity utility and price regulation based on the costs incurred to provide the service. This is what will be referred to in the present discussion as the “traditional” regulatory approach. Under this scheme the relations between different electric utilities were generally characterized by voluntary co-operation in a number of areas, such as joint management of frequency regulation or operating reserve capacity, exchange for reasons of economy or emergency –normally the latter– and third-party use of grids for current transmission or distribution under terms negotiated by the parties concerned.

This regulatory uniformity was altered in 1982 when Chile introduced an innovative approach, which separated the basic activities involved in the provision of electric power. Under the new arrangements, most of the industry was privatized and an organized, competitive (within rather strict limits) power pool or wholesale market was created, with centralized dispatching based on declared variable costs. All generators were paid a “system marginal price”, and long-term contracts were instituted to offset price volatility. The new scheme also envisaged planning guidelines for generation –in which the State assumed a merely subsidiary role– and free access to the grid subject to payment of transmission tolls. Similar reforms were not introduced anywhere else place until 1990 when the elec-

tricity industry was –much more radically– transformed in England and Wales, and shortly thereafter in Argentina (1991) and Norway (1991). Since then, many other countries, including Colombia, Sweden, Finland, New Zealand, the Australian states of Victoria and New South Wales –later to give rise to the Australian national market–, Central America, Peru, Ecuador, Bolivia, El Salvador, many states in the United States and Canada, The Netherlands, Germany, Italy, Portugal and Spain, among others, have established or are in the process of establishing regulatory frameworks for a free electric power market. Certain elements of free competition have been introduced in traditional regulatory contexts by countries in Eastern Europe, as well as in Mexico, Malaysia, Philippines, Indonesia, Thailand, Japan, India and Jamaica.

1.4.2 New regulatory environment

Motivation

The regulatory change in the electricity industry, which forms a part of the present wave of economic liberalization affecting businesses such as air carriage, telecommunications, banking services, gas supply and so on, has been possible thanks to a variety of factors. On the one hand, the development of the capacity to interconnect electric energy systems has led to an effective increase in the size of relevant potential markets, eliminating or reducing the possible economies of scale to be had in a single production unit. On the other, competitive generating technologies that can be built in shorter times are, at least initially, opening the recently created markets up to a flood of new entrants. In some countries the determining factor has been dissatisfaction with the traditional approach due to its most common shortcomings: excess of governmental intervention, confusion over the State's dual role as owner and regulator, financial and technical management inefficiencies due to the lack of competition, or lack of investment capacity. Finally, technological advances in areas such as metering, communications and information processing have paved the way for the advent of competition in the supply of electric power to the final consumer.

Fundamentals

Electricity industry regulation is based on a fundamental premise: that it is possible to have a wholesale market for electric power open to all generators –those already existing and those that voluntarily enter the market– and all consumer entities. The core of this wholesale market is typically a spot market for electricity, with respect or as an alternative to which medium- and long-term contracts of different types, and even organized markets for electricity derivatives, are established. The agents trading on such markets are generators, authorized consumers, and different categories of supplier companies, acting on behalf of non-eligible consumer groups or eligible consumers, or simply as strict intermediaries. The new regulatory context must also address many other issues, such as: creation of a retail market enabling all consumers to exercise their right to choose a supplier; the mechanisms and institutions needed to co-ordinate organized markets and, especially, system technical operation; transmission grid and distribution network access, expansion and remuneration, as well as quality of supply and the establishment of transmission tolls to use them; or the

design of the transition from a traditional to a competitive market, protecting consumers' and utilities' legitimate interests.

Requirements

In this environment, sight must not be lost of the technological and economic features of the electricity industry that condition the design of the regulatory provisions governing it, namely:

- The infrastructure needed for electric power generation, transmission and distribution is costly, highly specific and long-lasting.
- Electric power is essential to consumers, making public opinion highly sensitive to possible service outages or poor quality.
- Electric power is not economically storable in significant quantities and therefore production must be instantaneously adapted to demand.
- Real operation of an electric power system is the result of a complex chain of scaled decisions, as described in detail in the preceding section.
- The supply of electric power combines activities that clearly conform to natural monopoly requirements –transmission and distribution services or system operation– with others that can be conducted under competitive conditions –generation and supply.
- The organization and ownership structures of electric companies vary widely across different electric energy systems.

Account must be taken of the fact that the supply of electric power under competitive arrangements is subject to the existence of certain activities associated essentially with the transmission grid and distribution network, whose control entails absolute power over the electricity market. Consequently, these grid/network-associated activities must be absolutely and wholly independent of the competitive activities, namely production and supply. For this reason, and given that when most liberalization processes are introduced, the industry is dominated by vertically integrated utilities, i.e., companies conducting all stages of the business from production to billing the final consumer, industry organization and ownership structure nearly always has to be modified before competition mechanisms can be implemented. Naturally, after such reform, attention also needs to be lent to issues such as the horizontal concentration of production and supplier companies and the vertical integration between them, to ensure free and fair competition.

1.4.3 Nature of Electric Activities

A careful examination of the whole process of electric power supply to end users allows the identification of various activities of a very distinct technical and economic nature, and therefore, capable of receiving a different regulatory treatment. The classic division into

generation, transmission and distribution is excessively simple and also has gross errors, such as integrating the activity of “distribution” into one single category. As a minimum, distribution includes two activities radically different in nature: on the one hand, there is the “distribution” service that permits energy to arrive physically from the transmission network to the end users and has the form of a natural monopoly; and on the other hand, there is the “marketing” service of such energy that is acquired in bulk and then retailed, and may thus be carried out in a competitive scenario.

Upon a first general classification, activities may be sorted into basic categories: production (generation and ancillary services), network (transmission and distribution), transaction (wholesale market, retail market, balancing market) and coordination (system and market operation), and some other complementary classifications, such as measurement or billing. This breakdown may be considered excessive; however, it is needed to start at the design level with such an analysis in order to set up an adequate regulatory framework. By way of example, planning the expansion of the transmission network is an activity that must be regulated in some way or other, given its characteristic of natural monopoly and its significant influence on the electricity market conditions. Conversely, once the characteristics and start-up date of a new transmission facility are decided, its construction may be assigned by some contest process where price and quality compete.

