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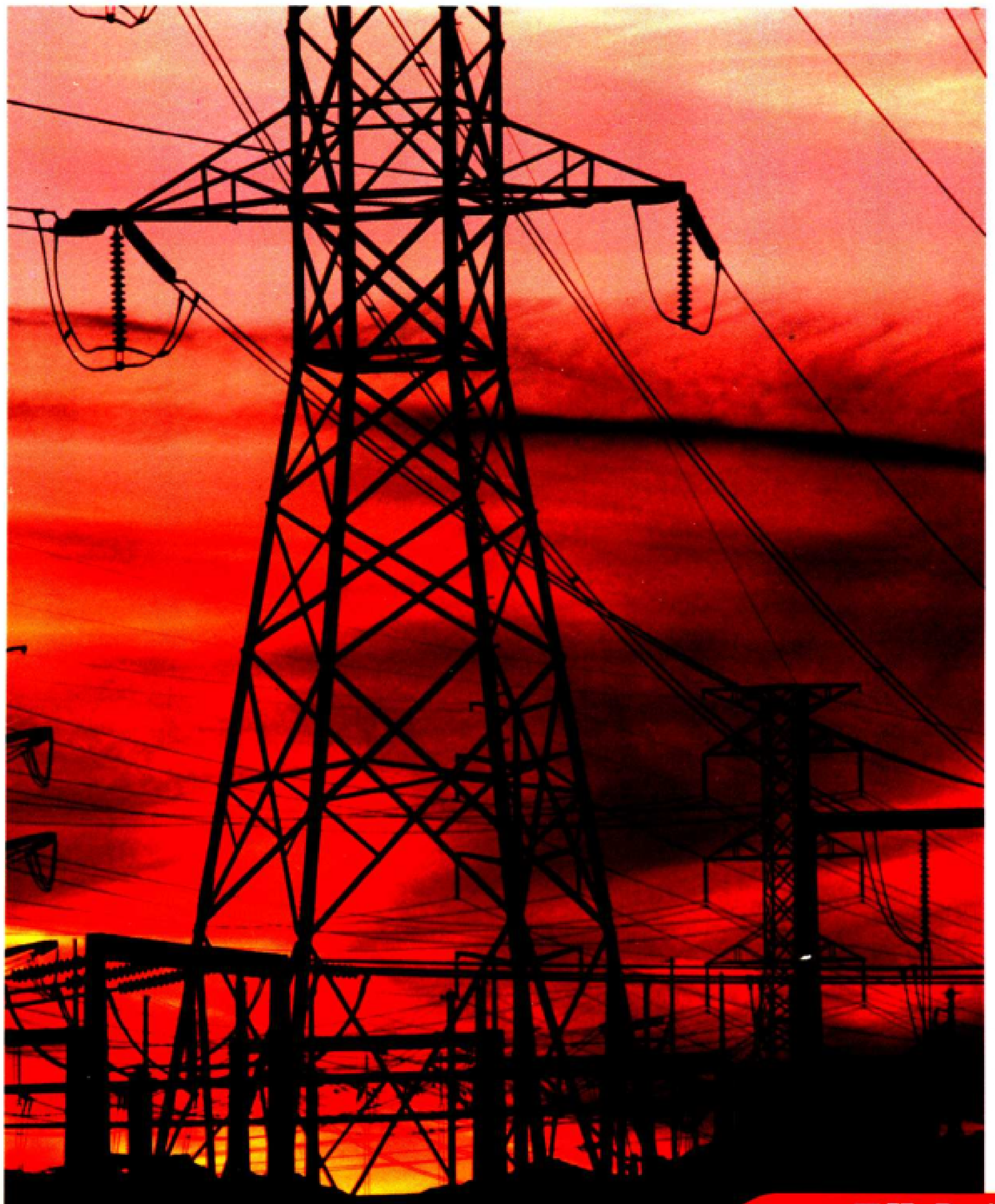

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加州大学伯克利分校
威杰 · 威塔尔
艾奥瓦州立大学
（美） 著

