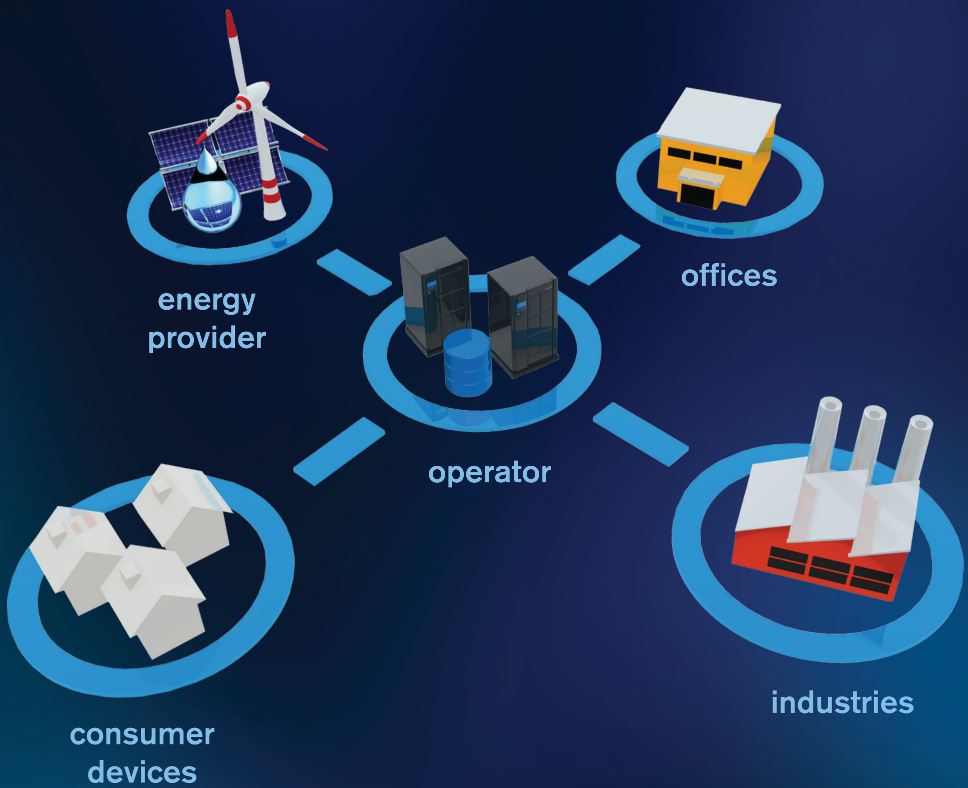
Electricity Markets and Power System Economics



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CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20130916

International Standard Book Number-13: 978-1-4665-0170-6 (eBook - PDF)

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Preface

The notion of electricity marketing is not new at all. After the first power plant in history was commissioned for commercial operation by Thomas Edison on Pearl Street in New York in 1882, electricity was sold as a consumer product at market prices. After a period of rapid development, electricity became such a fundamental product that regulation was believed to be necessary. Since then, the power industry had been considered a natural monopoly and undergone periods of tight regulation. Deregulation started in the early 1980s and as a result, most developed countries run their power industries using a market approach.

The practices involved in marketing electricity markets change quickly. Market rules are published every year, then updated and published again. Additionally, relevant publications and research reports are reviewed and archived. The need to describe the basic building blocks of electricity market theory systematically is obvious and this book was written to meet the need. After reading this book, an electric power professional should understand the ramifications of mainstream market rules and be able to read scholarly articles.

About half the material covered in the book came from our research results. However, the book is more of a textbook and clarity is the top priority when writing a text. The intended audiences are senior undergraduate students and first-year graduate students. Chapters 1 through 3 provide a basis for understanding the rest of the book. The remaining chapters can be read almost independently. Figure 0.1 depicts the dependency of the chapters in this book.

We thank our co-workers for doing a great job in performing the research described in this book and for their generosity in allowing us to report their research results. The co-workers are named in the papers we cited in each chapter.