Unbundling of Activities

The number of activities indicated before does not necessarily imply a corresponding multiplicity of entities for their execution. As shall be seen below, there are synergies and transaction costs that make it convenient in certain cases for a single entity to undertake several activities. It will also be stated, however, that conflicts of interest may arise for an entity that is in charge of more than one activity, when the execution of one such activity may benefit it against other agents in another activity that is open to competition. Different separation levels may be applied, but it is necessary to adjust them to each particular case. Basically, these activities may be separated into four types: accounting, management, legal status (i.e. different companies that may belong to same owners through a trust) and ownership.

The basic rule on separation of activities under the new regulation is that a single entity cannot execute regulated activities (for instance, distribution) and competitive activities (such as generation) at the same time. The potential support to be provided by the regulated activity to the competitive one is an evident advantage for the latter and such advantage is legally out of order. Similarly, the risk of the competitive activity cannot be transferred to the regulated one, since it will definitely fall on consumers who do not have the option to choose.

An adequate transparency in the regulated activities also requires at least accounting separation among the corresponding business units. Companies engaged in regulated activities are not permitted to conduct diversified activities (i.e., activities not related to electricity) or must at least be subject to the authorization of the regulatory agency. Such authorization shall be initially based on the non-existence of negative impacts on the regulated business which could ultimately be borne by consumers who do not have the option

to choose.

The new regulatory framework design shall consider the various benefits and inconveniences when assigning activities to entities and setting the separation levels, and shall also take into account the specific characteristics of the actual system, particularly, the initial business structure. Several valid alternatives are generally possible, as shown by the diverse experiences undergone in countries that have adopted the new electricity regulatory framework.

Generation Activities

Generation activities include ordinary and special power generation. Special power generation is typically understood as co-generation and production technologies that use renewable resources, and regulatory differ from the ordinary one in that it receives a more favorable treatment by way of compensation, priority in operation, among others, as is the usual case in a number of countries. The so-called ancillary or complementary services should also be included when they are provided by generators, contributing to an adequate level of quality and security of energy supply.

The ordinary generation is a non-regulated activity conducted in competitive conditions, with no entry restrictions and free access to the networks. Selling production may take place through different transaction processes –basically in the spot market or through contracts, as described below when referring to transaction activities. The special generation, from the regulatory point of view, bears no other difference from the ordinary generation. The fundamental reason to support the special generation is its lower environmental impact as compared to the ordinary generation. The failure to explicitly consider environmental costs in the prices of the electricity market today is offset by the use of different regulatory patterns so as to level off the playing field for all production technologies enabling them to compete at arm's length conditions by tacitly or explicitly recognizing the total costs effectively incurred.

The following rules are included in the regulatory schemes currently in use or proposed in order to promote the special power generation: (a) obligation for companies that trade or distribute energy to offer them at administratively fixed prices; (b) a premium, whether pre-fixed or assigned by means of competitive mechanisms, per each kWh produced with generators that are eligible for that purpose; (c) exemption from certain taxes, particularly those that are imposed on the production of energy; (d) assistance to investment or to R&D programs related to these technologies; (e) obligatory quotas for the purchase of energy from the special generation sector by qualified traders and consumers, thereby encouraging the creation of a parallel market for the purchase and sale of this energy; (f) voluntary purchases of renewable energy by end users who pay an extra amount for it in order to finance the special generation activity. When choosing the adequate approach, efficiency –i.e. the degree of target attainment versus the additional cost incurred– should be basically valued while avoiding interference with the market operation as much as possible.

In addition to the production of energy, the groups engaged in generation contribute to the provision of other services that are essential in an efficient and safe supply of electricity: they provide reserves for future operations enabling them to act within different time scales

and face the unavoidable mismatches between demand and generation; they help regulate voltage in the electricity network in the different operating conditions; or else they permit a prompt recovery of the service in the event of a general failure. The current tendency in the regulations of this group of additional generating activities, globally called ancillary services, is summed up in two basic views: (a) the use, whenever possible, of a market approach for the allocation and compensation of said services, or, otherwise, the direct application of regulation; (b) the assignation of the charges arising from the incurred costs to the agents that caused the demand.

Network Activities

As stated above, the electric power supply necessarily requires the use of networks which given their technical and economic characteristics have to be managed and regulated as a natural monopoly. Such a requirement is a basic condition for the new sector regulation.

Network activities include: investment planning, construction, maintenance planning, actual maintenance and operation. The investment planning process determines the commissioning date, location, capacity and other characteristics of the new assets of a network. The maintenance planning process determines downtime periods for each line in order to make the repairs and actions required to keep them functional and reliable. Construction and maintenance are activities that may be executed by specialized companies, not necessarily electricity companies. Network operation is the management of energy flows within the network through actions executed directly in the physical transmission facilities and in coordination with actions executed in the production and use facilities. Networks may also take part in the provision of certain ancillary services –such as voltage regulation– that are usually directly regulated.

Both the planning of additions and the planning of maintenance for the transmission network have an impact on the manner in which activities are coordinated that, in turn, affect the electricity market. Consequently, the independence of the relevant responsible entity –typically the operator of the system– regarding market agents should be guaranteed. However, both planning activities also have obvious effects on the planning of the network construction and maintenance to be made by the transmission companies. Even though it cannot be denied that the synergies among the different network activities suggest that they should be managed by one single company, there are important regulatory reasons to separate the system operation from any transmission company.

On the other hand, the distribution networks do not have the problem of interference in market coordination. Thus all network activities in a given area may be easily executed by the same company, namely, the local distributor. Within the regulatory purview, there are two other fundamental differences between the distribution activity and the transmission activity: (a) the great majority of end users are connected to the distribution network, which is the reason for the particular importance of quality in the services; (b) the high number of distribution facilities makes the individual regulatory treatment impossible, particularly regarding payment, and results in the use of global simplifying procedures. The new regulation on electricity networks may be reduced to three main aspects: access, investments and prices, which are discussed below.

