Energy Cogeneration Handbook

Criteria for Central Plant Design

Design criteria for central plants that facilitate energy conversion, utilization, and conservation; an evaluation of project alternatives and an examination of systems and their functions to achieve optimum overall design in the generation of heating, cooling, and electricity.

by

GEORGE POLIMEROS

INDUSTRIAL PRESS INC.
200 Madison Avenue, New York, N.Y. 10157

Library of Congress Cataloging in Publication Data

Polimeros, George.
Energy cogeneration handbook.

Includes bibliographies and index.
1. Cogeneration of electric power and heat.
I. Title.
TK1041.P64 1981 621.1′9 80-27186
ISBN 0-8311-1130-5

Second Printing

ENERGY COGENERATION HANDBOOK

Energy Cogeneration Handbook

Foreword

George Polimeros, a native of Greece, earned his Bachelor's and Master's degrees in Mechanical Engineering in the United States. I first met him in the late 1950s when we both worked for the same HVAC consulting firm. Since then, we have collaborated on several major engineering projects, principally dealing with industrial refrigeration. Knowing him for as long as I have and working with him on those projects, I can appreciate his intelligence and technical competance.

For the past 10 years George devoted most of his free time to preparing this handbook, drawing on his many years of engineering experience to offer the reader an array of new and useful information on energy cogeneration—a most important field in this age of energy shortages and increased energy cost.

When the manuscript was first sent to Industrial Press for publication, they recognized it as an important contribution to the energy engineering field, and, to confirm this impression, they asked me to read the preliminary manuscript; my view completely concurred with theirs.

Unfortunately, in the fall of 1979, before he could see his work in print, George Polimeros died. I was asked by his widow, Demetra, to assist Industrial Press in bringing this book to fruition. I accepted since I was delighted to be involved in a book that would surely be a valuable contribution to the cogeneration literature.

In life, George thoroughly enjoyed teaching young engineers the fine points of the "trade." His book will perpetuate this effort to benefit the whole profession.

Harrison D. Goodman
New York, 1980

Preface

As the energy crisis emerged in recent years, many conflicting explanations and proposed solutions were attempted, but from the outset it was clear that whatever mix of ideas was adopted, Conservation, the more efficient use of energy, would be central. As potential savings associated with a variety of conservation measures were better understood, it became apparent that cogeneration was a very attractive option and opened a rich and complex field for exploration. (A cogeneration plant is designed to capture waste heat that usually escapes to the atmosphere. This waste heat is then used to generate additional energy, process steam, etc.) This book deals with energy conversion, utilization and conservation. It attempts to gauge the experience of the last thirty years in central plant design and suggests how we may improve on past experience. It emphasizes the proper application of criteria as a means of controlling initial and operating costs and securing satisfactory plant operation that fulfills its main design objectives. Its general philosophy is to promote central plants, thus discouraging disorganized and inefficient utilization of energy at various dispersed, smaller plants.

Conservation of energy presupposes full knowledge of the critical plant processes as a basis for intelligent use of energy. The objective of the subject matter and its arrangement is to acquaint the reader with the critical aspects of the plant and its various systems and to study prime equipment arrangement and modes of operation and service for maximum performance at minimum cost. The purpose of this text is not merely to describe equipment but rather to explain the dynamic relationship between combinations of various pieces of equipment and how these dynamics actually affect plant performance.