机械工业出版社
China Machine Press

电力系统分析

（英文版 · 第2版）

本书是加州大学伯克利分校电力系统分析课程教材，为国外许多学校采用。书中全面介绍了电力系统的分析和设计方法以及相应的运行实践，其中特别强调了这一领域的业界实践及计算机应用。内容包括：电力系统的背景和基本概念、输电线路的建模、发电机建模、电力潮流分析、电力系统保护、电力系统稳定性等。书中的每一章都给出了大量的示例和习题。其中从第3章开始，提供了一个贯穿全书的设计问题，这个设计问题是面向计算机的，学生可以使用现有的软件或使用MATLAB自行开发软件来逐步求解。通过求解该问题，学生将对有关电力系统工程的广泛主题有清楚的认识，特别是可以借助计算机充分地理解电力系统的基本理论和方法，并得到相应的训练。

本书可作为高等院校相关专业的教材，也可供从事电力系统工作的工程技术人员参考。

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ISBN 7-111-15916-0
9 787111 159162

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读者服务热线：(010) 68995259 68995264
读者服务信箱：hzedu@hzbook.com
ISBN 7-111-15916-0/TM.1342
定价：59.00元

经 典 原 版 书 库

电力系统分析

(英文版 · 第2版)

江苏工业学院图书馆
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加州大学伯克利分校
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机械工业出版社
China Machine Press

English reprint edition copyright © 2005 by Pearson Education Asia Limited and China Machine Press.

Original English language title: *Power Systems Analysis, Second Edition* (ISBN 0-13-691990-1) by Arthur R. Bergen and Vijay Vittal, Copyright © 1986, 2000.

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Published by arrangement with the original publisher, Pearson Education, Inc., publishing as Prentice Hall.

For sale and distribution in the People's Republic of China exclusively (except Taiwan, Hong Kong SAR and Macau SAR).

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本书版权登记号：图字：01-2005-1177

图书在版编目（CIP）数据

电力系统分析（英文版·第2版）/（美）伯尔根（Bergen, A. R.）等著. -北京：机械工业出版社，2005.4

（经典原版书库）

书名原文：Power Systems Analysis, Second Edition

ISBN 7-111-15916-0

Ⅰ.电… Ⅱ.伯… Ⅲ.电力系统-分析-英文 Ⅳ.TM711

中国版本图书馆CIP数据核字（2004）第141022号

机械工业出版社（北京市西城区百万庄大街22号　邮政编码　100037）

责任编辑：迟振春

北京牛山世兴印刷厂印刷·新华书店北京发行所发行

2005年4月第1版第1次印刷

787mm × 1092mm　1/16 · 39.5印张

印数：0 001- 3 000册

定价：59.00元

凡购本书，如有缺页、倒页、脱页，由本社发行部调换

本社购书热线：（010）68326294

前言（第2版）

自从本书第1版于1986年出版以来，许多情况发生了变化。美国的电力工业在其结构及运行实践方面经历了较大的变化。在美国的许多地区，垄断的和垂直管理一体化的公用事业体制正在被（部分）非管制性的多层次性体制所替代，这种新体制向竞争和其他市场驱动力是开放的。第2版包含的材料反映了这些变化，并论及了新的环境问题。

此外，本书还包含了使用本书第1版的教授和学生们所提出的若干有创见性的建议。尽管新版仍注重基础知识，但其中特别强调了这一领域的业界实践及计算机应用。

在第2版的许多变化中，包含如下内容：章的次序已重新排列，以便教材的内容能更系统地展开。从制造商那里取得的确定输电线路参数表的内容已作为新的一节放入第3章中。在该章里，还提供了更为完善和准确的关于输电线路具有接地回路的阻抗参数。第9章是关于网络矩阵全新的一章，包括矩阵分解及其在矩阵求逆中的应用，还包含了决定阻抗矩阵必要元素的现代方法。第10章对有关电力潮流计算进行了扩展，讲述了实际限制条件下所必需的修正。在第11章中，介绍了用于当代电力系统运行控制的一些新思路。关于不平衡系统运行和故障分析的第12章已作了相当大的修订，描述业界实践的新资料。

第2版的突出特点之一是一个贯穿全书的设计问题，首先在第3章中作了介绍，并在后续的每一章介绍有关新概念时继续展开。设计问题是面向计算机的；学生可以使用现成的软件，或者可以利用MATLAB来开发软件。这些设计例子是互相关联的，非常适用于分组项目。