Transmission

Access: The systems that have adhered to the new regulation have implicit access to the transmission network for all agents authorized to take part in the wholesale market. The network capacity obviously imposes a physical limitation to access and there are several restriction management procedures in order to solve the potential conflict situations that may arise. These procedures extend from the application of nodal prices or zone prices in an organized wholesale market (thereby implicitly solving the network restriction) to auctions held to assign the limited capacity among the different agents, or to dispatch modifications by the System Operator according to pre-established rules, and even to the previous assignment of long-term rights of use of the network, whether through an auction or based on participation in the construction of lines.

Investments: As stated in Section 3.3, the purpose of the new regulations at the design level is to obtain a network that maximizes the benefits added to producers and consumers, who should finally undertake the network costs. Certain explicit reliability criteria are generally used in the network planning instead of being fully included in the economic functions that will be optimized.

The approach that is mainly used is centralized planning, conferred to a specialized entity, subject to pre-established selection criteria regarding the best alternatives and always under a final administrative consent for each facility. Traditionally such an entity is a vertically integrated company, which is the System Operator under the new regulations. Payment for the network is fixed by the regulator or for certain facilities it is determined directly from the construction and maintenance bidding processes. Such procedure may be open to the participation and proposal of interested parties, with the regulator's intervention preventing the possibility of an over investment. This approach may pose a difficulty in a liberalized environment, since, as aforesaid, it is very difficult to foresee the future development of power generation as it may also be affected by the network expansion.

A second approach makes the single transmission company fully responsible for the operation and planning of the network. In this case, the company would also be the operator of the system, who shall: (a) inform the users of the foreseeable congestion or "remnant capacity" of the network at its different access nodes within a reasonable time limit, (b) ensure that the network complies with certain formally pre-established design and service standards, and (c) assume the expansion of the network facilities, if required, in order to respond to access requests, provided the standards continue to be met. Transmission payment would be pre-set by the regulator and should cover the costs of an efficient company that provides the service within the established conditions. This method does not guarantee, nor does it foster, an optimal expansion of the network.

A third approach is to leave the initiative of network reinforcement to the actual users thereof, who can weigh the contribution to investment costs required from them against the benefits arising from every possible reinforcement due to better access, less congestion or loss reduction. The regulator assesses the public convenience of the proposed reinforcements and, if the evaluation is positive, it calls a bidding process for the execution of its construction and maintenance. The awarded transmission company is compensated according to its bidding terms, leaving the operation of the facility to the system's operator. This procedure

is as market-oriented as permitted by the network regulation; however, its administration is complex and relies mainly on the availability of adequate network prices to promote an appropriate location of its agents.

Prices: Since transmission activities in the network are regulated, the prices applied in this field must allow sufficient funds to cover the entire costs (equity or feasibility criteria). It is also fundamental that the agents receive adequate economic signals (efficiency criteria) regarding their location within the network, both in the short run –for a correct market operation considering losses and possible congestions– and in the long run –to promote a correct location of future producing or consuming agents. And prices should not be discriminatory. Four cost concepts are often mentioned under the title of prices in the transmission network that need to be distinguished and treated correctly: network infrastructure costs, ohm losses, congestions and ancillary services. The only relevant network costs are investment and facility maintenance costs and, in practice, none of them is related to the electrical use of transmission assets. Losses take place in the network but are actually related to production costs; the same occurs with excess reprogramming costs that may be derived from the existing congestion or other restrictions related to the network. As stated above, ancillary services are mainly a generation activity and, as such, they must be regulated.

Losses and congestion in the network give rise to economic signals that may be seen each time as modifications of the market price. Thus, the single market price becomes a nodal price, i.e., a different price in each network node that adequately conveys the economic impact of the different locations of generators and consumers. If the use of a single market price is preferred, this should not lead one to dismiss the economic signals of losses and restrictions. Losses that are imputable to each agent, either at a marginal value or at a mean value, may have a correcting effect on the prices of supplies or, preferably, on the actual amounts produced or generated, so that agents may absorb the losses in their supplies to the wholesale market. The economic treatment of congestion has already been covered in the section on access to the network.

The application of nodal prices instead of a single market price gives rise to a surplus that may be used to cover a part of the network costs, usually not over 20%. In any case, whether a single market price or nodal prices are applied, the issue of assigning all or a great portion of the transmission network costs to the users has to be solved. Very different methods have been used or proposed to carry out such distribution. The most popular one –especially in countries that have well developed networks and no such large distances to cover between generation and demand– is simply the “postage stamp” method consisting in a uniform charge per kWh that is injected into or withdrawn from the network, or per installed kWh, independent from the location in the network. When reinforcement of the short-term location signals in the network has been deemed convenient in relation to losses and restrictions, procedures have been implemented that lead to quantifying the electric use of the network made by each agent of the network, or the economic benefit each user gets from such network, or else, each one’s responsibility in the development of the existing network. In the context of several interconnected systems, with electricity regulations that are generally different but allow for transactions between their respective agents, a basic regulatory error has to be avoided when determining the network toll to be applied to two agents involved in a transaction, who are located in different systems. In the United States

such error is called “pancaking” and means that charges are applied to the transaction adding the tolls charged by the electricity grids that they should have to cross to implement such transaction. It should be noted that in this situation, the toll amount critically depends upon the territorial structure, whether electricity companies or countries, which has little to do with the true costs imposed by such a transaction on the electric network of the group of systems. Failing the coordination level required to establish a single regional toll to cover the global network cost, a reasonable and easy-to-apply approach could be that each agent only pays the network charge corresponding to the network infrastructure in his country, as a single right to connect to the regional network, with a separate charge for losses and restrictions considered jointly. Coordinated procedures could also be established in order to assign the costs of losses and the management of restrictions that affect international transactions.