How attractive and viable is the central plant approach in our future? Unfortunately, the current energy production and distribution system is not geared to the exigencies of energy shortages. A good percentage of our national energy is rejected through cooling towers. The central plant is coming to the forefront because it is capable of plant efficiencies as high as 65-75%, compared to the usual 32-35% of the public utilities, provided there is constant demand for its services. The central plant can offer its energy at substantially lower rates and first costs. Therefore, this is an area of huge potential for profits for the investor and savings for the consumer and is a meeting point for both groups. The central plant concept, which incorporates the concept of cogeneration as it is currently known, is being promoted by the government through tax credits because it is conducive to energy conservation and can reach into areas that the public utilities do not. *Power* magazine, among others, says that central plants will fill the blank spaces in the electrical distribution networks. Central plants have the advantage of flexibility, the ability to serve their surrounding communities in complete harmony with their needs. In addition to electricity, which is the only product of the utility plant, central plants can provide chilled and hot water, steam and, in some cases, domestic hot water and can interface with local industries by absorbing or transmitting energy to industrial processes. Local economies will benefit by creation of jobs in the central plants and by additional employment in supporting industries and in in manufacturing plants producing equipment for central plants.

What kind of legal framework can aid construction of central plants? The recent passage of the National Energy

Act (NEA) constitutes the basic legal foundation. It is difficult to predict the exact form that the implementation and approval procedures will take. However, State or, preferably, local commissions will be necessary to license the construction of plants after ascertaining their economic viability. As part of their work, the commissions will supervise plant activities and rate structure and will create the legal basis for electrical interconnections between utility networks and central plants. Central plants will then be able not only to generate their own commodities but to exchange them with anyone, including the utility, to improve load factor and dispose of excess capacity. Chapter 2 explains the rationale for the central plant and points out that engineering and management techniques can be employed to optimize energy use, promote safety, effect economies, recapture waste heat and protect the environment. The provisions of NEA pertain not only to space heating but to industrial applications as well.

The applications of this book lie in several areas:

1. Large, single buildings where some people live and work.
2. Institutional or civic complexes such as campuses, hospitals, airports, government offices, shopping centers, apartment house complexes and military bases.
3. New cities, where the plant itself and all piping and underground cables can be incorporated into the master plan. A prototype of this application is the new town of Reston, Virginia.
4. Old cities, involving a combination of community facilities. Digging up streets in an old city is an expensive affair, since interference with other utilities may be expected and a thorough analysis of underground obstacles and cost factors is required.
5. Downtown commercial districts, composed mainly of large office buildings and department stores. A perfect example of that can be seen in Hartford, Connecticut.
6. A combination of residential, commercial and industrial uses, where the probability of obtaining a more constant load factor and balanced load is improved.
7. Industrial establishments where heavy refrigeration, large boiler installations and electric generation facilities prevail such as breweries, pharmaceutical plants, paper mills, etc.
8. Industrial complexes where interchange of energy between the various units of the complex is feasible and profitable. Undoubtedly this area constitutes the main arena for industrial cogeneration.
9. Chemical and petrochemical industries where, in some plants, central cooling is already being practiced.
10. Some heat-producing industries where energy conservation has not been prevalent in the past. Among industries having considerable potential are steel, copper, aluminum, glass, synthetic rubber, textiles, the food industries, selected plastics and paper. A fine example is the hot water district heating system of Bellingham, Wash., which derives its energy from the exhaust gases of the nearby Intalco Co. aluminum plant.

What kind of subject matter does this book examine and how does it treat this material?

A great deal of information on central plants has been published in many magazines, much of it contradictory and dated. Many of the systems discussed in this book have been in existence for many years and some limited historical data are available. There are some books on district heating and, at least, one on aspects of total energy. However, for the first time, an attempt is being made here to deal comprehensively with central plant activities, be they heating, cooling generation or process, from an engineering and design point of view. The aim is to intergrate certain aspects of what we know about the central plant and equipment with practical experience into useful design approaches and to examine various design and engineering philosophies to stimulate original solutions. No step-by-step plant design procedure is attempted. There are literally hundreds of plant designs; any effort to cover all possible combinations would be inadequate and, in the final analysis, counterproductive.

