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An Assessment of Stirling Engine Potential in Total and Integrated Energy Systems

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T. J. Marciniak, J. C. Bratis,
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ENERGY RESOURCE
APPLICATIONS GROUP

ENERGY AND ENVIRONMENTAL SYSTEMS DIVISION

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AN ASSESSMENT OF STIRLING ENGINE POTENTIAL IN TOTAL AND INTEGRATED ENERGY SYSTEMS

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T.J. Marciniak, J.C. Bratis, A. Davis, and C. Lee
Energy and Environmental Systems Division

February 1979

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U.S. DEPARTMENT OF ENERGY

Assistant Secretary for Energy Technology
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Heat Engines Branch

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PREFACE

This report is the first in a series on advanced heat engine concepts for use in the residential/commercial/institutional sector. This work is sponsored by the Heat Engines Branch of the Fossil Fuel Utilization (FFU) Division of the Department of Energy as part of the Total Energy Technology Alternatives Studies (TETAS) program. The TETAS program is a joint effort between the Energy and Environmental Systems (EES) Division and the Components Technology (CT) Division at Argonne. The systems analysis work is performed in EES while the detailed technology work is the responsibility of CT.

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ABSTRACT

The development of Stirling engines for stationary power applications in Total Energy Systems is attractive for two main reasons: (1) high potential engine efficiency, and (2) fuel flexibility especially in the use of coal and coal-derived fuels. Total Energy applications are unique in that they offer an option for using fuel energy most effectively on a local basis by recovering the rejected heat from electric power generation to meet thermal requirements within a community. These thermal requirements include space heating, cooling, and hot water service demands.

This report addresses the advantages and disadvantages of large Stirling engines in Total, or Integrated, Energy Systems and looks at the performance and cost characteristics of such engines while comparing them with the main competitors (Diesel engines and gas turbines) for such applications. The comparisons are made through simplified and detailed systems' analyses.

Lastly, based on the systems studied and intercomparisons of competing technologies, the requirements for the development of a large Stirling engine are outlined along with a suggested developmental program.

From this study it is clear that, given the attributes of the competing technologies involved, the main advantage of the Stirling engine lies in its ability to use fuels other than distillates. This attribute must be developed further in order to provide engine technologies which can burn abundant fuels such as coal or coal-derived fuels. Secondarily, the potentially high efficiency of Stirlings would be especially advantageous in applications where a high electrical-to-thermal-energy demand ratio exists.

EXECUTIVE SUMMARY

1. INTRODUCTION

Total, or Integrated, Energy Systems offer a technically feasible and economic solution to the problem of encouraging reduced consumption of natural gas and distillate fuels in the residential/commercial sector. The main component of the energy system is the prime-mover which drives an electric generator and helps supply thermal energy through heat recovery from exhaust gases, lube oil and prime-mover coolant.

The main prime-movers used to date in Total, or Integrated, Energy Systems include Diesel engines, gas turbines, and steam turbines. Generally, Diesel engines have been used in the smaller systems; whereas, the larger systems are centered around gas turbines or steam turbines. No matter what prime-mover is chosen, the overall system efficiency is improved, but these systems generally have lower electrical generation efficiency than an electric utility and use fuels such as natural gas and distillates.

Technological advances in materials, heat transfer, and combustion have made feasible the development of alternative prime movers with attractive characteristics, e.g., high thermal-electrical efficiency and/or the ability to use fuels such as coal, coal-derived fuels, and industrial or municipal wastes. Among these options are; (a) Stirling-cycle engines, (b) external-combustion, Brayton-cycle engines, (c) advanced, small steam turbines, and (d) coal-using Diesels.

This study is concerned with the first option -- the Stirling-cycle engine -- and is aimed at providing; (a) technical and economic evaluations, (b) comparison of the technical and economic performance with currently available technologies, (c) specific engine performance and cost characteristics that will lead to a significant penetration of the engine market, and (d) a general research and development plan for the engine.

