Chapter 2
Electric Power Systems, Their Properties, and Specific Features

The electric power industry and electricity as its product are characterized by essential features and distinctions from other industries and commodities. Electric power systems (EPSs) underlie the electric power industry and determine its properties and the specific features of the electricity market. They are, in fact, the main subject of the studies described in the book and the focus of this chapter.

First, a general notion of EPSs (Sect. 2.1) and system effects (Sect. 2.2) that can be lost due to poor market organization is given. Special attention is paid to EPS properties that condition the specific features of the electricity market (Sect. 2.3). Section 2.4 presents briefly certain differences between EPS expansion and operation in the planned economy (in the USSR) and in the market economy.

2.1 General Definitions and Classification of EPSs

EPSs are rather diverse in terms of territory, degree of centralization in their management, composition of power plants, types of transmission lines, etc. In many countries and regions of the world there are also power interconnections that include two or more EPSs, interstate ones in particular, with their respective intersystem ties.

The most general definition of EPS can be as follows [24]: An EPS is an integration of interconnected power plants, transmission lines, and consumer substations that are combined by the common process of electricity generation, conversion, transportation, distribution, and consumption. This definition is applicable to an EPS of any territorial level and any composition of power plants and transmission lines.

Let us just note that electricity produced by each EPS is a standardized product with a normalized frequency of alternating current, voltage, and some other indices. There cannot be several "types" of electricity on the territory of one EPS, i.e., it is not interchangeable for a consumer. A similar situation arises in water, gas, and heat supply systems.

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An EPS to be considered as an individual ("independent") system should meet certain requirements (conditions):

- Maintaining a balance between electricity production and consumption with consideration of the required generation capacity reserves. Thus, the EPS should be *self-sufficient*, capable of operating separately from other EPSs.
- Unity of dispatching control (hierarchical, if needed) of the operation processes in normal and emergency conditions.
- Centralized forecasting, designing, and planning of power plants and EPS network development.

The first two conditions apparently do not need any special explanation. As for the united EPSs, they should be satisfied for the interconnection as a whole. In the course of development, some EPSs in the interconnection may become deficient or surplus.

The last requirement is of great importance for the subject of the book and needs to be commented upon. EPSs, as any other technical systems, should be designed and developed as an organic unity. Otherwise, they will not be able to perform their functions properly (in an optimal way). In the USSR, in the second half of the twentieth century, a special kind of economic and engineering activity emerged: "the electric power systems design" [25–29]. This activity favored optimal development and reliable operation of the Unified Power System (UPS) of the country.

In countries with a market economy, EPSs were also developed mainly in a centralized way within the regulated monopoly companies. After restructuring the power industry and transition to a competitive market (in some countries), expansion of generation capacities of EPSs was initially left to "an invisible hand of a market." However, experience and later studies have shown (see, for example, [19, 30]) that this "hand" does not always ensure adequate commissioning of power plants. Therefore, special measures were elaborated to contribute to deficit-free development of EPSs. These measures, in one form or another, provide for centralized forecasting of electricity consumption growth and "forced" (nonmarket) generation capacity expansion. As will be shown in Chap. 6, on the whole, transition to the competitive market complicates the fulfillment of the third condition, inevitably influencing further development of EPSs in the countries that have moved to the competitive electricity market (see Chap. 7).

EPSs and power interconnections were and are formed and developed gradually with transition to higher integration levels. These processes in different countries and regions of the world are highly diverse and depend on specific economic, geographical, and political conditions. On the whole, they are, however, objective and are caused by the effects of creating and interconnecting EPSs that are considered in the next section. Generally, EPSs can be classified as follows:

1. *Individual EPS*, which has been dealt with above.
2. *Interconnected EPS* (IPS) in one country. In the USSR, for example, there were 11 IPSs (Russia now has 7). The USA and China have several IPSs each.
3. *National or Unified EPS of the country* (NPS or UPS). These systems or interconnections were formed in the majority of European countries, in South Korea,

and many other small countries. The UPS of the country was in the USSR and is now in Russia. UPSs are being formed in China and India. In the USA, there is no UPS yet; however, almost all of their IPSs are connected to neighboring countries (Canada and Mexico).

4. *Interstate electric power interconnections* (ISEPI). These were formed in Europe, North and South America, in CIS countries, in the north of Africa, and in some other world regions. First of all, they aimed to trade in electricity with the neighboring countries, but in some of them other interconnection effects (system, capacity) have been achieved. ISEPIs are rather diverse in the number of countries involved, in terms of organization of their development management and operation control, the effects achieved, etc.

This book will address primarily interconnected and National (or Unified) EPSs in one country with a definite type (model) of electricity market organized. The international electricity markets created in ISEPI will be considered only at times to show how they are influenced by the types of market operating in the countries to be interconnected. In particular, the type of electricity market determines to a great extent the efficiency of intersystem electric ties (see Sect. 6.5).

Box 1 Classification of EPSs

1. Territorial levels of EPSs:
   a. *Individual ("independent") EPS*, which must be self-sufficient and balanced in electricity production and consumption
   b. *Interconnected EPS* (IPS) within one country
   c. *National or Unified EPS of the country* (NPS or UPS)
   d. *Interstate electric power interconnection* (ISEPI)
2. The book deals primarily with the EPS, IPS, and NPS (or UPS) located in one country with one or another type of electricity market organized.
3. In parallel with the unity of dispatching control, the *centralized* development forecasting and planning of the EPS, IPS, or NPS as an entity should be provided.
4. Electricity is a *standardized* product that is not interchangeable for a consumer on the territory covered by an EPS, IPS, or NPS (UPS).

2.2 Benefits of Creating and Interconnecting EPSs

It is widely known (see, for example, [16, 24–26]) that some objective reasons and factors have given rise first to creation of and increase in EPS capacity with extension of the territory served and then to expediency of their interconnection. On the whole, they impart a distinctive economic property to EPSs—*economies of* *scale*, i.e., an integral effect of decrease in costs of production, transportation, and distribution of electricity (and its price) with the growing EPS sizes. This property is seen in both individual EPSs and at their integration, encouraging creation of power interconnections of increasingly higher levels.