The economic aspects of cogeneration plants are not being examined for five plausible reasons. First, up to November, 1978 (National Energy Act), it was illegal to tie into the local electrical network for the purpose of selling electricity. The financial aspects of cogeneration are not on record yet. Second, the high rate of inflation and the rapidly-changing relationship between material and labor costs invalidates financial conclusions and data very quickly. The third reason is that our economy is designed around fossil fuels of uncertain availability and whose price structures are unpredictable. A fourth reason, although not of primary importance, is that most plants belong to the one-of-a-kind category and are designed on a tailored basis to fit particular conditions and to accommodate predetermined performance and efficiency limits. Data derived from one plant may not be entirely applicable to another. Lastly, cogeneration has diminished from 20% of our total electric output in the 1930s to the current 5%. This experience has not been systematically gathered, is of limited nature, and is historically dated. However, a number of short economic analyses are carried out for specific applications.

Here criteria are stressed. Subject matter, project alternatives and examination of systems and functions are consistently evaluated in the text. The details of boilers, cooling towers, pumps, absorption machines, condensers and other equipment are thus not discussed since adequate literature abounds.

Setting up criteria and parameters of a project is very difficult for most people. Most textbooks avoid this most critical area, which is precisely the area we stress here. The main concern of the central plant engineer is to design a workable plant based on sound criteria and concepts and to make the plant operationally attractive. Therefore, we concentrate on criteria for basic system design and primary equipment selection and examine those factors which affect plant efficiency. We embrace this point of view as a practical means to an effective plant. Because properly specified controls, pumping systems, equipment arrangement and drives contribute so importantly to a well-conceived plant, we deemed these subjects each worthy of a chapter.

These are some of the key subjects that we will examine:

1. *Quick energy estimating* data for preliminary load and equipment sizing have been assembled from many sources.
2. The pros and cons of *steam versus hot water,* with all related criteria, so that a balanced decision between them can be arrived at.
3. *Economical use of coolants or heating media.* Temperature and velocity parameters, control philosophy, thermodynamic advantages of hot and chilled water or steam are examined, so that one may find quickly what is good practice.
4. *Energy conservation and heat recovery* opportunities in a central plant are examined in some detail.
5. *Chiller arrangement*, which has a very important effect on energy conservation, is amply discussed.
6. *Power cycles* of all descriptions. Special emphasis is placed on combined cycles and their importance to energy conservation. Combination centrifugal-absorption machine cycles are studied from many points of view.
7. *Heat balance* techniques are elaborated in detail and a step-by-step method is worked out for an industrial plant-district heating combination.
8. *Prime movers* receive attention because they can affect plant efficiency adversely when improperly selected. Quick-estimating turbine performance curves are given that serve most preliminary design purposes. Variable-speed drives are examined from the standpoint of improving system hydraulic performance. Industrial gas turbines and their critically important role in heat recovery are are analyzed.
9. *Controls* for major equipment and plant processes are examined extensively as the key to good plant performance. Items such as compressor surge and efficiency are dealt with as are the complexities of hot gas bypass. The role of plant automation and computer programs in plant operation and their benefits are surveyed.
10. *Pumping systems* of all descriptions are examined as part of an effective equipment arrangement and the main means of successful energy delivery. The interaction of the various components of the pumping system is looked at carefully from the standpoint of system stability.
11. *Distribution systems* are the delivery arms of the pumping systems. Hydraulic circuit performance of various types are analyzed.
12. *Waste disposal* as a source of energy and its significance in the power picture are examined.
13. *Organic Rankine cycles* are surveyed to determine their current and future potential in central plants.
14. *Pressurizers* and water expansion of chilled water and particularly high temperature water systems are analyzed.
15. *A bibliography* at the end of each chapter enables the reader to look further into various aspects of each subject.