本教材的内容在扩充后需要两个学期讲述。但是如果没有那么多的教学时间，也可以采用其他的教学方式。第7、8章和第11章可以省略而不致严重影响其余内容的连贯性。对于已有能量转换和电机知识背景的学生，则第1章、第2章、第5章的第一部分以及第6章可以跳过。如果时间很紧，则第10章以及第11、12、13、14章末尾的许多材料可以省略，不会影响教学连续性。

我们衷心感谢下列对本书提出宝贵建议和意见的审阅者：得克萨斯A&M大学的Ali Abur教授、佐治亚理工学院的Miroslav Begovic教授、爱达荷大学的Brian K. Johnson教授、弗吉尼亚综合工学院暨州立大学的Arun G. Phadke教授。

我们还要感谢许多对本书内容作出贡献的学者，其中尤其要感谢我们的同事：M. A. Pai、S. S. Venkata、G. B. Sheblé、K. C. Kruempel以及J. D. McCalley，感谢他们的忠告和意见。此外，还要感谢我们的学生，他们帮助开发了一些新的例子。

最后，我们要对Sunanda Vittal女士表示诚挚的谢意，她对本书进行了仔细的校对。

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CHAPTER 1

Background

1.0 INTRODUCTION

In this chapter we give a simplified description of a power system. The system consists of power sources, called *generating plants (or generators),* power end users, called *loads,* and a transmission and distribution network that connects them. Most commonly the generating plants convert energy from fossil or nuclear fuels, or from falling water, into electrical energy.

1.1 ELECTRIC ENERGY

Electricity is only one of many forms of energy used in industry, homes, businesses, and transportation. It has many desirable features; it is clean (particularly at the point of use), convenient, relatively easy to transfer from point of source to point of use, and highly flexible in its use. In some cases it is an irreplaceable source of energy.

Figure 1.1 is a useful summary of electric energy sources and their transition to end uses for the United States in 1996. The basic energy sources are shown on the left. The end uses of the electricity are shown on the right. Only about one-third of the resource energy is converted into electricity; about two-thirds is lost as "waste heat." In some cases this heat is not wasted. It can be used for heating homes and offices or for some industrial processes.

In Figure 1.1, the T & D losses are transmission and distribution losses (almost 10% of the net generation of electricity). Also, note the significant amount of nonutility energy generated in 1996. Changes in government energy policy have encouraged this growth. In the period from 1990 to 1995, nonutility power generation grew by 47%.

Figure 1.2 provides more detail regarding the major sources of utility-generated electrical energy and some trends in their relative importance. It can be seen that most of the production has been in conventional steam plants. *Conventional steam* refers to steam generation by burning coal, petroleum, or gas. In 1996 approximately 3000 billion kilowatthours of electricity were produced. Of this, coal