Let us consider at first the *factors contributing to the formation and expansion of EPSs*. Among them are the following:

- *Decrease in the required capacity reserves.* Increase in the total number of power units is known to decrease the probability of simultaneous emergencies of their specified share (percentage) (see, for example, [31]). As a result, the share of standby units to ensure the same reliability level of power supply is reduced with the growth of their total number. This concept is illustrated quantitatively in [24]. Dependence of the required emergency reserve on the total installed capacity of EPS proves to be nonlinear, namely, the reserve required increases to a lesser extent than does the total capacity of EPS. This objective regularity gave impetus to EPS formation, increase in EPS capacity, and territorial coverage as well as interconnection of EPSs.
  Here we note the following factors:
  - The considered effect is achieved by the increasing *number* of units regardless of their capacity, i.e., the "scale" in this case emerges in the growing number of units (blocks) of power plants, rather than in their capacity.
  - The effect is realized by the construction of *transmission lines* interconnecting power plants and consumer substations into the unified whole. Hence, this effect is typical of an EPS as a whole—in the interaction between the spheres of electricity generation and transportation (distribution).
  - With increase in the size (total capacity and area) of an EPS and preservation of its *integrity*, the effect will "fade away," i.e., decrease in the relative value, but continue increasing in the absolute one. This regularity can be violated by splitting the EPS into spheres and the spheres into several individual companies.
- *Improvement of specific economic indices of EPS facilities* with the enlargement of power plants and increase in transfer capabilities of transmission lines. This trend is well known. It showed up in the process of EPS dimensions growth, when it became possible (and economically sound) to construct power plants of higher capacity with larger units and higher voltage transmission lines. At present, the unit capacity of blocks of coal-fired steam turbine plants and nuclear power plants with thermal reactors has virtually reached its economic limit. Further increase in their capacity does not actually lead to decrease in their specific capital investments. However, it is still reasonable to construct such power plants with blocks of high (economically sound) unit capacity, if their commissioning is needed for the optimal EPS structure. Special place is occupied by hydropower plants (HPPs), whose capacity depends on concrete river conditions (water heads and flow rates), power plants on natural gas with combined-cycle installations (CCIs), whose sufficiently low specific investments can be

achieved at low capacities of blocks, and also nuclear power plants (NPPs) with fast reactors, whose unit capacity has not yet reached an economic limit. Economic transfer capability of transmission lines, especially DC lines, can also increase.

Note that just this factor is often considered as economies of scale in the electric power industry. It is asserted, in particular (for example, in [32]), that with the appearance of CCIs the economies of scale have been lost. However, this is not so. First, this factor is one of many considered here. Second, the emergence of highly economic CCIs cannot lead to expediency of "destroying" EPSs or ceasing growth of their dimensions. CCIs, on the contrary, increase the variety of types of generation capacities and possibilities for creation of their more optimal structure, i.e., enhance an overall efficiency of electricity generation sphere, in particular at EPS expansion.

Construction of CCIs by independent power producers (IPPs) in regulated monopolies is a special case. The high efficiency of CCIs makes it possible for IPPs using them to successfully compete with monopoly companies. In this situation, it is obviously expedient to connect IPPs to the networks of the EPS that is owned by the monopoly company and conclude corresponding contracts on electricity supply. Such a condition is laid down by the Law in many countries (the USA, Japan, China, etc.). At the same time CCIs can be constructed by the monopoly companies themselves, which is practically the case.

- *Improvement of economic indices of EPS as a whole owing to the technological progress in any sphere of electricity production, transportation, or distribution.* The impact of technological progress is observed constantly and the EPS (as a system) "accumulates" the effects achieved in any sphere. Specific technological innovations are highly diverse. However, on the whole, they improve the EPS efficiency (reduce electricity prices and tariffs for final consumers) and contribute to the growth of their scales in both territory and capacity. Examples of the latest achievements in technological progress are the creation of the aforementioned highly efficient CCIs and the design of the FACTS (Flexible Alternating Current Transmission Systems), increasing transfer capability and controllability of AC transmission lines (see, for example, [33]).
  When an EPS is split into spheres and numerous independent companies, as is the case at transition to the competitive market, the effect of technological innovations can "remain" in the companies and not "apply" to consumers.
- *Optimization of structure, schemes, and operating conditions of EPSs*, whose possibility (and necessity) enhances economic efficiency of power supply to consumers, reduces costs in the system and electricity prices. Optimization implies selection of the most economically efficient power plants and transmission lines and the best modes of their usage. This factor, therefore, contributes to the formation of EPSs and assists their expansion (increase in EPS dimensions).
- *Decrease in the share of administrative expenses* with the growth of EPS scales, which is typical of vertically integrated companies that monitor the whole system.

Such a trend occurred everywhere in the last century. Nowadays, in the countries entering the competitive market, in which the single monopoly companies are split into sets of generating, network, and sales companies, these expenses have not fallen, but risen instead.

In general, as was already mentioned, the indicated factors create economies of scale, providing an incentive for the formation of EPSs, successive increase in their capacity, and territorial expansion. In the planned economy countries (including the USSR), this process proceeded under centralized management. In the market economy countries, in the first half of the twentieth century, it brought the *natural monopolies*[1] in the electric power industry into being that should be regulated by the State to prevent them from taking advantage of their monopoly position. Formation of the regulated natural monopolies was a structural transformation of the electric power industry of these countries in comparison with the earlier free market that existed there. The deregulation of the power industry taking place in some countries is a reverse transformation (return to the competitive, though institutionalized, market). The present book is devoted exclusively to the analysis of this transformation.

Now, we pass on to the *effects owing to the interconnection of EPSs* with the formation of IPSs and the NPS (or UPS). These effects are also well known and studied (see references indicated at the beginning of this section). Therefore, they will be commented on briefly. Part of the effects is due to the same factors that were mentioned above; however, there are specific factors as well.