The West Germans are creating a central national heating network tied to their nuclear generating plants. On the other hand, some engineering firms, mostly Canadian, propose to utilize purchased electricity and local heat pumps in connection with chillers, and solar energy where applicable, to achieve energy efficiency. Undoubtedly this approach has its applications, with some limitations to large projects. The main objections are that self-generated electricity is ordinarily cheaper than purchased and that substantial uses must exist in the summer for the heat generated by the heat pump. In addition, heat pumps have climatic limitations and because they cannot produce process steam, do not easily fit industrial heat recovery into their arrangement. However, the U.S. Department of Energy has recently let out contracts for the incorporation of the heat pump concept into central plants, using various working fluids and steam as a source. The flexibility of the central plant in accommodating the needs for electric generation, industrial process steam, building facilities and industrial heat recovery, give the central plant concept a wider range of application and acceptability. Of course, all proposals, including the central plant, must be proven economically justifiable.

This book will be of interest to a number of people of diverse technical interests and levels. However, it is written principally for professionals rather than as a textbook or primer, but is certainly full of information for the serious student of plant cogeneration.

The author would like to express his appreciation to the many publishing, manufacturing and other organizations who gave permission to use graphs and other items, and to the librarians of the United Engineering Center, New York for their helpfulness. The following companies have provided assistance in various forms: American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE); *ASHRAE Journal; Building Systems Design* magazine; Carrier Corp.; Cleaver-Brooks Div. of Aqud-Chem. Inc., Cosentini Associates; Electric Machinery Mfg. Company; Elliott Company, Division Carrier Corp.; Gas Turbine Publications, Inc.; General Electric Company; *Heating/Piping/Air Conditioning* magazine; International District Heating Association; Johns-Mansville Corp.; John Wiley & Sons, Inc.; Kinetics Corp.; McGraw-Hill Book Company; National Climatic Service; *Plant Engineering* magazine; *Power* magazine; *Power Engineering* magazine; Solar Turbines International, an International Harvester Group; The Trane Company; Thermo Electron Corp; U.S. Electric Motors, Div. of Emerson Electric Company; Woodward Governor Company; York, Division of Borg-Warner Corp.

The author is indebted to Harland E. Rex and Harrison D. Goodman for reviewing the entire manuscript and offering helpful suggestions, to Kadir Karakus for checking heat balance and other calculations and wishes to thank, for various reasons, Patricia Flanagan, Charles Egbert, Thomas Blatner, Edward F. Doyle, Rohit Desai and Edward L. Von Stein. I wish to acknowledge the contributions of my editors, Richard Koral, William Semioli, and Maryanne Colas. The editing of Richard L. Koral improved the cohesion, clarity and arrangement of this book. I am especially indebted to my wife, Demetra, for the encouragement she offered and to my sons, Mark and Nicholas, for their patience over the years when I was unavailable to them.

George Polimeros
Brooklyn, N.Y.

Introduction

The recent emergence of the energy crisis gave rise to numerous and often conflicting explanations and proposed solutions. But from the very outset one thing was clear—whatever mix of solutions we adopted, conservation, which above all means the more efficient use of energy, would be central. And as the potential savings associated with a variety of conservation measures became better understood, it also became apparent that cogeneration was an especially attractive option.

The study of cogeneration opens a rich and complex world to exploration. Here, I would like to focus on how such a study offers a number of rewarding insights into three salient dimensions of the energy crisis. First, in cogeneration we have an example of a readily available conservation measure that can yield immediate and dramatic savings; it reminds us that conservation is a vast and untapped source of energy. Second, the recent experience of cogeneration in the United States confirms what some shrewd observers have known for some time—namely that in forging a new energy base the nontechnological problems would turn out to be the most difficult of all. And third, cogeneration points to the importance of placing each technology in the context of an overall energy system and incorporating "external" costs into decisions about the desirability of each technology.

If we have learned anything about energy in the past six years, it is surely that the past holds valuable lessons and that we should not count on quick technological fixes to resolve our problems. Consider the case of cogeneration, a proven technology dating back to the turn of the century.

In the early 1900s, some 58 percent of the total power that was produced by on-site industrial power plants was cogenerated.[1] By 1950, however, on-site industrial generation accounted for only 15 percent of total U.S. electrical generation; and by 1974 this figure had dropped to about 5 percent.