Distribution

Access: The distribution activity is regulated, and distributing companies have an obligation to supply in the area where they have been granted an explicit or implicit territorial license. Accordingly, any consumer located in this area is entitled to be connected to the network and receive the supply under the quality conditions legally established for such purpose.

The great majority of the systems that have adopted the new regulation offer free access –i.e. freedom to choose a trading company– to the end users, who shall generally be connected to a certain grid. It should be noted that the change of trading company in no way modifies the rights and duties of a consumer regarding the distribution network to which the consumer is physically connected.

The foregoing does not mean that any consumer may demand special connection requirements from the distributor if the consumer is not obliged at least to cover the excess costs incurred. Regulation of the intakes is usually detailed and conditioned upon the rules established by local administrations and seeks to find the fair middle point between two sides. On the one hand, it may require the distributor to provide a universal network service in its area, with no other cost than the one acknowledged by the rules of this activity; on the other hand, it may impose some kind of economic restraint on consumers in an attempt to prevent demands from becoming excessive and unreasonable. The problem of access to distribution worsens with the existence of users of these networks, other than the end users. They are the generators, typically those of small to medium capacity, who are connected to the distribution network and to other distributors who are generally small and whose supply comes from another upstream distributor. **Investments:** As in the case of transmission, the object here is also to obtain an “optimal” network to provide the consumer with a more satisfactory balance between cost of electricity and quality of service. However, distribution requires a specific approach, since the large number of utilities makes it more difficult to apply an individual treatment and requires global solutions.

The basis of distribution regulation is the compensation procedure, as it needs to allow for a return on capital invested that is consistent with the risk involved in this activity, while accurately promoting service quality and loss reduction. Simultaneously one should avoid the tendency to use the effectively incurred costs as a basis, since they cannot be

verified or justified in detail. The general tendency is to use procedures such as price cap or revenue cap, which determine the trajectory of distribution rates or total revenues for the distributor in a number of years, usually four or five, until the regulator conducts a new revision. Rates or revenues are established from an analysis of the most adequate remuneration for the available network and the anticipated operating and expansion costs of the network over the considered period of time.

Several procedures are used to determine these costs. Thus, for example, a starting point may be a regulation based on a yardstick competition between similar distributors. On the basis of a cost database that includes the most significant characteristics of companies, advanced statistical techniques permit the establishment of different types of comparison among them and the adequate level of compensation for any additional distributor that may be considered. Another approach would be based on “model companies” or “benchmark networks”. A much greater analysis of the distribution activity is required here, although it is also possible to get closer to the conditions that warrant the compensation level for each company, particularly when compared against others. Reference models design perfectly adjusted networks and business organizations, the costs of which –with timely adjustments to adapt to the actual conditions– serve as a basis to set the remuneration for each distributor. During the period until the next review, other factors may also be added in order to adapt the compensation to the growth of the market. Having such a reference model in the network, this approach can conveniently represent the levels of losses and quality of service in an explicit way. Consequently, remuneration is consistent with the losses and quality pre-established by the regulator for each area, and economic incentives for the improvement of performance, and sanctions for non-compliance may more easily be created based on the historical performance of distributors in both aspects. The enforcement of obligatory design and operation standards that have been formally put into force for the network allows the assurance that investments, even though not optimal, comply at least with some minimum quality criteria.

Prices: Since distribution is a regulated activity, its prices should permit to cover the total costs involved in this activity which are basically related to investment, operation and maintenance. The distribution network is not relevant for the actual activities of market coordination and system operation; therefore, when setting distribution prices, it is important to ensure that the user of such network, mainly the end user, receives an adequate economic indication of its contribution to the network costs and losses. Today this can be only achieved approximately, as for most consumers, the installed measurement and billing system facilities only consider the use of energy within extended periods of time. The most frequent approach used to establish distribution tolls is simply the allocation of the regulated costs of this activity among the users of the network, and the only discrimination refers to the level of connection voltage and contracted power. Users connected in each voltage level will only take part in the costs incurred at their level and above. Since distribution networks are largely designed to cover peak demands, it is important to estimate the contributing factor of each consumer to the peak demand. For those consumers that fail to have meters with an adequate time discriminating capacity, standardized load profiles, which reflect the usual characteristics of the different kinds of consumers, should be applied.

Ohm losses in the distribution network affect the charges to be paid by consumers in

at least two basic ways. On the one hand, in calculating network tolls, the demand of each consumer at each voltage level is already affected by its corresponding loss factor. On the other hand, excluding payment of the network expenses, the energy consumption charge should be applied to this value as increased by the losses inflicted on the system rather than to the actual consumption at the consumer's facilities.

Transaction Activities

Risk management is a key aspect when considering transaction activities in any of its modalities. For generators, risk management consists in weighing the opportunity to wait for selling energy in the uncertain spot market versus acquiring sales commitments through different kinds of medium- and long-term agreements in pre-established quantities, prices and terms. For consumers who have access to the wholesale market, risk management is symmetrical to that mentioned above. In the case of trading companies that deal with consumers who have the option to choose, the managed risk shows two sides: on the one hand, the acquisition of energy in the wholesale market either at the spot price or through agreements, and, on the other, the sale of energy at rates freely negotiated with consumers. For trading companies dealing with consumers who do not have the option to choose, the managed risk level depends critically on its regulation: in a extreme scenario, the regulator permits a total pass-through of the wholesale price for energy at the regulated rates, fully annulling the risk of the transaction; in another extreme scenario, the regulated rate is established a priori based on some estimation of the medium market price, probably subject to some subsequent adjustments, with the trader fully absorbing the risk in the purchase price. Reasonable regulation methods are between the extremes, limiting the risk for the trading company, but not completely, so that there is an incentive for taking an active part in the wholesale market by making the best possible use of the available transaction means.