The key effects achieved owing to the interconnection of EPSs are as follows [24]:

1. Power transfer from an EPS with cheaper electricity to an EPS with a more expensive one
2. Reduction in the required emergency and repair capacity reserves
3. Decrease in coincident maximums and leveling of the joint load curves of consumers
4. Possibility of construction of larger-scale power plants with larger units
5. Rationalization (coordination) of putting into operation large power plants in EPSs to be interconnected
6. Improved usage of power plants when interconnecting EPSs with a different structure of generation capacities
7. Environmental, social, and other effects

Decrease in the necessary emergency reserves (point 2) and the possibility to construct larger power plants (point 4) were also important in the creation of individual EPSs. The rest of the effects may be treated as specific that emerge when

[1] A natural monopoly is an industry in which the economies of scale is so high that the product can be manufactured by one firm at lower average total costs than if it was manufactured by several firms [34].

interconnecting EPSs. In concrete IPSs or NPSs, not all the enumerated effects, but only a combination of them or even only one key effect can naturally be found.

Each effect has to be estimated in monetary terms (in rubles, dollars, etc.) in one way or another, and if their sum exceeds the cost of an intersystem electric tie (ISET), it is advisable to interconnect EPSs. As a rule, the economic assessment of the effects, in particular the environmental and social effects, proves to be difficult enough. It requires special calculations on the basis of appropriate mathematical models [24].

Note that the specific features of realizing different effects are important for a further study of the electricity markets. These features are stipulated in particular by the fact that many effects owing to the interconnection of EPSs are expressed in generation capacity saving, and are achieved by the construction of intersystem transmission lines. Some market models propose separation of the spheres of electricity generation and transmission (and distribution) and creation of independent generation and network companies. In this case, the network companies will bear the costs and the generating companies will take advantage of the effect. Such an inconsistency (in comparison with single vertically integrated companies) will complicate the substantiation of the ISET efficiency, and hence the interconnection of EPSs (see Sect. 6.5).

Transmission (export) of cheap electricity from one EPS to another will shift the construction of new power plants, and, as a result, the first EPS will become surplus and the second deficient. At the same time it may influence electricity prices: they can fall in the receiving EPS and, on the contrary, rise (electricity demand will increase) in the transmitting (exporting) one. In different models of electricity market organization these factors will show up in different ways. In the markets with regulated electricity prices, such an export may be mutually beneficial if the export price is set within the range of prices of EPSs to be interconnected. Then the consumer price can be reduced in the exporting system owing to the export earnings, and in the receiving system owing to cheaper electricity received. In competitive markets with free prices, electricity export will cause a loss to consumers of the transmitting system because of increase in electricity demand and prices (see Sect. 6.5).

The following two types of effects—decrease in the required reserves and coincident maximum load (in comparison with the sum of maximums for EPSs at their isolated operation)—directly lead to savings in generation capacities. They may be called "capacity" effects of interconnecting EPSs. These effects are very substantial for some countries. Their quantitative assessments for the UPS of the USSR are presented in Sect. 2.4. They are typical of the EPS as a whole at a joint consideration (efficiency assessment) of the electricity generation and transmission spheres, when construction of transmission lines decreases demand for generation capacities of EPSs to be interconnected and the total costs for EPS expansion.

The capacity effects of interconnecting EPSs are observed at any type of generation facilities and transmission lines. This fact is often underestimated when one speaks of the loss of the economies of scale in the power industry. The economies of scale implies not only economic feasibility of increasing power plant sizes and transfer capability of transmission lines. It is typical of EPS as a system, i.e., costs in the transmission sphere decrease costs in the electricity generation sphere. It cannot disappear and will constantly manifest itself with the increase in EPS scales, if it is not split into spheres and sets of companies.

The considered three types of effects also occur when interconnecting EPSs of different countries and creating ISEPIs. The intensive formation of interstate power interconnections in almost all world regions proves it [24]. Hence, the economies of scale is inherent in EPSs both at the national and interstate levels.

The rest of the effects will not be commented upon. As a rule, their realization depends to a lesser extent on the electricity market type. They are described in greater detail in the mentioned works, in particular in [24].

Box 2 Efficiency of EPS Creation and Interconnection

1. EPSs are characterized by the economies of scale that implies decrease in costs of electricity production, transportation, and distribution and *its price* with the EPS expansion. It is specified by many factors and was the main economic incentive in the formation of up-to-date EPSs and their subsequent interconnection.
2. Owing to the economies of scale, *the regulated natural monopolies* were formed in the middle of the twentieth century in the electric power industries of countries with market economies. They ensured a fast growth of electricity consumption and the appropriate expansion of EPSs. There are no reasons to suppose that in the current EPSs the economies of scale have changed into the diseconomies and the electric power industry has ceased to possess properties of a natural monopoly.
3. Interconnection of EPSs yields rather diverse effects that can be estimated one way or another in monetary terms. If the total economic effect exceeds the costs of construction of an intersystem tie line, interconnection of EPSs is expedient. The interconnection effects have led to the extension of EPS areas over the whole country and to the formation of interstate interconnections.
4. Part of the effects (capacity effects) consists in decrease in the necessary generation when EPSs are interconnected. In this case the final effect is achieved due to interaction of electricity generation and transportation spheres, i.e., for IPS, NPS (UPS), or ISEPI as a whole. Compulsory separation of these spheres can cause problems in achievement of the capacity effects.
5. In general the effects of both EPS creation and interconnection are a reason for the economies of scale in the electric power industry. Undoubtedly, it is a favorable property that contributes to the reduction of the total production costs and prices of electricity. Its loss at power industry reform should be treated as a disadvantage.

2.3 Properties of EPSs

Properties of large energy systems (LESs), including EPSs, have been studied to a great extent (see, for example, [35–37]). Main attention was paid to the common properties characteristic of all or several types of LESs: hierarchical structure, uncertainty of initial information, reliability, dynamics, etc. These studies resulted in the elaboration of certain methodological approaches, principles, and methods to be applied for development and operation management of different types of LESs. In parallel, specific types of systems, including EPSs, undoubtedly have individual properties appropriate only to them. As a rule, some scope of common (for LESs) and individual properties proves to be important for one or another aspect of specific large system management, individual properties being often of crucial importance.

Sets of physicotechnical, economic, social, and environmental properties are surely typical of EPSs. In our discussion below, consideration is given to those influencing market organization in the power industry in one way or another. Based on the variety of possible market types (models), the display of these properties will be noted in different (and sometimes in all) market models.

Chapter 4 deals with models of electricity market organization in detail. Here, the most general idea about them seems to be expedient for further illustration of the impact of different properties of EPSs on them.