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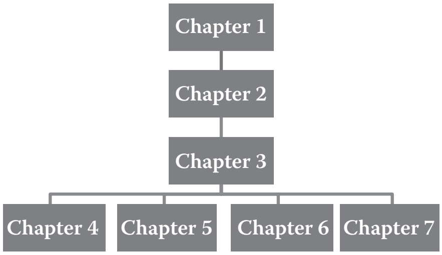

Figure 0.1 Dependency of chapters in the book.

Chapter 1

Introduction

This chapter briefly introduces the basic concepts of microeconomics. By explaining terms such as supply, demand, and market equilibrium that appear frequently in this book, we aim to prepare readers who have no economics background to understand all the economic aspects of electricity marketing. Readers are referred to Pindyck and Rubinfeld (1997) at the undergraduate level or Luenberger (1995) at the graduate level for more details. Later in this chapter, we summarize the history of the development of electricity markets.

1.1 Demand and Supply

In a modern society, people everywhere participate in markets by creating demands and buying commercial products. Every buyer exerts preferences by buying certain products. As a result, the total demand for a product is determined by the preferences of consumers. Another important (and obvious) factor that affects total product demand is price. When studying demand functions, we often view demand for a product strictly as a function of price.

As an example, we denote electrical power demand as $P(\rho)$; ρ represents the price of power. It makes perfect sense to assume that the power demand function $P(\rho)$ decreases monotonically, as Figure 1.1 shows.

In subsequent text we often mention the concept of the inverse demand function $\rho(P)$. Figure 1.2 depicts a typical inverse demand function. On the other side of a market, the behaviors of suppliers can be described using a supply function that shows the relationship of price and quantity supplied (Figure 1.3).

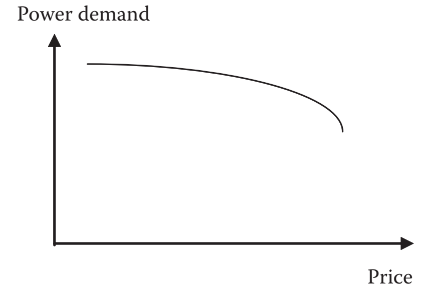

Figure 1.1 Relationship between demand and price.

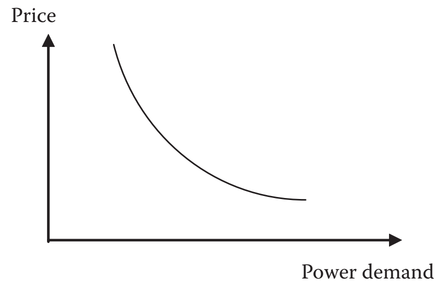

Figure 1.2 Typical inverse demand function.

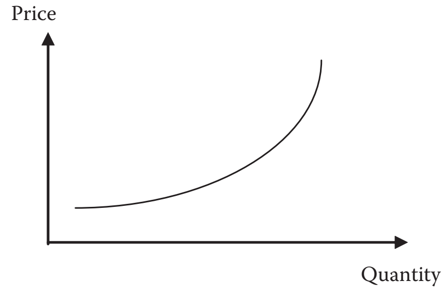

Figure 1.3 Relationship of price and quantity supplied.

1.2 Market Equilibrium

The concept of market equilibrium is central to microeconomics. Figure 1.4 shows an equilibrium point at which the demand and supply curves meet (Figure 1.4). Point P denotes the market clearing price. If the market price is $P1 > P$, a surplus of supply exists. This surplus forces market suppliers to lower prices, pulling market prices back to the equilibrium point. When the market price equals $P2 < P$,

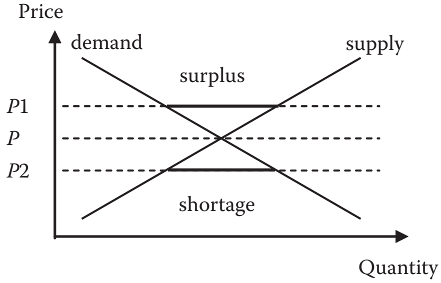

Figure 1.4 Supply and demand.

a supply shortage exists and causes suppliers to increase prices, pushing market prices back to the equilibrium point.