Transactions in the wholesale market context

In the wholesale market, generators, authorized consumers (generally starting from the larger ones) and trading entities of any kind (those which trade with consumers at a regulated rate, those which trade with clients who are able to choose their supplier, dealers and brokers) may freely carry out transactions amongst each other, either at the spot market or by means of a contract. The relevant rules often establish restrictions on transactions between agents, sometimes just transitory, usually intended to prevent positions leading to the abuse of dominating position when there is a strong horizontal concentration or vertical integration. The current trend worldwide is towards a total liberalization of the transaction means, for as much as it is possible.

Even though an organized market is not essential at the design level, all competitive electricity markets have established some kind of organized market with standardized transactions and generally with an anonymous (i.e., non-bilateral) matching of production and demand offers. Such an organized market normally includes a spot market, with a daily horizon and hourly or semi-hourly matching intervals that serve as a reference for other transactions. In the more developed electricity markets, whenever the volatility and competitive conditions permit and there is sufficient contracting volume, organized electricity

markets of derivatives or futures have arisen, providing the agents with a more flexible means of contract to manage the risks involved. In the organized spot market, generators usually offer their energy from one day to 24 hours later. These production offers are matched to the demand offers by making use of very different proceedings that are based on economic criteria. Demand is simply estimated by any independent entity in systems where the demanding agents cannot supply. Each generator gets paid after one hour for the energy it produces at the system marginal price, which is basically the price of the marginal offer at that hour. When the installed capacity of a given technology is well adapted to the system demand and to the rest of all the generating system, such payment for the energy at the marginal price of the system allows the recovery of the fixed and variable production costs.

The uncertainty about the spot price results in the use by both the generators and the demanding agents of several safeguard mechanisms against risk, among which bilateral agreements on spot price differences can be highlighted, which are solely economic in nature and are ignored when establishing a priority order when matching supply and demand offers. Other contract variables that are only authorized in some systems are the physical bilateral agreement that enables a sales agent to supply to a specific buyer, without making use of the mechanism of spot-market offers. This seems to be the current tendency: the co-existence of a voluntary spot market and physical bilateral agreements. However, the question whether the hypothetical freedom of action provided by these agreements compensates for the apparent regulatory and organized complexity of managing another type of transaction is still being discussed. International exchanges are a particular transaction case in the wholesale market where the novelty is the treatment to be given to foreign agents who are generally subject to different regulatory frameworks that are open to competition at another level.

The practical differences in the regulation of international exchanges arise from the reciprocity demands existing in the regulatory treatment between one country and another, since distribution among systems of the economic benefits provided by interconnections may critically depend on such reciprocity. Consistency within the multinational regulatory context where exchanges occur is essential. One extreme would be the total absence of regulatory integration leading to transactions being subject to discretionary and negotiated access conditions to the network with no restriction on opportunistic behavior based on the position within the network or in the monopoly where certain transactions take place. The other extreme is one of a strong regulatory integration, which, as a minimum, guarantees access to all networks under regulated, transparent and non-discriminatory conditions. In this case, the rules adopted shall reach a minimum level of consistency in their design and application of access charges, that may avoid, for example, the repeated payment of network tolls in all of the systems supposedly affected by a transaction –the above-mentioned “pancaking”– and be closest to the concept of a regional access toll, that would exist if the aggregate of all systems should constitute a single system.

Transactions in the context of the retail market

At the retail level, consumers who are unable to choose their supplier have to purchase their energy at the regulated rate from the assigned trading company, which is typically closely related to the distributor to which they are physically connected. In most regula-

tions, the company may be the same, with separate accounting. Depending on the specific regulation, and normally for a transitory period, consumers who have the right to choose may be permitted to continue to purchase the energy from their original trading company at the corresponding regulated rate. Trading to consumers who do not have the option to choose –or to those who being able to choose are permitted to continue to pay at a regulated rate– is a regulated activity, which is paid for according to acknowledged costs and subject to standards of quality in the services provided to the client. Consumers with the right to choose may turn to any trading company to contract their electricity supply at a price that is freely negotiated between them. Such a price shall include the regulated rates for the transmission services and the distribution network to which they are connected, as well as other regulated charges that are applicable in each actual regulation and are adequately settled by the trading company. The price for the trading service and for the energy is freely set by the trading company. Consequently, the sale to consumers who have the right to choose is a non-regulated activity basically intended to manage risk. Indeed it is a business with very high monetary cash flow and a reduced margin of benefits based on the presumably high competition in the activity, which largely depends on adequate wholesale purchase management and its adjustment to negotiated supply contracts with qualified consumers.

Ancillary Activities

It is generally the market operator who settles the economic transactions performed in the different markets it manages. The operator may also be in charge of settling other transactions and concepts related to the wholesale market, such as ancillary services, losses, technical restrictions, balances of final deviations and even, in some systems, bilateral agreements among agents. The settlement of regulated activities, such as transmission, distribution, or other issues, such as assistance to the special generation, is in general entrusted to the management, or the specialized and independent entity to which it delegates such activity.

Traditionally, measurement of consumption and the corresponding billing were an integral part of the trading activity while they formed an inseparable set with distribution. Under the new regulation it is possible that these activities take place independently by expert companies competing for the provision of these services. This is also the case with the installation of intakes for end users, an activity that is usually considered a part of distribution, but may be –and in fact often is– performed by competing independent installers. It is possible that in the future other activities may be identified, which can logically be executed separately, or new activities may appear, for instance within the purview of the revived philosophy of “multi-utility”, where trading companies offer other services apart from electricity.

Coordination Activities

Market operation

Theoretically, agents could deal among themselves solely through any kind of bilateral relationship and in any period of time, as they may freely negotiate. However, as stated above, virtually all of the electricity systems that have adopted the new regulation have

created at least one organized spot market, with very different formats but managed by an independent agency which in this document has been called the market operator (and corresponds to the usual English term Power Exchange.) Often the same entity manages other organized markets that complement the spot market, either within a time limit still more reduced (“regulatory” or “intra-daily” markets destined to make adjustments in generation or demand through competitive resources) or otherwise extending the time from weeks to years, i.e. organized markets for forward electricity agreements. Since offer matching in all these markets takes place anonymously, the market operator must act as a clearing house. Even though every system has a specific entity that formally acts as a market operator, there is no problem, in principle, that other organizations may compete in this activity, both by offering electricity derivatives and partially matching production and demand offers in the short term. The market operator must be seen as a “facilitator” of transactions rather than the agent of a specific electricity-related activity.