Figure 2.1 presents four major models of the electricity market [32, 38]:

1. *Regulated natural monopoly* (absence of competition), which was already mentioned above. In the electric power industry these are the so-called vertically integrated companies embracing all the spheres of electricity production, transportation, distribution, and sale. This market form has given rise to restructuring or reform discussed in the book. The following market models are characterized

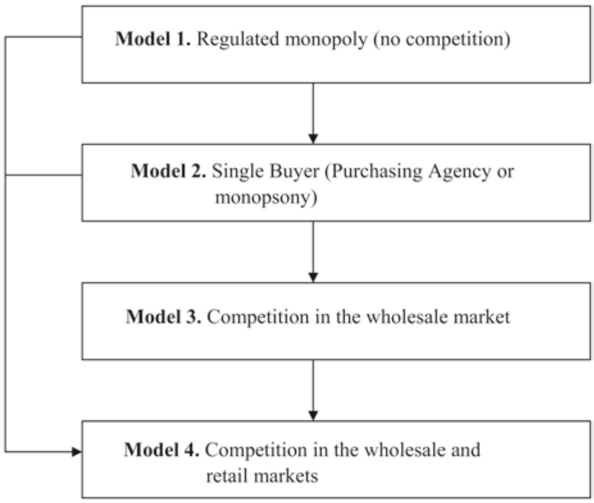

Fig. 2.1 Major models of electricity market organization

by successive separation and differentiation of the indicated spheres with formation of the corresponding generation, network, and sales companies.

2. *Single buyer* (Purchasing Agency, monopsony), when the generation sphere is divided into several separate (financially independent) power generation companies (PGCs) that start to compete with each other in electricity supply to the common Purchasing Agency. The other spheres remain vertically integrated in the agency and it is a monopolist with respect to consumers as before. Business of the Purchasing Agency, therefore, should be regulated by the State, including price quotation of electricity purchased from producers and sold to consumers.
3. *Competition in the wholesale market*, when the electricity transportation sphere is separated, the spheres of electricity distribution and sale are split into territories and the wholesale market is organized. This leads to creation of transportation-network company, territorial distribution-sales companies (DSCs), and specialized market structures. The wholesale market prices become free and the activity of DSCs and the retail prices are regulated as before.
4. *Competition in the wholesale and retail markets*, when the spheres of electricity distribution and sale are additionally divided with formation of regulated distribution companies (by territory) and sets of independent sales companies. Retail electricity markets are organized with competition between sales companies (buying electricity in the wholesale market) and consumers. The retail prices are no longer regulated.

We should underline that all the enumerated models are market models, as often only the last two models are called markets. The nonmarket electric power industry under a planned economy will be discussed in the next section. The first two models are markets with regulated prices—tariffs[2]—and we will call them, for short, regulated markets, while the third and fourth models will be markets with free prices or competitive markets. For brevity's sake, these models will sometimes be referred to by the numbers under which they have been listed above (Model 1, Model 2, etc.).

The arrows on the left in Fig. 2.1 show transition at restructuring from the regulated monopolies at the regional level and the single-buyer model at the federal level to Model 4. The transition is stipulated by the Law of the RF "About electric power industry" [39] (for more details see Chap. 8).

Now we will address directly the *properties of EPSs*, which determine specific features of the electricity market.

The following are the well-known properties and features of EPSs:

- A special role of electricity in the economy and society; damage caused by sudden interruption of electricity supply exceeds manifold the cost of undersupplied electricity, which requires special measures to support electricity supply reliability.

[2] To be more precise, the regulated prices will be called "tariffs" as opposed to market prices formed in the competitive markets.

- Inability to store (accumulate) electricity in rather large volumes.
- Necessity to balance electricity production and consumption at every moment.
- Inevitability of equipment failures, and hence the necessity of backup generation capacity and electric ties.

These properties undoubtedly influence and complicate market organization in the power industry to a varying extent in different market models. However, note some other features of EPSs that are also important in this context and are interrelated with the above properties in one way or another:

1. *Specialized electricity transport* (by wires). It excludes electricity delivery by general types of transport (railway, motor, water, air), which is possible for production of the majority of other branches and renders a local character to EPSs. New electricity producers and consumers can emerge only by connecting them to EPS networks. This property leads to:

- Territorial limitedness of the electricity market: only consumers and producers directly connected to the EPS through electric ties with a sufficient transfer capability are able to participate in the market. In particular, there is no world electricity market or world electricity prices.
- Participation of only existing (operating) power plants in the market.
- Existence of the technological (physical) barrier to the entry of new producers into the market; to this end new power plants should be constructed and connected to EPSs. Thereby, one of the principal conditions of *perfect* competition—*free entry of new firms into the industry and free exit of existing firms from it* [34]—is not observed in the power industry.

It should be noted that a physical barrier for new power producers (NPPs) is especially important. It plays a decisive role in electricity markets in the short run (in the microeconomic sense; see Chap. 3). NPPs simply cannot appear in the market, because a new power plant should be designed, constructed, and connected to the EPS, which requires several years. In the short-run electricity market the operating producers are protected from competition of NPPs and can raise prices. It is one of the basic reasons for electricity market imperfection and it cannot be eliminated (i.e., it is impossible to make the market perfect) by any organizational and methodological measures or rules.

2. *Daily, weekly, and seasonal load variations* that determine:

- The need to expand generation capacities in accordance with an annual load peak (taking into account reserves); in other periods of the year power plants will be underloaded and get lower revenues which may turn out to be insufficient to pay back investments.
- The economic expediency to have different power plants (basic, peak, and semi-peak) with various economic indices (specific capital investments and production costs).
- The need to optimize the structure of generation capacities (by type of power plants) and operating conditions of power plants for different time periods of a year.

The presence of power plants of different types, in turn, leads to specific supply curves of producers and to formation of marginal prices and producers' surplus [40] for more efficient power plants in the competitive wholesale market (for more details, see Chaps. 3 and 5).

This feature of EPSs also caused the need for centralized dispatching control of normal and emergency operation of the power system (which is foreseen in all market models) and also engendered the next property (or even paradox) in the electric power industry which is observed in no other industry.