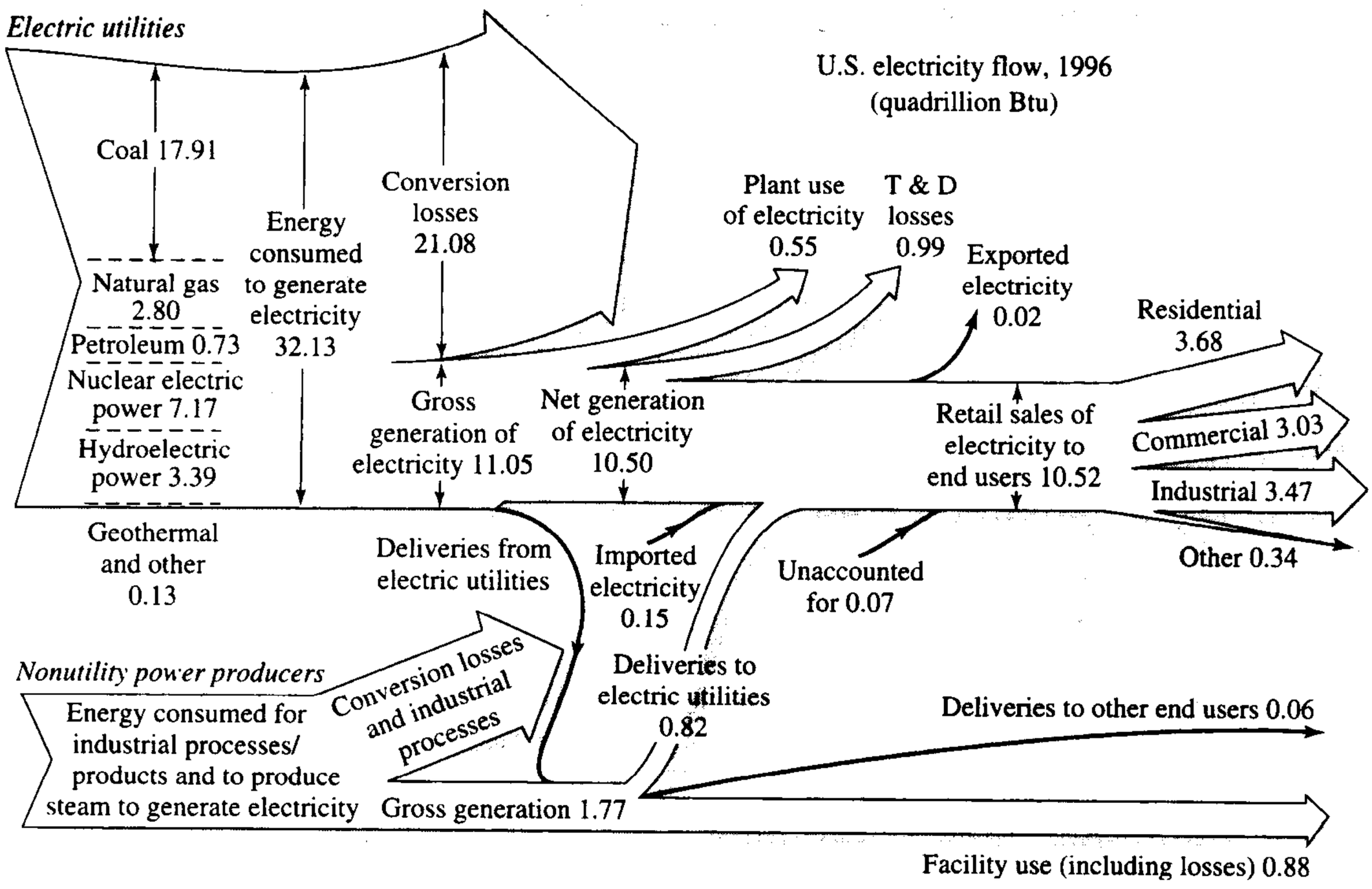

Figure 1.1 U.S. electricity supply and demand. (From *Annual Energy Review 1996*, U.S. Department of Energy.)

accounted for approximately 56%, petroleum 2%, natural gas 8% (totaling 66% for conventional steam), hydropower 11%, nuclear power 22%, and others, including gas turbines, about 2%. Note that nuclear and geothermal power plants also generate steam but not by burning fossil fuels.

The units used in Figure 1.1 are quadrillion Btu (10^{15}, or quads), while those in Figure 1.2 are in billion kilowatthours (or 10^9 watthours or gigawatthours). In attempting to align the figures, we can use the conversion factor 1 watt = 3.413 Btu/hr.

Turning to the growth in utility electricity production, we see in Figure 1.2 an almost exponential growth rate until about 1973. Until that time electricity use doubled every 10 years or so. Subsequently, the growth rate dropped, at first reflecting the general slowdown of worldwide economic growth precipitated in large part by the oil crisis of 1973 and later by an increasing awareness of the cost-effectiveness of energy conservation.