The most characteristic duty of the market operator is the management of a spot market. This market plays such a relevant role that its design is a constant central subject matter of the new regulation. A characteristic of spot-market models in the first systems that were open to competition was generally the passive role of demand, which basically took the form of an agent who accepted prices, who was obliged to cross this market in order to purchase or sell energy and used algorithmic optimization procedures –similar to those of the daily generation dispatch or weekly programming within the traditional regulatory framework– to match production and demand offers. Conversely, the tendency in the most recent spot market models is to (i) let production and demand offers act at arm’s length conditions –both in quantity and price–, allowing agents to use physical bilateral agreements as an alternative to using of the spot market, (ii) make matches in more real time, either by reducing the matching time limit in the main market, or through a succession or “zoom” of markets, or by giving priority to the final regulation market where production or consumption deviations by agents are valued in respect of scheduled amounts, and (iii) simplify the form of offer submission as well as the corresponding matching process to make it more transparent, transferring the complex processes involved to the preparation of offers by the agents.

System Operation

The system operation is an activity intended to guarantee the functioning of the electricity system under safe conditions and in a way that is consistent with the production and consumption decisions made by market agents. Strictly speaking, there is a classic coordination activity in every electricity system, the starting point of which in the new regulation is the result of matching offers and physical bilateral agreements, instead of the result of traditional proceedings aimed to minimize production costs. Such activity determines the actual production method by generators and the network operating instructions for transmission companies, so as to implement the market results provided by the market operator and the agents, if any, by way of physical bilateral contracts and considering the available technical restrictions, especially all those relating to safety in the system.

From its privileged position, the System Operator, as a connoisseur of the functioning and technical limitations of the electricity system, shall be responsible for applying technical

access criteria to networks and keeping the agents of the system informed of the foreseeable conditions of use of the same in the short, medium and long term. Given the nature of the electric energy system, its operation is an activity that has to be performed in a centralized fashion, subject to regulation, regarding service costs, operation viewpoints and control of actions. An essential aspect is that of the independence of the entity in charge of the system operation –the System Operator– to ensure a non-discriminatory treatment to agents, for example in the application of technical restrictions to the transactions conducted in the market. The aspects relating to the independence of the System Operator are reinforced when, as is reasonable due to the synergies existing among the different activities, it is entrusted with other tasks such as management of ancillary services or expansion planning or maintenance of the transmission network. And, as stated when discussing the network activities, a conflict of interest arises when the System Operator also acts as a transmitter.

1.4.4 Practical aspects of regulation

This section outlines certain basic regulatory concepts, together with the fundamentals and requirements of new electricity industry regulation. As noted earlier, this subject has been addressed in greater depth in other modules. However, no overview of this environment would be complete without at least a brief mention of certain general aspects that must be dealt with to practically implement the new legislation.

Transition to competition

A change from the traditional to the new regulatory model must define not only the final aim pursued, but also how to reach it. Obviously, the key conditioning factor is the baseline state of the electricity industry to be transformed –its organizational and ownership structure. When ownership is private, two types of possible difficulties may appear in connection with implementation of the new regulations. On the one hand, the probable maladaptation of existing generating plants to both demand and modern production technologies. This gives rise to what are known as stranded costs when the regulatory framework changes, since the market valuation of the maladapted generating assets is normally lower than acknowledged in the former traditional framework. On the other, the degree of business concentration, and vertical integration, may not be acceptable. What is relatively simple to solve when utilities are publicly owned –by passing the bill on to the taxpayer– is more difficult when private interests are involved. One possible strategy in the changeover to the new arrangements consists of reaching an agreement with company shareholders whereby the government makes concessions respecting the first difficulty in exchange for greater company flexibility in solving the second.

Stranded benefits

“Stranded benefits” is the term used by some authors to mean the social benefits forfeited when certain public goods are no longer produced in the move from a traditional to a competitive electricity industry. The public goods involved can be divided into three categories:

- Protection for consumers unable to meet the real cost of electricity;
- Environmental protection, since the cost of the environmental impact of electric power supply is not internalized in the market price;
- Others, such as the diversification of production technologies, or R&D activities with no clear short-term impact on competitive business.

Environmental costs

The substantial environmental impact of electric energy systems must be specifically addressed by the legislation, since the market will not be able to suitably deal with this aspect until environmental costs are included in the price of electricity. It is for this reason that the different regulatory frameworks must adopt measures to correct market failings in a number of areas:

- Encouragement of less polluting production technologies through specific regulatory mechanisms;
- Implementation of programmes for energy savings and electric power demand-side management;
- Imposition of pollution limits and pollution-related excise taxes in electricity generation in place of real internalization of environmental costs.

Structural aspects

Regulatory theory and experience to date show that, even where regulatory development is appropriate for each activity, if business structure is not suitable or consumer choice is not guaranteed, the new legislation will fail. A transitional period for the gradual adaptation of structures is, obviously, acceptable, but the basic requirements to ensure the existence of competition, which is essential to the new regulatory environment, are at least as follows:

- A limit to horizontal concentration, since competition needs well-matched rivalry; this entails establishing a minimum number and a maximum size of utility companies, relative to the volume of the geographically relevant market;
- A limit to vertical integration to prevent situations of privilege existing in one area of the business from being used to the detriment of competition in another: e.g., the vertical integration of two activities, one conducted under regulated monopoly arrangements and the other on the free market.
- Consumer freedom of choice of supplier and producer and supplier access to the wholesale market.