3. *The need for optimization of the power system operation with regard to instantaneous (hourly) variable costs of power plants, while their total costs (and economic efficiency) are determined by integral operation results for the whole year with an account taken of fixed costs.* Load variations during a year cause changes in operating powers (load) of power plants, which should be optimized according to the criterion of the least hourly, daily, weekly, or seasonal variable (fuel) costs throughout the entire power system. While carrying out optimization we have to use hourly characteristics of power plants, which represent only variable costs.

Meanwhile, the real electricity value (and its price) is determined by the average total costs, including fixed costs of power plants as well. In the electric power industry the average total costs can be determined only for the whole year. They will depend on an annual output of a power plant, its operation during a year (which determines annual variable costs), and annual fixed costs. This difference between hourly and annual costs influences essentially the organization of electricity markets and the process of price setting. In particular, the spot electricity markets organized in real time (with hourly or half-hourly intervals) are not real short-run markets considered in microeconomics, and their prices do not reflect the real value of electricity, which makes the spot markets inappropriate (Sects. 5.1 and 5.2). The real short-run electricity markets can only be the markets that cover the period of one or more years and are implemented through respective contracts.

4. *Great capital intensity, long periods of construction, and service of power plants and some transmission lines, which result in:*

- The impossibility of quickly eliminating shortage if it occurs for some reason. It will take several years to design and construct new power plants. Moreover, if power plants are constructed by private investors (Models 3 and 4), nearly 10 years more will be necessary to pay back the investments. Hence, private investors should know the power system expansion conditions, including the prices in the wholesale market, 15–20 years in advance. These conditions are rather uncertain, which create a large risk for investors and make construction of new power plants and elimination of shortage even more complicated.
- The need for prior planning and subsequent financing for the expansion of generation capacities in power systems to avoid shortage in the electricity market.
- Power plant service life (30–40 years) exceeding "reasonable" payback periods (10–15 years), which will make private investors construct power plants (Models 2–4).

This feature of EPSs manifests itself to a greater extent under competitive markets (Models 3 and 4) when the criteria, incentives, and financing mechanism for construction of new power plants change dramatically as compared to the regulated monopoly and single-buyer market. These changes create problems of investing in the expansion of generation capacities, which are considered in [19] and in Chap. 6.

Moreover, the competitive market concepts (including those in Russia) usually envisage no centralized planning of the generation capacity expansion. The generation capacities are supposed to expand on the basis of "market signals." However, as was pointed out in Sect. 2.1, the experience of the countries that introduced the competitive electricity market and recent research have shown that the market does not generate these signals timely and special "non-market" measures are required to prevent power shortage.

5. *High level of mechanization, automation, and even robotization (at nuclear power plants) of electricity production, transportation, and distribution*. Normally, power plants and substations have only administrative, duty, and maintenance personnel. The number of personnel practically does not depend on the amount of actually generated and transmitted power. All process lines and units at power plants are designed on the basis of their maximum (installed) capacity.

This feature of EPSs along with the said huge capital intensity of power plants leads to a high share of fixed costs in the total electricity production costs. At the same time, there are practically no variable costs at HPPs, and those at nuclear and thermal power plants are made up of fuel costs only. The characteristics (curves) of average costs of power plants, therefore, differ principally from the cost curves of "typical" firms considered in the theory of microeconomics (see Chap. 5). This makes the short-run competitive wholesale electricity market "nonstandard," i.e., different from the markets in other industries. In particular, power plants (or power generation companies) will have to enter the market with their supply bids reflecting the total costs rather than the marginal ones.

6. *Interdependence of electricity production processes of different power plants in the power system.* All power plants operate to cover the total EPS load which changes daily and seasonally. Their operating conditions are optimized centrally, depending on the mix of generation capacities in the EPS.

This feature of the power system brings essential peculiarities in the electricity market:

- Power producers (sellers) do not enter the market with already finished products with known volumes and prices. Electricity is produced *jointly and simultaneously* by all producers. Volumes and costs of each producer will depend on centrally assigned operating conditions for different hours, days, and seasons. The most economically important *annual* volumes and costs of each producer will be determined only at the end of the year by integral results.
- Thus, the *uncertainty* exists in the characteristics of short-run costs of power producers. This uncertainty is not observed in the industries where firms (companies) produce commodities *independently* of one another. The uncertainty of power plant costs makes the electricity market very special. In the regulated

markets (Models 1 and 2), this creates difficulties in establishing tariffs by the regulatory bodies. The regulation should envisage adjustment of tariffs in the event that the actual output of power plants deviates considerably from the planned one (this is particularly necessary for HPPs, whose output depends on random inflow of water). In the competitive markets (Models 3 and 4), the situation is even more complicated—the electricity producer in the market does not know exactly how much electricity he will produce throughout a year and what total costs he will bear. Naturally, he will overestimate the prices both in the spot market (if it exists) and in the long-term contracts with buyers.

7. *Facility-by-facility expansion of power systems.* The market in any power system expands through the construction of individual new power plants and transmission lines. This property reveals itself differently in different models of electricity market organization.

New power plants can be funded and constructed by:

- Vertically integrated companies (VICs) (Model 1)
- Power generation companies (PGCs) (Models 2–4)
- New independent power producers (IPPs) (Models 1–4)

As is shown in Chap. 6, financing mechanisms for the construction of power plants can vary. The primary distinction is that under regulated markets (Models 1 and 2) the investments in new power plants are paid back at the expense of the total electricity output generated by VICs (or in EPSs), whereas under the competitive wholesale market (Models 3 and 4) the investments in some power plants should be paid back at the expense of the electricity generated by only that one power plant.

Under the competitive market, each new power plant constructed by a private investor, along with operation costs, will have its own investment components required to pay back the investments. Therefore, the price to be offered by the new electricity producer in the wholesale market will be higher than the price offered by the operating power plant of the same type. This creates an economic (price) entry barrier for new producers in addition to the physical barrier mentioned above, which makes the electricity market imperfect in the long run as well (Sect. 6.4).

Additionally, the facility-by-facility expansion of generation capacities in EPSs influences the shape and sense of the long-run cost curves of the electricity generation sphere. Under competitive markets the short-run costs of new power plants should be considered as long-run production costs of IPPs and PGCs (Sect. 6.3).