We explained that market surpluses and shortages stabilize market prices and act as "invisible hands" behind a free market. Furthermore, at the market equilibrium point, both demand and supply enjoy certain levels of surplus (Figure 1.5) for this reason. Since the market price is equal to *P*, certain consumers are willing to pay more than *P* (say, *P*1 > *P*). The area of the triangle above line *P* = 0 is a measure of demand surplus. Similarly, a supply surplus exists and the area of the triangle beneath the line *P* = 0 is a measure of supply surplus.

A government may regulate or intervene in a market by setting a price ceiling on a product. Let the price ceiling designated *P*2 (Figure 1.6) push the supply side to lower the production level to *Q*2. We can see from the figure that the demand surplus varies by the area A – B while the supply surplus varies by –A – C. The end result of this regulation policy is that social welfare is decreased by the area B + C. A standard term for this inefficiency caused by government regulation is *deadweight loss*.

What if the government sets a minimum price instead of a price ceiling? Let the minimum price level be *P*1. As a result of government intervention, the demand drops to *Q*1 (Figure 1.7). It can be seen that the demand surplus varies by –A – B,

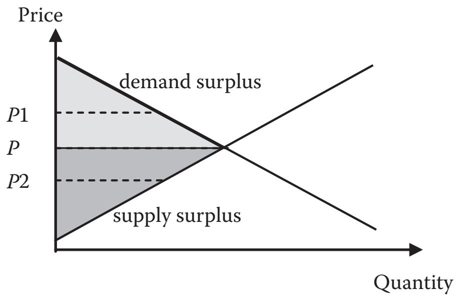

Figure 1.5 Demand surplus and supply surplus.

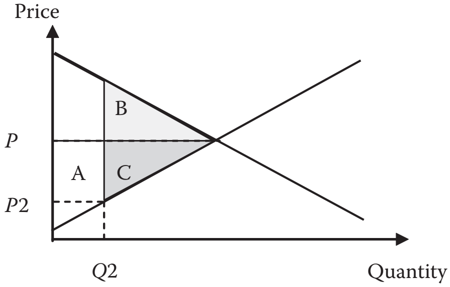

Figure 1.6 Setting a price ceiling on a product.

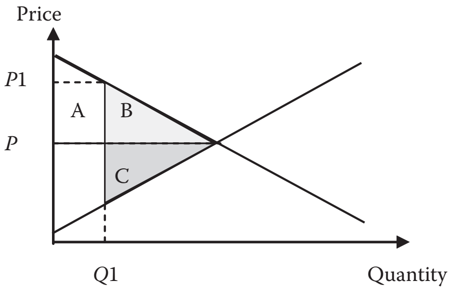

Figure 1.7 Setting a minimum price on a product.

while the supply surplus varies by A – C. The end result is also unsatisfactory: social welfare is lowered by B + C. This equilibrium analysis shows that government intervention (the "visible hand") usually introduces a social welfare loss, but this assertion may not apply to all markets.

1.3 Price Elasticity and Competitive Markets

The familiar concept of demand elasticity has a precise mathematical definition:

$$\varepsilon(\rho) = \frac{\rho}{P}\frac{dP}{d\rho} \tag{1.1}$$

We are not very interested in the specific quantity of demand elasticity in this book; rather we are interested only in two extremes. At one extreme, the demand for a certain product can be very elastic to the price of the product. For such products, the inverse demand functions are horizontal, as shown in Figure 1.8.

Figure 1.8 Demand is very elastic to price.

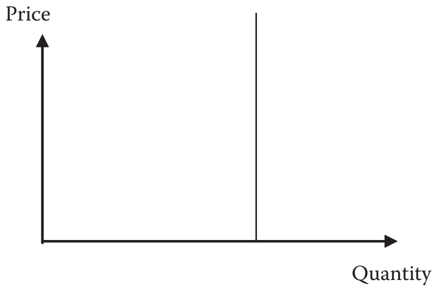

Figure 1.9 Demand is very inelastic to price.