Security of supply in generation

In the systems governed by the new regulatory provisions, production companies are generally under no obligation whatsoever to supply electric power, whilst there is no centralized planning of generating resources, which is left, rather, to private initiative. For distributors, the obligation is limited to being connected to the grid and providing network service and customer support. Supplier companies typically commit to purchasing electricity at the price applicable to their wholesale market operations. The question posed, therefore, is whether the market, of its own accord, will provide satisfactory security of supply at the power generation level or if some additional regulatory mechanism needs to be introduced. No international consensus has been reached in this regard, with countries opting for one alternative or the other. This is arguably the issue of greatest importance still waiting for a solution under the new regulatory scheme.

Independent regulatory body

This new regulatory model calls for an independent and specialized body whose chief function is to ensure fair competition and settle differences arising around market operation. This regulatory body should preferably be independent of government to prevent political aims from interfering with industry regulation, and to attain higher staff specialization, provide for greater transparency in the action taken and ensure greater regulatory stability.

1.4.5 The trends in regulation: international experiences

The innovations that were started in the 1980s in the electricity industry, where the basic activities of electricity supply were separated and competitive wholesale markets were created, have extended worldwide. Experience in the introduction of wholesale competition has been mixed and good and bad reform processes have taken place. The positive deregulation of Australia and the Nord Pool countries (Denmark, Finland, Norway and Sweden) have stimulated new reforms and improvements of existing ones. The California reform 2000-2001 fiasco was a hard blow for changes being formulated elsewhere. Thus, supporters and opponents of the changes have arisen, arguing to either extend competition or to retract reform. Nevertheless, the ongoing tendency continues to be towards deregulation and introduction of competition, with the new processes learning from the successes and failures of previous regulatory schemes.

Countries in advanced stages of reform have continued implementing and refining competition, for example introducing full retail competition by opening their domestic residential markets. In some of the countries, such as Sweden, a household consumer may even buy electricity from suppliers in any Nordic country. While load management was seen as a tool to defer investment in pre reform monopolistic energy supply, demand price response is now searched for as a means to face energy shortages in competitive markets.

As new efficient thermal generation technologies develop, through the combined cycle natural gas plants, electricity markets have become intermingled with gas markets. The need to make coherent arrangements in both markets is seen as a necessity. In this new context,

electric transmission expansion needs to be assessed in direct relation to the development of gas duct networks.

Energy security has become an issue worldwide, given the dependence of many large world economies of fossil fuel supply from third countries, and the political use that is being made of energy resources. This is coupled to an increase in prices for oil and gas, given escalating global demand for fuels and stretched supply chains. The energy security issue has become so relevant that the European Union defined a policy for energy security. The policy identifies the need to diversify Europe's energy sources, entering into strategic partnerships of consumers with major potential suppliers, and to strengthen coordination and cooperation amongst countries in the internal energy market.

Coupled to the above developments, electricity trades are crossing international boundaries and are merging to form multinational markets. The merging of trading structures implies the need to harmonize regulations as well as operational practices. Of particular interest is the need to harmonize tariffs for the use of transmission networks for international trade, with open access to wires being extended across boundaries. Multinational energy integration also requires the creation of supranational institutions to coordinate system operation as well as for conflict resolution. The global aim of enforcing wholesale competition must be always kept in mind.

An issue that has been a continuous source of discussion since the first reforms took place is how to achieve an adequate expansion of supply. The supply adequacy objective aims at ensuring an optimal level of overall generation capacity to respond to growing demand and an optimal mix of generation technologies to ensure continuity of supply. The discussion has centered on the needed economic signals for new installed capacity, fundamental in markets with significant growth and highly subject to supply shocks (e.g. droughts). Essentially three regulatory paths have developed worldwide to provide these economic signals:

1. Capacity payments: This method remunerates investment in generation by its contribution to peak capacity, related to its technology and availability, independent of its energy contribution. Besides paying for consumed energy, consumers pay an uplift proportional to their maximum demand.
2. Capacity markets : Capacity markets have developed, based on a contract reliability base and financial options. Distributors are requested to contract a product "capacity", assuring a certain minimal level of long term reliability.
3. Energy only markets: Generators and consumers interact through energy spot prices, without restrictions, resultant from a bid based dispatch. Remuneration of installed capacity comes from the difference between the resultant market energy spot price and the production variable costs.

Finally, while deregulation aimed at promoting competition in generation and supply markets, regulations were introduced to deal with the monopolistic segments of the electricity chain. Different forms of incentive based regulation of transmission and distribution tariffs have been introduced, with governments and regulators taking the lead, and successfully stimulating cost reductions that have benefited the final consumer. However, the risk

that frequently arises is the potential for governmental and regulatory intervention in these markets, with the excuse to protect customers from monopoly or achieve new social benefits. The boundary between minimum government intervention to correct market failures and direct full intervention to orientate markets is easily crossed. Energy security, subsidy of renewables, nuclear power, transmission expansion, are just a few examples where governments have increasingly intervened the market to orientate certain social changes, particularly when markets have faced difficulties in energy supply.

1.5 Modeling requirements of modern electric energy systems

As electric energy systems grow in size and complexity, the need to adequately model their operation and expansion becomes a growing challenge for engineers. The alternative operational conditions and contingencies that affect systems, make system operation a multidimensional mathematical problem, that not only needs to consider technical issues but also economic ones. On another hand, the design of future system expansions often requires to consider multiple stochastic conditions that imply handling thousands, if not million, variables and options. The building of mathematical models for generation plants, system controls, networks, loads, and other equipment, is a challenge. Data collection and handling to feed those models are also demanding tasks. There are so many elements that interact in a diversity of time frameworks in major scale networks that the challenge keeps growing.