This dramatic decline may be attributed to a number of factors. Increasing regulation at both the state and federal levels over all forms of electrical generation, the extent to which most utilities discouraged the on-site generation of electricity, the tendency of industry to favor market-oriented over cost-cutting investments—all these contributed to cogeneration's decreasing role. But the most powerful force was that, increasingly, energy costs came to represent a declining percentage of industry's expenses. Indeed, between 1940 and 1950, the real price of electricity for industrial consumers was cut in half.[2]

The European experience has been very different. "Historically, industrial cogeneration has been five to six times more common in some parts of Europe than in the United States. . . ." In 1972, for example, "16 percent of West Germany's total power production was cogenerated by industries; in Italy, 18 percent; in France, 16 percent; and in the Netherlands, 10 percent."[3]

One factor accounting for the greater success of cogeneration in Europe was that prior to 1945 Europe did not have a utility grid system capable of supplying easily available and reliable power; another was that there were fewer regulations restricting the sale of electricity than in

[1] U.S. Department of Energy, *Cogeneration: Technical Concepts Trends Prospects*, September, 1978, p. 22.

[2] *Energy Future*, Report of the Energy Project at the Harvard Business School, edited by Robert Stobaugh and Daniel Yergin, New York, 1979, p. 159.

[3] U.S. Department of Energy, *op. cit.*, p. 23.

the United States. But, again, the principal reason had to do with the price and supply of energy resources. Europe has never been endowed with plentiful and therefore cheap energy resources. Necessity, if not the mother of invention, certainly became the mother of efficiency. It is no mere coincidence that West Germany's industries, the leading users of cogeneration, use 38 percent less energy per unit of output than do industries in the United States.[4]

What the above comparison demonstrates is that cogeneration's rate of adoption and success has not been shaped by technological considerations. Rather, this technologically successful option has succeeded or failed in response to market forces: in the case of the United States, cheap and abundant energy resources; in the case of Europe, scarce and expensive energy resources. To the extent that market forces in the United States now resemble those in Europe, the future for cogeneration in the United States looks promising.

However favorable, market forces alone will not suffice to assure the widespread adoption of cogeneration systems, for the road to success is strewn with some formidable institutional, regulatory, and legal barriers. In the words of the Report of the Energy Project at the Harvard Business School, *Energy Future,* where cogeneration is called "Industry's North Slope," in cogeneration we have "a near-perfect example of obstacles being not technical, but almost entirely institutional and organizational."[5]

Among the most serious regulatory obstacles are "the uncertainty regarding the jurisdiction of the Federal Energy Regulatory Commission and state public utility commissions over different cogeneration arrangements (such as joint ventures) and the sale of excess power to utilities."[6] Additionally, private companies are reluctant to enter this highly regulated arena and risk the possibility of being classified as a public utility. By imposing restrictions on joint ventures, antitrust and tax laws also impede the adoption of cogeneration systems. And federal and state environmental protection laws pose additional costs, delays, and risks.

Even in an environment characterized by diminishing energy supplies and ever-higher prices, surmounting these obstacles will not be easy. To be sure, technical problems remain: for example, to develop cogeneration systems capable of using alternative fuels, to improve fuel efficiencies, to make up for the current lack of hardware to retrofit existing equipment. But the real challenge remains the resolution of nontechnological problems.

Finally, in advancing the cause of cogeneration it is important to consider all of its implications and to accord due attention to "external" costs. These are costs induced by the adoption of a technology or fuel and not borne by the individual consumer. For example, although "the effects of environmental pollution for a region will be reduced as a result of the fuel-saving benefits of a cogeneration installation, increases in localized pollution may occur."[7] Who will pay for the control of this local pollution? What effects will this pollution have on the local community? Do the savings to be derived from the cogeneration systems offset the environmental risks? These are just a few of the many questions which must be answered. And what they suggest is that fuel efficiency alone cannot be the final arbiter.