Moreover, the transition to the competitive wholesale market changes the mechanism of financing the intersystem and interstate electric ties, which makes it difficult to substantiate their efficiency (Sect. 6.5).

8. *Economies of scale*. This was already considered in the previous section. To the greatest extent, this effect is realized in the regulated monopoly (Model 1). In other models, it subsequently decreases (Model 2) or is even lost completely (Models 3 and 4) due to the splitting of one company into several separate companies. It should be emphasized once again that this effect is typical of the entire EPS (as

a system) and not only of power plants in the electricity production sphere as it is sometimes interpreted (for example, in [32]).

The overall analysis of power system properties shows, on the one hand, the principal distinctions of the electricity market from the markets in the other industries and, on the other hand, its obvious imperfection.

The main distinctions are:

- Territorial limitedness of the electricity market (within the territory covered by the networks of a specific EPS).
- The need for dispatching control of normal and emergency conditions of the power system.
- The need for centralized design and advance planning of the power system expansion with account taken of the required capacity reserves.
- Impossible to organize "normal" electricity spot markets (for more details, see Sects. 5.1 and 5.2).
- Nontypical and uncertain costs in the generation sphere of EPSs, which makes the competitive (unregulated) wholesale electricity market "nonstandard" in the light of the theory of microeconomics (for more detail, see Sects. 5.3 and 5.4).
- Obvious uniqueness of intersystem electric ties that connect different territorial electricity markets (for more details, see Sect. 6.5).

The electricity market imperfection is first of all conditioned by the technological (physical) barrier to new producers in the short run and by the price (economic) barrier to them in the long run (Sect. 6.4). Whether or not the other conditions (requirements) of perfect competition are met is analyzed in Sect. 3.2. The imperfection of the electricity market reveals itself under any models of its organization. In Models 1 and 2, its monopolistic character is obvious and this leads to the necessity to regulate electricity prices (tariffs). In Models 3 and 4, as will be shown in Chaps. 3 and 6, electricity producers on the one hand may form an oligopoly[3] and on the other hand maintain "market power," thus having the chance to create shortage and raise electricity prices through cessation or delay in construction of new power plants. This is also facilitated by the economic barrier mentioned above.

It should be noted that the electric power industry differs from other infrastructural industries, such as transport or telecommunications, in the production of commodities. It is the sphere of electricity generation that creates many of the foregoing EPS distinctions and makes the electricity market imperfect. This, in particular, relates to a nontypical character and uncertainty of costs in the sphere of EPS generation, to the impossibility of organizing electricity spot market, and to the existence of physical and price barriers to entry of new producers into the market. It is important to indicate this distinction, since in some countries (for example in the USA) one of the arguments for deregulation of the electric power industry was successful reforms in the air transport and telecommunications. This distinction of the power industry is analyzed in [3].

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[3] Oligopoly is a market form in which a small number of sellers dominate in selling a certain product and the entry of new sellers into the market is either complicated or impossible [41].

Box 3 EPS Properties and Their Impact on the Electricity Market

1. Certain properties and specific features inherent in power systems cause *imperfection* of the electricity market and its distinctions from markets in other industries. In addition to the well-known EPS properties, it seems advisable to underline the following ones:

   (a) *Economies of scale* considered in Sect. 2.2 that can be lost due to poor market organization.
   (b) *Specialized electricity transportation* that leads to territorial restriction of the market and creates a technological (physical) entry barrier for new producers in the short run.
   (c) *Variability of daily, weekly, and seasonal loads of consumers.* In combination with the other properties analyzed in this section, this one determines, in particular, the:

      – Uncertainty of short-run costs of electricity producers.
      – *Impossibility* of organizing "normal" spot electricity markets (for more details, see Sects. 5.1 and 5.2).

   (d) *High level of mechanization, automation, and even robotization of processes.* As a result, the characteristics (curves) of the average costs of power plants differ essentially from the cost curves of the "typical" firms studied in the theory of microeconomics (See Sects. 3.1 and 5.3). This fact renders a *short-run wholesale* electricity market to be "nonstandard."
   (e) *High capital intensity, long period of construction and service of power plants, facility-by-facility expansion of EPS.* These properties lead to:

      – Impossibility of fast elimination of *shortage*.
      – Necessity of advance *expansion planning* of EPS generation capacities to prevent shortage.
      – *A price barrier* for new electricity producers in the competitive market in the long run (for more details, see Sect. 6.4).

   It should also be noted that the electricity market type (model of organization) radically influences the *mechanisms of financing* construction of power plants (Sects. 6.1 and 6.2).

2. The key *distinctions* of the electricity market from markets of other goods that are worth considering are:

   (a) Its territorial restriction and the absence of the world electricity market and the world prices.
   (b) The necessity of dispatching control over operating conditions and centralized EPS expansion planning.
   (c) "Nontypical" character and uncertainty of costs in the EPS generation sphere.

(d) Economic incompatibility of organizing spot markets of electricity.
(e) Unique nature (in the microeconomic sense) of intersystem electric ties connecting different territorial markets (see Sect. 6.5).

3. *Imperfection* of the electricity market (in terms of microeconomics) creates, first of all, a technological entry barrier for new producers, and transition to the competitive electricity market leads to creation of a price barrier for them. The monopolistic position of electricity producers in the market is retained in all models of market organization, except for the single-buyer model (for more details, see Chaps. 3, 4, and 6).
4. *Commodity production* distinguishes the electric power industry from "purely" infrastructural branches (such as transport or telecommunications). The EPS generation sphere causes the aforementioned distinctions and imperfection of the electricity market.

2.4 Electric Power Industry in Planned and Market Economies

This section will address the distinctive features of the development and operation of the electric power industry in planned and market economies, the issues of state and private ownership, including corporatization of power companies, and some aspects of Russia's and China's power industry transition from the planned to the market economy.

Under planned economy, there is naturally no market in the power industry or at best there can only be some of its elements. In the USSR, in particular, the development and operation of the power industry were planned centrally along with other sectors of the economy. The plans were funded from the national budget and implemented by a hierarchical system of state organizations and enterprises, with the Ministry of Energy of the USSR at the upper level. In China, a similar centralized management of the power industry continued till 1985 or even up to 1997 when the Ministry of Power Industry was abolished [42].