Figure 1.3 shows the growth in installed utility-generating capability in the United States. In 1996, of the total installed generating capability of approximately 710 million kilowatts, some 63% was conventional (fossil fuel) steam, 14% was hydropower, 14% was nuclear, 8% was gas turbine, and others totaled about 1%. Comparing these with the production figures given earlier, we see great differences in the utilization rates of the various sources. Nuclear power has the highest rate. Gas

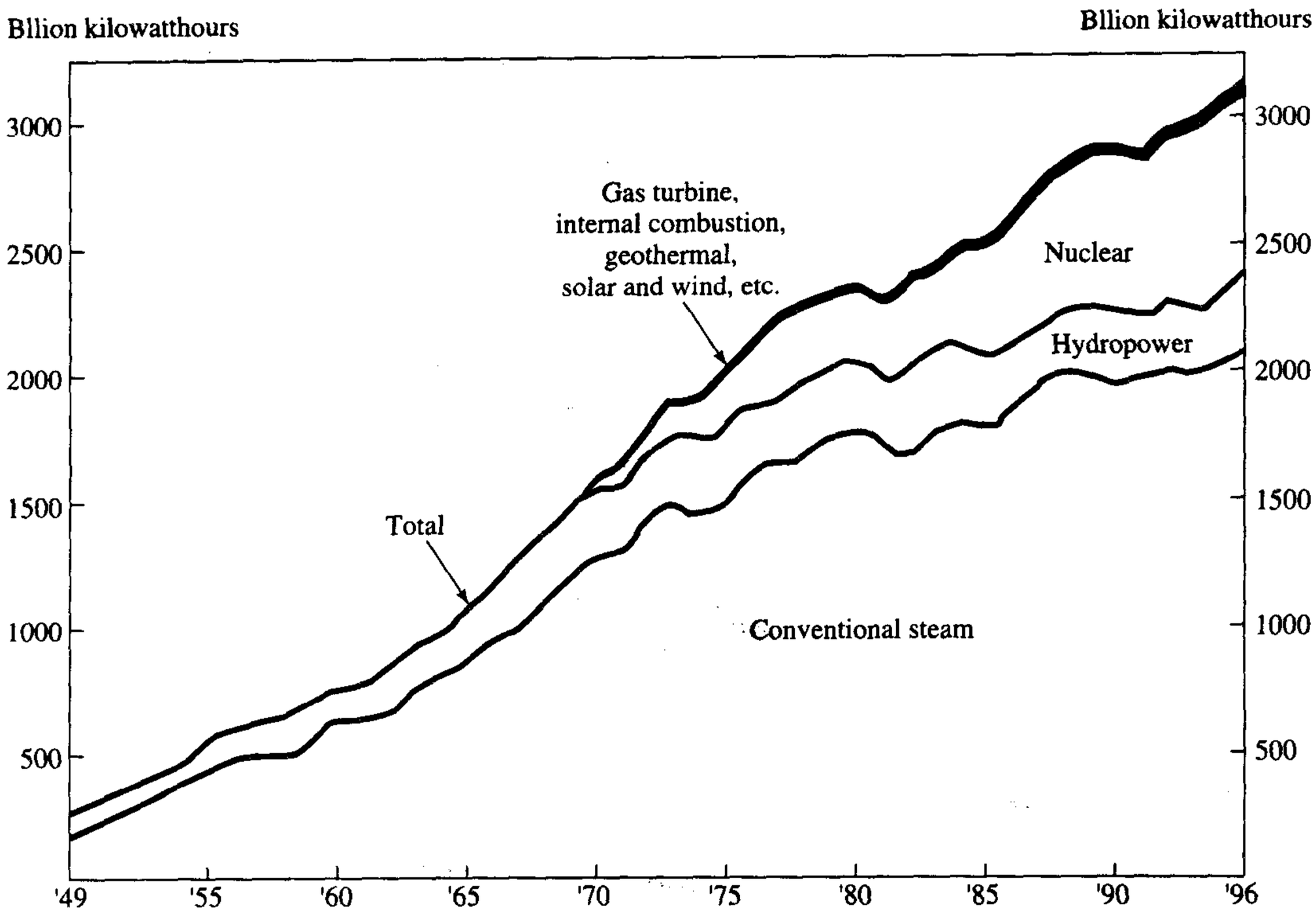

Figure 1.2 Electric utility energy production (United States). (From *Annual Energy Review 1996*, U.S. Department of Energy.)

turbines and internal combustion engines are among the lowest in the rate of utilization. We will discuss the reasons in a moment.