Thus, since the birth of computers and digital processing in the 1940s, they have been used extensively in electric energy system studies. Digital models and calculation tools have been developed in a wide range of applications, with engineers in the field trying the latest state of the art advances to better assess and simulate system behavior. Computer algorithms have been developed for, at least, the following areas of analysis, several dealt with in later chapters:

1. load flow analysis (power flow and voltage analysis and control)
2. short circuit analysis
3. system stability (angular and voltage stability)
4. electromagnetic transients
5. economic operation (economic dispatch, unit commitment, hydrothermal coordination, optimal load flow)
6. protection coordination
7. expansion planning
8. reliability analysis
9. risk assessment

10. load forecasting
11. state estimation

Even with increasingly powerful computer technologies (processing times and digital storage), the difficulty to study energy systems makes it impossible to handle simultaneously steady state and dynamic conditions, so that a study time segmentation is often made, depending on time constants. Computer analysis is made separately of problems dealing with steady state, mid term and long term time constants, as illustrated in Figure 1.16.

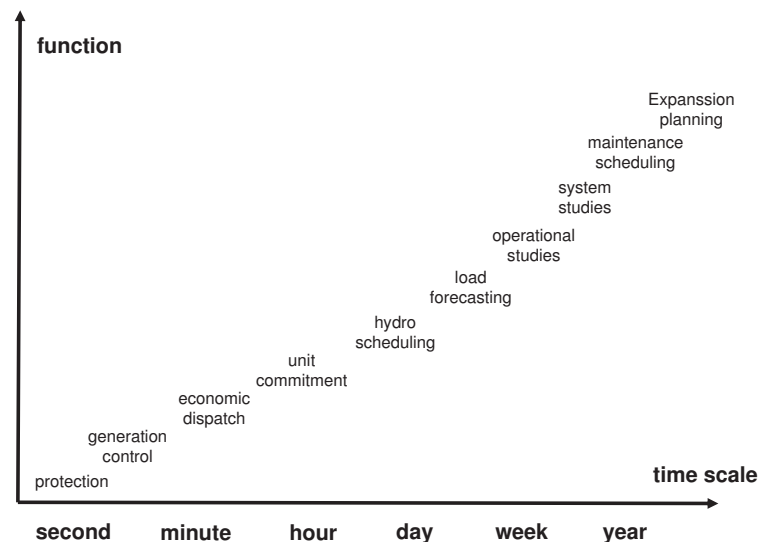


Figure 1.16: Time scales and computer studies.

The study of electric energy system engineering problems involves the development of special computer programs that require mathematical and operational research algorithms (linear and non linear, real and integer, continuous and discrete, deterministic and stochastic) to study steady-state conditions, and eigenvalue and step by step integration algorithms to study dynamic conditions.

Another dimension of computer use in electric energy systems is in the on line control of equipment and networks. Data collection, online monitoring and control make direct use of computers to operate complex networks. Human machine interface becomes then a main need, to provide analysts with the minimum and sufficient results to take actions in real time applications.

1.6 Future challenges and prospects

This section is not intended to be a lengthy or detailed discussion of the prospects for change in the electricity industry, presently one of the most dynamic sectors of the economy. Rather, it contains a necessarily incomplete but hopefully representative annotated list of technological, economic or regulatory developments that are expected to acquire relevance in the electricity industry in the years to come. Some of these may change the industry radically in the future. In most, the enormous potential for change lies in the interactions between technology, economics and regulation.

- **Distributed generation:** The encouragement of the use of renewable energy and CHP for environmental reasons, together with technological advances leading to lower wind generation, microturbine or fuel cell costs, may prompt spectacular growth in decentralized generation. This in turn may entail profound change in the functions, planning and operation of transmission grids and distribution networks and the economic management of electric energy systems. The growth of distributed generation may be more intense in developing countries, where traditional electric infrastructure is still highly insufficient.
- **Off-grid rural electrification:** The most suitable solutions for electric service to the over two billion people who presently lack access to electricity may often be small isolated grids or individual systems, using suitable distributed generation technologies.
- **Environmental and strategic considerations:** Environmental restrictions and the progressive internalization of costs deriving from environmental impact, together with long-term approaches to security of supply, will have a gradual and significant effect on future investment in new production resources. Specific markets for “green electricity” and pollutant emissions will tend to sprout up everywhere.
- **Use of the electricity grid for telecommunications:** Recent technological developments make it possible to use local distribution networks for the high-speed transmission of information. Electric utilities may therefore provide competitive Internet services as well, very likely, as many others yet to be defined, such as remote metering of electricity consumption or demand-side management.
- **Multiutilities:** As some electric utilities did in the past, today’s companies are beginning to offer additional services –gas, water or telecommunications distribution– in a single package, to take advantage of the synergies existing in these various lines of business.
- **Superconductors:** Although the use of these components in electric power is still limited to the manufacture of large electromagnets and experimental facilities, superconductivity may change the future design of large transmission equipment, particularly in and around large cities.
- **FACTS:** the difficulties encountered to enlarge transmission grid capacity and the technical and economic problems caused by loop flows –especially on multinational

markets— will further the development of electronic devices to control grid flows to optimize the use of the individual transmission capacity of each grid. Their universal use will change the traditional approach to transmission grid supervision and control.

- **Technical and economic management of regional markets:** The creation of multinational electricity markets—consisting of the coordinated operation of organized competitive markets or energy exchanges in parallel with countless bilateral transactions—while leaving technical management of security of operation in the hands of a series of independent system operators, poses complex organizational problems which must be suitably solved if both system safety and economic efficiency are to be suitably guaranteed. A paradigmatic example of such a problem is the coordinated management of grid restrictions. New organizational schemes and communications and information systems, along with co-ordination models and algorithms, will have to be developed in response to this challenge.
- **Electricity trading in the digital economy:** The liberalization of an industry as important as electric power, together with the development of e-commerce, is already leading to the spectacular development of electricity trading on the Internet, with products ranging from long-term contracts to on-line purchases and including risk insurance—to cover climate risk, for instance.
- **Clean development mechanisms:** Clean development mechanisms have created an international emission market under the Kyoto Protocol. The market allows industrialized countries committing to reduce greenhouse gas emissions to invest in emission reducing projects in developing countries. Emission reductions are paid to new generators that can demonstrate that through their investment are replacing other generating facilities that would emit CO₂.

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