At the other extreme, demand can be very inelastic to price. Examples of products in this category include food, clothing, and, of course, electricity. The inverse demand functions for such products are vertical (Figure 1.9). In this book we are mainly concerned with inverse demand functions.

A commercial product incurs costs for raw materials. A simple example is electricity generation that consumes gas, coal, or another form of primary energy. In general, the cost of a product is a function of the amount of raw materials required and the production quantity. Here we assume that the cost of a product is a function of production quantity only. In particular, the cost function of generating electricity is denoted as $c(P)$. The marginal cost of production is defined as dc/dP. Figure 1.10 depicts the production function.

Now we are in a position to introduce an important result of production theory: the *fundamental law of production*. Understandably, the objective of a firm is to maximize its profit. Suppose that the inverse demand function of a firm's product is $\rho(P)$. The profit maximization problem is formulated as

$$\underset{P}{Max} \qquad \pi(P) = v(P) - c(P) = \rho(P)P - c(P) \tag{1.2}$$

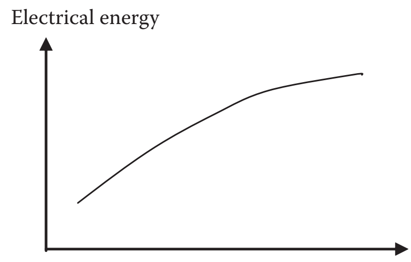

Figure 1.10 Production function.

where $v(P)$ is the return on the product. Differentiating with respect to P, we obtain:

$$\frac{dv}{dP} = \frac{dc}{dP} \tag{1.3}$$

which states that profit maximization is achieved when the marginal cost of a product is equal to its marginal profit. Notice that $v(P) = \rho(P)P$, so

$$\frac{dv}{dP} = \rho(P) + \frac{d\rho}{dP}P.$$

The fundamental law of production can be reformulated as

$$\rho(P) + \frac{d\rho}{dP}P = \frac{dc}{dP} \tag{1.4}$$

Recall the definition of price elasticity:

$$\varepsilon = \frac{\rho}{P}\frac{dP}{d\rho}.$$

Thus we have

$$\frac{d\rho}{dP} = \frac{\rho}{P\varepsilon}.$$

Substituting it into Equation 1.4, we find:

$$\rho = \frac{\frac{dc}{dP}}{\left(1 + \frac{1}{\varepsilon}\right)} \tag{1.5}$$

In general, $dP/d\rho < 0$, which implies $\varepsilon < 0$. Equation 1.5 points the way to a pricing strategy. If the price elasticity of a product is low, the corresponding price should be high; if the elasticity is high, the price should be low. This is the outcome we usually see in daily life. Now let us consider an idealized situation in which product elasticity is extremely high. Under such a situation, the inverse demand function $\rho(P)$ is a horizontal line, so $1/\varepsilon = 0$. As a result Equation 1.5 simplifies to

$$\rho = \frac{dc}{dP} \tag{1.6}$$

This indicates that the market of a company facing a horizontal inverse demand function is perfectly competitive because the product price equals the product marginal cost. Mainstream economists believe that such a market yields maximum social welfare. Mas-Colell et al. (1995) explained the fundamental theorem of welfare economics under mild conditions: "If the price and quantity of a market constitute a competitive equilibrium, then this allocation is Pareto optimal." We will later use a game-theoretic method to show that as the number of suppliers in a market approaches infinity, the market becomes perfectly competitive.

1.4 Economy of Scale and Natural Monopoly

A production function describes the relationship between the inputs and outputs of a firm or industry. Using a coal power plant as an example, let z be the coal consumption level, E denote the electrical energy produced, and $E(z)$ indicate the production function of the firm. Production functions generally increase monotonically.