First, it is interesting to calculate an overall utilization factor for 1996. Suppose that it had been possible to utilize the 710 million kilowatt capability full time. Then the plants would have produced $710 \times 10^9 \times 8760 = 6220 \times 10^{12}$ watthours in 1996. They actually produced 3078×10^{12} watthours. Thus the annual capability factor or load factor was $3078/6220 = 0.49$ or 49%. Why isn't the figure higher?

There are two main reasons. The first is that generating units are not always available for service. There is downtime because of maintenance and other scheduled outages; there are also forced outages because of equipment failures. The availability of fossil-fuel steam turbine units ranges from about 80% to about 92%.

The second reason involves a characteristic of the load. While there must be enough generating capability available to meet the requirements of the peak-load demand, the load is variable, with daily, weekly, and seasonal variations, and thus has a lower average value. The daily variations are roughly cyclic with a minimum value (the *base load*) typically less than one-half of the peak value. A typical daily load curve for a utility is shown in Figure 1.4. The (weekly) capability factor for this particular utility is seen to be approximately 65%.

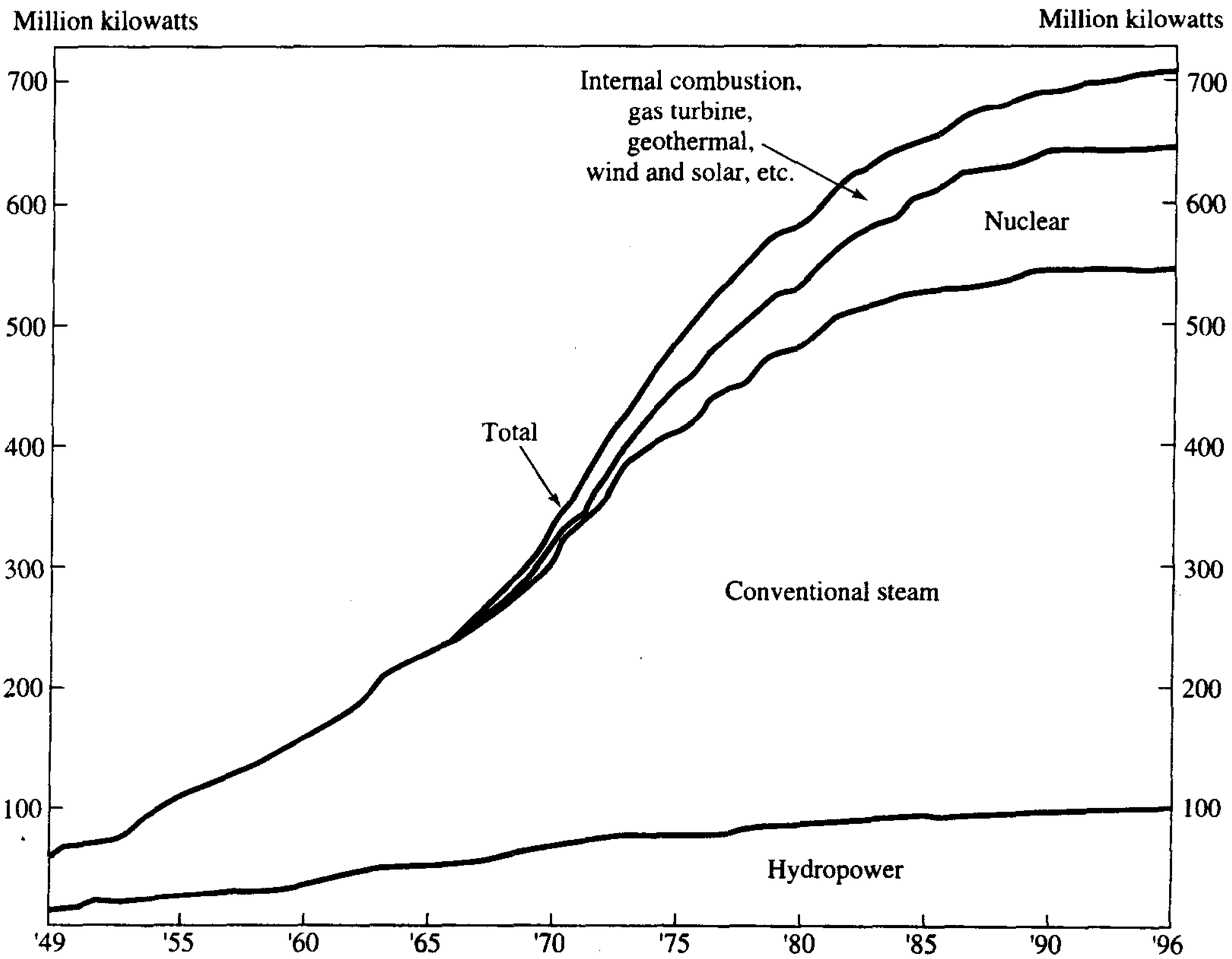

Figure 1.3 Electric utility generating capability in the United States in the summer. (From *Annual Energy Review, 1996*, U.S. Department of Energy.)

In meeting the varying load requirements, economic considerations make it desirable to utilize plants fully with low (incremental) fuel costs while avoiding the use of plants with high fuel costs. This, in part, explains the use of nuclear plants for base-load service and gas turbines for peaking-power service; the different rates of utilization of these sources were noted earlier.