Very often, the situation in the power industry under the planned economy is compared to the regulated monopoly under market conditions. There are, undoubtedly, some common points, but there are also considerable differences. These concern, first of all:

- The mechanisms of planning and regulation
- The establishment of electricity prices
- The types of ownership (state, municipal, private)

The differences between planning and regulation reveal themselves, to a greater extent, in the development of the power industry. In the USSR, for example, planning the development of industries was an integrated process that covered various interrelated time periods: perspective planning for 10–15 years, 5 years, and the 1-year plan. In the electric power industry this process was based on the designing of the power systems, i.e., the elaborated development strategies of UPSs and IPSs, feasibility studies on the most crucial issues, and the like. The plans for the development of the power industry suggested providing the national economy with electricity (and heat) on the one hand, and the power industry itself with the required resources including the financial ones on the other hand. Owing to the directive character of plans, particularly those annual ones, the uncertainty of forecasting electricity demand, commissioning of power plants, transmission lines, etc., was minimum. Development of the electric power industry (UPS) was planned for the whole country with regard to the development of individual regions (IPS). Here, due to the general trend toward minimization of expenditures, the effects of EPS interconnections were realized to the maximum extent, the minimum required level of capacity reserves was maintained, and so on.

Regulation of EPS expansion within the natural monopolies differs from planning in several aspects. First of all, the proposals for expansion of power systems on their territories are made up, as a rule, by the monopoly companies themselves. The regulatory bodies then coordinate (or correct) these proposals. This implies that:

- The work on analysis and optimization of power system expansion is done twice—by the monopoly company and by the regulatory body; the latter should be staffed with highly qualified personnel.
- The monopoly companies, particularly the private ones, are interested in the maximum expansion of their power systems, both to guarantee reliable power supply and to increase their capital, which is materialized in new energy facilities.
- The regulatory bodies are subject to constant pressure from monopolistic companies and, therefore, should be protected from corruption; simultaneously, being also responsible for power supply to consumers, they are inclined to allow surplus generation capacities rather than their deficit.

Secondly, expansion of power systems is planned and carried out by the monopoly companies, yet only within the territories they serve. If there are several such companies in the country, as for example in the USA, Canada, and Japan, it becomes difficult or even impossible to realize the effect of interconnection of individual power systems and create the most efficient Unified (or National) Power System of the country. This also leads to different electricity prices (tariffs) throughout the country, which will be discussed in more detail below.

Thirdly, it should be noted that power system expansion planning in the market economy is related to a much greater uncertainty than under the planned economy.

As to the control of power system operation, in particular dispatching control, it differs in planned and market economies to a lesser extent, and so we are not going to dwell on this. It can only be mentioned that the planned economy makes it possible to organize centralized dispatching control of the UPS (or NPS) of the whole country, with an appropriate increase in economic efficiency and reliability of the power supply. However, this is not feasible, generally, in the case of market economy countries with several monopoly companies in the power industry. In the USSR, the level reached in the development of methodology and facilities for hierarchical dispatching control of the UPS, including emergency control systems, was high indeed [43–48].

The principles and methods of establishing electricity prices (tariffs) in the planned economy and regulated monopolies differ greatly. In the USSR the prices were established on a centralized basis and were common throughout the country.[4] Moreover, taking into account the centralized planning and funding, the power industry could both be subsidized and a profitable industry. The authors in [49] and [50] show that in 1960–1965 the power industry did not recoup its expenses completely and then up to 1990 was profitable despite large capital investments allocated for its development. Here the electricity tariffs for industry and for the population (higher) were quite acceptable.

In the regulated monopolies the tariffs are established by the regulatory bodies individually for each company. The tariffs include all the required costs of the company, investment components, ensuring power system expansion, and normal profit. Sometimes, at the request of state or municipal authorities, the tariffs include some "indirect" costs, or, vice versa, the subsidies are allocated, for example, to implement renewable energy sources. The mix of generation capacities in the power system, fuel types and cost, as well as other conditions in each monopoly power company can naturally be different, which results in different electricity tariffs throughout the county if there are several such companies. The techniques of establishing tariffs, especially in terms of investments and profit, are country-specific. On the whole, the process of tariff regulation is rather complicated and affects enormously both tariff value and the financial state of regulated power companies. The difficulties and flaws of state regulation of monopoly power companies were, as already mentioned, one of the arguments in favor of transition to the competitive market.

In Russia, at the beginning of the 1990s when the electric power industry was split into joint stock companies, the state regulation of newly created power companies (RAO "EES Rossii," AO-Energos, AO-Electrostantsiyas) had to be organized anew and urgently. Naturally, there were many drawbacks aggravated by a general economic crisis in the country. Later, the system of regulation improved slowly, but surely it is still far from completion.

As to the property in the power industry, under planned economy (in the USSR and up to 1985, in China) it was 100% state-owned. In the regulated monopolies it can be state-owned (or municipal) (France, Norway, and some other countries) or privately owned (Japan, England, many states of the USA, etc.). In any case, the activity of monopoly power companies is regulated by the State. Starting in the 1980s,

[4] There can be different viewpoints on the expediency of equal electricity prices throughout the country. However, the efforts of Federal bodies in the USA and the EU indicate to their endeavor to equalize the prices among the countries (states).

private independent producers that sold electricity to monopoly companies at regulated tariffs emerged almost in all the countries (England, the USA, China, etc.).

In some countries, power industry restructuring was accompanied by the privatization of the generation companies, and in others they remained under the state ownership. Electric networks were not privatized, as a rule.

The process of separation of economically independent generation (and other) companies from monopoly vertically integrated power companies, with them remaining in the state ownership, is called "corporatization" [2]. Such corporative (state) companies act in the market similarly to the private companies, i.e., they also seek to gain maximum profit and compete with one another and with the private companies. Corporatization can be performed at different extents of power industry restructuring. For example, China and South Korea have corporate generation companies at the single-buyer market (Model 2), while Norway has them at the competitive market (Models 3 and 4).