We make two remarks here. First, it is often assumed that a firm or an industry always chooses the most economic means available to organize its production. For instance, a power company always uses an optimization solution to dispatch its units. The second remark about production function is relevant to our discussion because it concerns the scale and economics of production. If for any $t > 0$ and z, we have $E(tz) > tE(z)$, we say that the production enjoys economy of scale; the opposite function demonstrates diseconomy of scale (Figure 1.11).

We can also determine the scale property of a production function by looking at the marginal cost function. If a production function decreases monotonically,

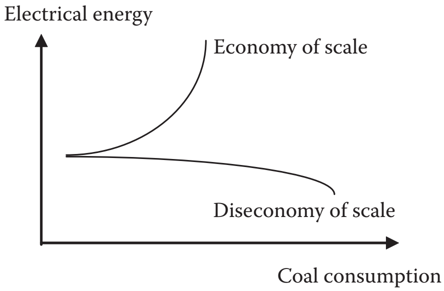

Figure 1.11 Economy of scale and diseconomy of scale.

the production exhibits economy of scale; if it increases monotonically, the reverse applies.

We conclude this part of the text with a fundamental concept of modern microeconomics: *an industry with economy of scale cannot achieve perfect competition using a market approach*. Such an industry is called a natural monopoly and invites government regulation.

1.5 Brief History of Electricity Markets

For a long period, economists believed that the electrical energy industry enjoyed an economy of scale and was thus considered a natural monopoly. In fact, the power industry faced and continues to face a nearly vertical demand. Government regulation had been applied and the industry operated in a centralized fashion using the common rate-of-return scheme.

Advances in generation technology changed the picture. In the early 1980s, the degree of economy of scale decreased to a level that competition on the generation side of the industry made sense. However, the transmission sector remains a natural monopoly worldwide. The following list summarizes important events in the development of electricity markets:

- 1978: The Public Utility Regulatory Policies Act (PURPA) was approved in the United States. It allowed non-utility generators to receive reasonable prices for energy they produced.
- 1982: Chile started running the first modern spot market. Fred Schweppe published a famous paper (Schweppe 1982) setting the foundation of nodal pricing now widely adopted in electricity markets.
- 1990: The United Kingdom established a pool-based electricity market that served many nations for many years as a market model.
- 1994: The Nordic electricity market started functioning and constituted the first multi-national spot market.

- 1996: Spot electricity markets appeared in Australia and New Zealand; California established a spot market based on zonal pricing—a coarse version of nodal pricing.
- 1998: A spot market was created in Pennsylvania, New Jersey, and Maryland and also served as a worldwide market model. Later, the New England region and New York State followed a similar market form.
- 2001: The United Kingdom completed a second market reform featuring bilateral contract-based free trading.

Looking into the future, the industry still faces many technical challenges. To mention just one, short-term electrical demand is still highly inelastic. An immediate consequence is the lack of an effective pricing system that introduces a fundamental limitation to the overall efficiency of electricity markets. Readers should read the three review articles (Green 2000; Joskow 1997; Sweet et al. 2002) listed in the reference section.

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Chapter 2

Fundamentals of Power System Operation

The physical constraints of modern power systems set electricity markets apart from other traditional markets. This chapter provides an overview of the basic operational concepts of power systems, such as load flow, spinning reserve, transmission capability, etc. The Karush–Kuhn–Tucker conditions are also introduced as the mathematical basis for analyzing the optimization problems in this book. Most of the materials covered in this chapter are standard and they can be found in the references at the end of this chapter.

Generally speaking, a real-time electricity market is indispensable for most electricity markets operating around the world. Therefore, to learn electricity market theory, we first should study the elementary theories of power system operation.

2.1 Economic Dispatch

The most important elements in a power system are generators that make use of the primary energy form coal, oil, gas, nuclear, or hydroelectric power. The costs for operating generators can be classified as fixed and variable. The operation of a power system should consider both kinds of costs. Generally, after a generator is commissioned, its fixed cost can be allocated to variable cost and engineers can devise generator cost curves. Let P_G denote the generator's output. Its cost curve can be expressed by using function $c(P_G)$.