Finally, it is interesting to reduce the enormous numbers describing production and generating capability to human terms. In 1996 the U.S. population was

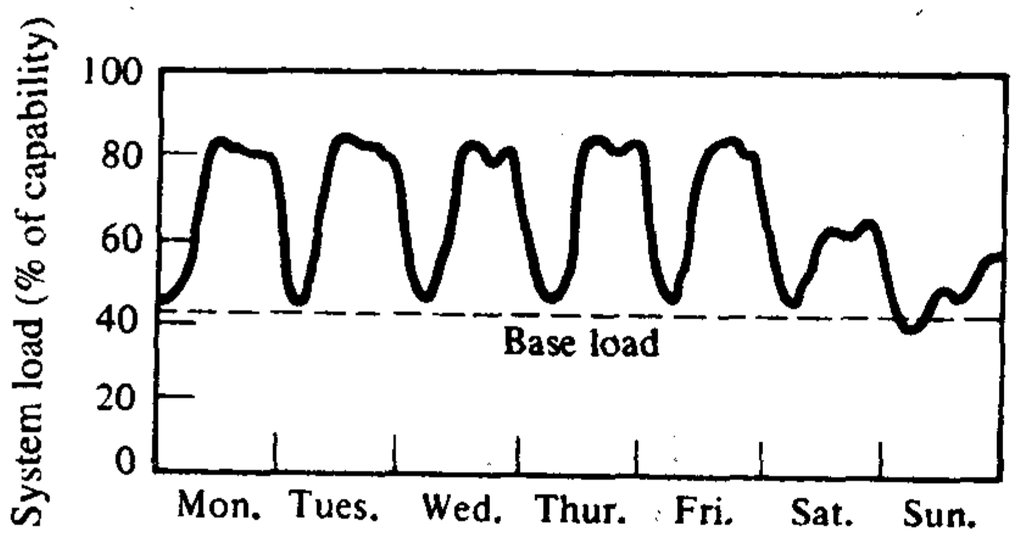

Figure 1.4 Daily load output (typical week).

approximately 265 million. Thus, there was a generating capability of approximately 710/265 = 2.68 kW per person. Using the figure 0.49 for the capability (or load) factor, this translates into an average use of energy at the rate 1.3 kW per person. The latter figure is easy to remember and gives an appreciation of the rate of electricity consumption in the United States.

In the next few sections we consider some typical power plant sources of energy: fossil-fuel steam plants, nuclear plants, and hydroelectric plants. Space does not permit a detailed physical description. For more details, see a standard reference such as the *McGraw-Hill Encyclopedia of Energy*. The Web site www.powerlearn.ee.iastate.edu offers pictures of various items of power equipment. If you can arrange it, there is nothing better than a visit to a power plant.

1.2 FOSSIL-FUEL PLANT

In a fossil-fuel plant, coal, oil, or natural gas is burned in a furnace. The combustion produces hot water, which is converted to steam, and the steam drives a turbine, which is mechanically coupled to an electric generator. A schematic diagram of a typical coal-fired plant is shown in Figure 1.5. In brief, the operation of the plant is as follows: Coal is taken from storage and fed to a pulverizer (or mill), mixed with preheated air, and blown into the furnace, where it is burned.