There is an opinion that private companies are more efficient than state-owned ones. At the same time, the latter have a number of advantages over private companies:

- Their costs do not include "normal" profit to pay dividends to shareholders (owners) of the company; hence, they can enter the market with lower prices than similar private companies.
- Profit gained is disposed under the direct control of state bodies, i.e., in the interests of the State.
- A company's administration wage is also established by the State; it certainly depends on the results of the company activity (including the profit obtained) but cannot be established by the company itself. Simultaneously, the salaries of company employees are regulated, though in private companies the salaries of employees can be understated.

The above advantages of state companies may turn out to be more significant than the possible advantages of private companies. For example, Noble Prize Winner Professor Joseph Stiglitz shows [51] that the managers of private companies cease to pursue the interests of shareholders (lose touch with the owners). They have more detailed information concerning the market and the situation in the companies managed by them, and they use it for their selfish purposes.

In the conditions of state ownership under centralized planning and financing, the UPS of the USSR was the most integrated and efficient power interconnection [52]. It realized to a greater extent the effects of power system interconnection considered in Sect. 2.2, that is:

- The effect of peak load diversity among interconnected power systems (situated in six time zones) resulted in the decrease in demand for generation capacity in December 1991 by 6 GW [52]. At the same time in each IPS this effect reached 2.33 GW in the Central IPS, 0.91 GW in the Northwestern IPS, 1.01 GW in the Southern IPS, 0.43 GW in the IPS of Middle Volga, 0.59 GW in the IPS of Northern Caucasus, 0.37 GW in the IPS of Transcaucasus, 1.07 GW in the IPS

of Ural, 0.32 GW in the IPS of Northern Kazakhstan, and 0.92 GW in the IPS of Siberia, i.e., in total another 8 GW.
- The saving of emergency and maintenance reserve in the UPS of the USSR is estimated at 3–4% [25].
- The effect of power plant utilization improvement (optimization of operating conditions) is estimated at 10–12 million tce saved yearly [52].

According to the gross estimation of the USSR UPS efficiency [25], the expansion and operation cost saving surpasses the costs of the UPS backbone network development by a factor of 1.5–2.5 (owing to the saving in the generation sphere).

On the whole, the UPS of the USSR, after its formation in the 1960s, ensured reliable and economical power supply to the country at the minimum required capacity reserves, optimal structure, and operating conditions of generation capacities.

After the USSR disintegration, the UPS was partitioned and many power systems of the CIS turned out to be deficient, and in the UPS of Russia the above effects considerably decreased. The reform of the power industry in Russia, which is currently underway, will cause further losses of the effects which were inherent in the UPS of the USSR (Chap. 8).

After the economic reforms launched by Den Siao Pin, China's power industry underwent dramatic changes. Introduction of market relations (and private ownership) at maintenance of the general centralized planning (and state property), i.e., transition to the mixed economy, resulted in an extremely good effect for China. The reform of the power industry in China will be described in detail in Chap. 7. Here, we will dwell only on the following circumstances.

Starting in 1985, China created very favorable conditions for the attraction of private investments into the sphere of generation. This was caused by the lack of own (state) funds to meet a speedy increase in power consumption and eliminate power shortage. As is shown in [19] and will be considered in Chap. 6, high rates of expansion of generation capacities make it profitable to involve credits for financing. In fact, the long-term contracts that were concluded with private investors and guaranteed payback of investments at a rather high interest rate represented a kind of these credits. This measure was economically feasible for China. It resulted in the emergence of many independent power producers (private owners) along with preservation and expansion of power plants that belonged to the state and municipal authorities.

Planning of power industry development had been performed by the Ministry of Electric Power Industry before 1998 and then by the State Commission for Development and Planning and was gradually replaced by state regulation. In 2002, power generation was separated from the transmission sphere (with formation of the respective state companies), and the Chinese Commission for Regulation of Power Industry was established. This commission controls development plans and establishes tariffs for the state companies, approves long-term contracts with independent power producers, etc.

Currently, China's power industry has been transformed into the regulated single-buyer market. Two companies have been founded: China's State Power Grid

Corporation, which covers the territory of the interconnected power system of Northern, Northeastern, Northwestern, Eastern, and Central China, and the South China Grid Company on the territory of southern and southwestern provinces of China. These companies, along with development planning and operation of electric network, perform dispatching control of power systems, plan expansion of generation capacities, hold tenders, and conclude long-term contracts for the construction of new power plants and power supply from them.

Thus, China has made a “gradual” conversion of the electric power industry under planned economy first to the regulated monopoly and then to the regulated single-buyer market. At the same time, there are both state (and municipal) and private PGCs that compete with one another. The system of state regulation provides, on the one hand, maximum possible construction of new power plants and, on the other hand, moderate tariffs for consumers (at the level of average power production, transportation, and distribution costs throughout the power system). In parallel with the central planning of the main indices and proportions of social and economic development of the country, this made it possible to effectively manage the widely expanded power economy and more thoroughly use the initiatives and capabilities of regional bodies and individual companies.

Box 4 Electric Power Industry in Planned and Market Economies

1. The regulated power monopolies (Model 1) and the regulated single-buyer market (Model 2) have a certain similarity with conditions of the planned economy. However, there are some distinctions in the mechanisms of EPS development planning and financing as well as price formation. The electricity tariffs for the indicated market models, in particular, will be individual for each regulated company, whereas in the planned economy they can be common for the whole country.
   Conditions for the competitive markets (Models 3 and 4) differ radically.
2. The state regulation of power companies is a rather sophisticated form of activity which has specific features in each country and should be constantly improved. In Russia, in the early 1990s, it was organized urgently from the outset. In China, transition from the state planning to the power industry regulation was performed gradually from 1997 to 2002.
3. In different countries, there are both private and state (corporate) generation companies. Despite the widely spread opinion that the activity of private companies is more efficient, the state companies have certain advantages:
   (a) The costs do not include “normal” profit intended for shareholders’ dividends.
   (b) The profit gained is used in the State’s interests.
   (c) Wages of managing staff, workers, and employees of the company are regulated.

4. In the centrally planned economy, the UPS of the USSR, being 100% state-owned, was the most reliable and cost-effective power interconnection. It enjoyed the effects of integrating interconnected power systems and regional power systems: decrease in generation capacities owing to diversity in peak loads reached 14 GW and the saving of emergency and maintenance reserves to 3–4%. The total effect in generation was 1.5–2.5 times higher than the costs for expansion of the UPS backbone network.

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