Notwithstanding all of the complex issues noted above, the case for cogeneration remains very strong. Here is a proven, adaptable, energy-efficient technology capable of tapping our principal energy resource—conservation.

Gerald S. Leighton

Director, Community Systems Division
Office of Conservation and Solar Energy,
Assistant Secretary
U.S. Department of Energy

[4] R. Goen and R. White, *Comparisons of Energy Consumption Between West Germany and the Untied States,* Government Printing Office, Washington, D.C., 1975.

[5] *Energy Future, op. cit.,* p. 160.

[6] U.S. Department of Energy, *op. cit.,* p. 31.

[7] U.S. Department of Energy, *op. cit.,* p. 33.

Contents

CHAPTER 3. CHILLER ARRANGEMENTS

CHAPTER 4. POWER CYCLES

CHAPTER **1**

Estimating the Need for Energy Cogeneration

Load and energy estimating in recent years have been largely taken over by computers. Many government agencies and the ASHRAE Standard 90-75 now require computer calculations. Some of the problems associated with computers emanate from the fact that most computer programs belong to outside services. The user most often does not have the time to evaluate or is not in a position to gauge the validity of such programs. Thus, many engineers feel resigned to accept computer printouts which they do not fully understand.

However, there are times when rapid estimates are needed before the costly and time-consuming computer programs can be run, as when, quite often, an energy estimate is required to size central plant equipment long before the surrounding structures the plant will serve have been designed. Most often, the central plant contract is let before contracts for the other structures. All these requirements demand quick-estimating methods, some of which are described here. Unfortunately, all manual methods were designed for either small and residential applications or for single, large structures.

Incomplete energy usage data are shown in Tables 1-19 and 1-20 as representative values of past energy utilization patterns. To present a complete energy use analysis is a monumental task that would require substantial funding and manpower.

1.1 Heating Degree-Day Method

The available degree-day data are, for the most part, connected with heating energy requirements of a single family residence. This method of heat estimating, by judicious extension, may be used for a complex of residential buildings. A degree-day method for cooling applications has been developed which will be examined in Section 1-5.

The American Gas Association,[1] the National (now International) District Heating Association[2] and the American Society of Heating and Ventilating Engineers (now ASHRAE) determined years ago that the heating requirements of a residence are proportional to the difference between indoor and outdoor temperatures, if the outdoor base temperature is 65F (18.3C). For industrial buildings degree-day figures are included in this chapter with the base temperatures of 45F (7.2C) and 55F (12.8C) in Table 1-4, which should not be used if the building control systems are radically different from those of residential units.

Concerning the 65F (18.3C) base, if the day's mean outdoor temperature is 45F (7.2C), it predicts that twice as much fuel will be consumed than when the outdoor mean temperature is 55F (12.8C). At 65F (18.3C) outdoor temperature, no heating is necessary.

Fuel consumption is estimated by employing the equation

$$F = U \times N_b \times D \times C_f \tag{1.1}$$

Where

F = Fuel or energy units (see Table 1-3)
U = Unit fuel consumption constant per degree-day (see Table 1-3)
N_b = Hourly heat loss, Btu/hr (W)
D = Number of degree-days in heating season
C_f = Temperature correction factor (see Table 1-1).

This method, like the calculated heat loss method described next, requires a calculation and implies that the number of degree-days per season and the heat load rate of the heated structure remain fixed. A previous knowledge of fuel consumption for similar buildings and a correction factor for other than 0F (−17.8C) outside design temperature are required.

[1] *House Heating*, Industrial Series. New York: American Gas Association, 1925?, pp. 10–16.

[2] Report of the Commercial Relations Committee "Steam Consumption and the Degree Day," *Proceedings of the National District Heating Association* (now International), 1932, pp. 177–204.