The furnace contains a complex of tubes and drums, called a *boiler*, through which water is pumped; the temperature of the water rises in the process until the

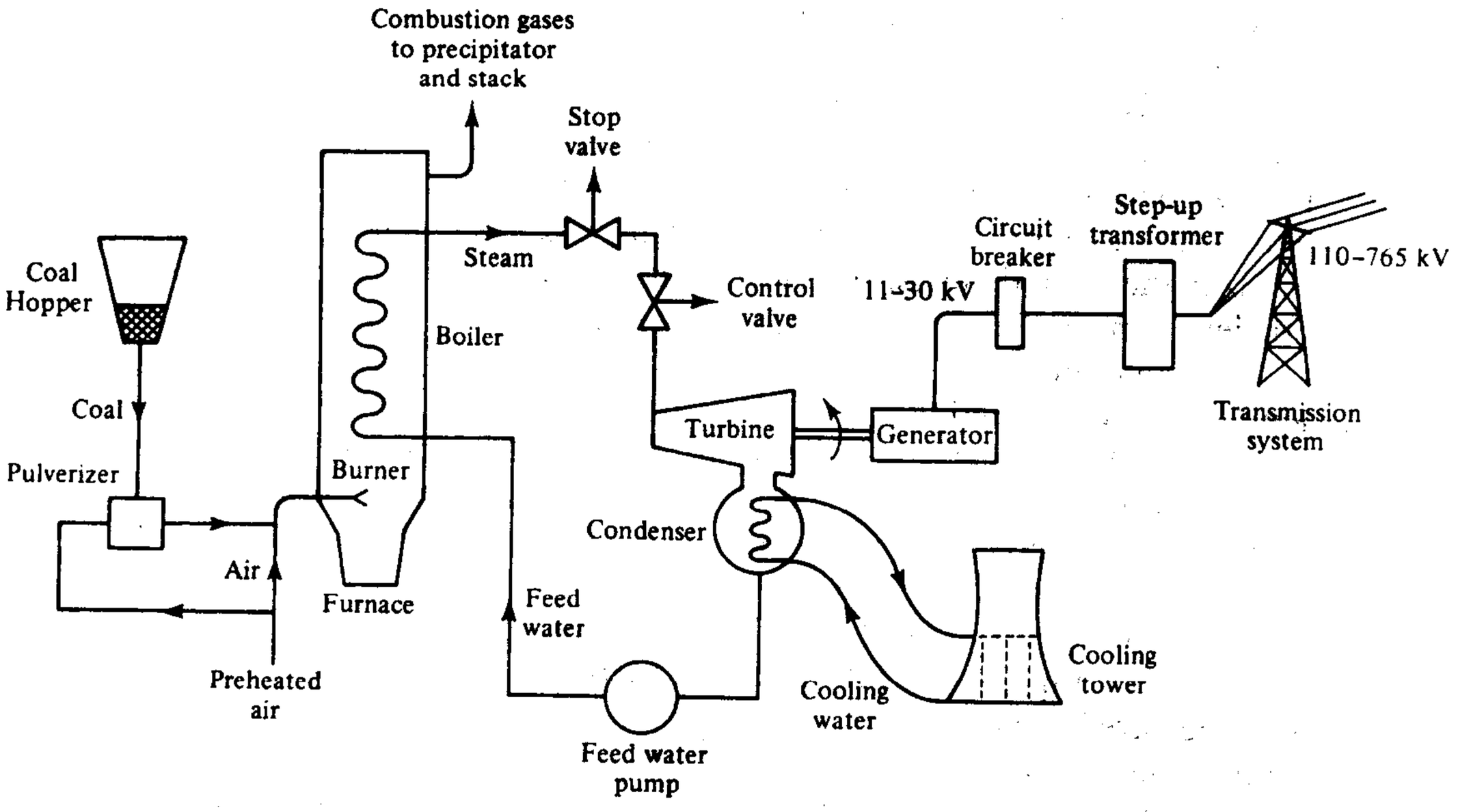

Figure 1.5 Coal-fired power station (schematic).

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