2. TOTAL OR INTEGRATED ENERGY SYSTEMS EXPERIENCE

This type of system is based, essentially, on the recovery of prime-mover rejected heat, from the exhaust gases, cooling water, or lubrication oil coolers, or, in the case of steam turbines, from extracted or uncondensed steam. These systems generally comprise district heating and cooling plants, Total Energy Systems (TES), Modular Integrated Utility Systems (MIUS), and Integrated Community Energy Systems (ICES). Of special interest in this study is the general experience of the Total Energy Systems that were installed in the 1960s and early 1970s under the aegis of the natural gas utilities. From this experience, it is possible to get some idea of the size and performance characteristics required of a new engine.

In reviewing the data on Total Energy Systems, several facts became clear:

(1) In this market, over 85% of the installations used Diesel engines, while 13% used gas turbines, and only 2% were based on steam turbines.

(2) The average size of these systems was about 4 MWe, although there were many single building applications at less than 0.25 MWe.

(3) Although most of the applications were in the residential/commercial sector, there were some systems in the 10-15 MWe range and served groups of buildings or industrial needs.

Furthermore, on average, there were about 3-4 prime-movers per installation with engine power ranging from 0.25 MWe to 1.8 kW--with a maximum engine size of 3.3 MW.

3. COMPARISON OF ALTERNATIVE PRIME-MOVERS

The Stirling engine has several advantages, including: (a) high thermal efficiency, (b) fuel flexibility, (c) good part-load characteristics, (d) low emissions, and (e) low noise and vibration. Of these, the first two are of prime concern and would be the most decisive if the engine is to be competitive with Diesels and gas turbines. The overall heat balances of the several prime-movers considered in this report are shown in Table ES-1, in which the work output efficiency, recoverable heat, and rejected heat are listed. Stirling engines offer the highest overall thermal efficiency, although they could be significantly challenged by the adiabatic, turbo-compound Diesel engine which is in the early stages of development for military applications.

Table ES-1 Nominal Heat Balances of Prime-Movers as a Percentage of Fuel Input

Engine Type	Work	Recoverable Heat	Rejected Heat
Diesel	36	42	22
Adiabatic Turbo-compound Diesel	47	36	17
Gas Turbine (Simple)	25	45	30
Gas Turbine (Regenerative)	38	22	40
Stirling (Current)	34	54	12
Stirling (Advanced)	46	41	13

Concerning costs of Stirling engines, it is expected that the cost of an advanced Stirling engine with high efficiency, but using distillate fuels, would be 20-50% more expensive than a comparably-sized Diesel engine. This will be referred to as an advanced, first-generation engine. A second-generation Stirling engine that can use coal or coal-derived fuels is expected to cost 50-80% more than a Diesel of the same size.

A simple electric generation cost comparison was made for the various engine types, including the Stirling, with the following results: for a first generation Stirling engine with efficiency ranging from 34-46%, the cost per kWh is shown in Table ES-2 for a fuel cost of $\$3/10^6$ Btu and an engine size of 1000 kW.

Here it is seen that the first generation Stirling engine can be cost competitive with Diesels provided that the efficiency is high. If the Stirling engine efficiency does not reach the target of about 40-45%, its capital costs must be reduced to be competitive.

An electric generation cost comparison of the second-generation Stirling engine and various other engine options is shown in Table ES-3. Here the capital cost of the Stirling is higher but it can now burn fuel costing in the range of $\$1.70/10^6$ Btu. The reduced fuel cost is clearly an advantage that makes the Stirling competitive, even if efficiency targets are not met.

Table ES-2 Summary of Electrical Generation Cost for Various Engine Options Vs First-Generation Stirling*

Engine Option	Cost (¢kWh)
Diesel (Current)	4.6
Adiabatic Turbocompound Diesel	4.2
Gas Turbine (Simple)	6.65
Gas Turbine (Regenerative)	6.30
Stirling Engine (First Generation)	4.3-5.4

*Engine size = 1000 kW, Fuel cost = $\$3/10^6$ Btu

Table ES-3 Summary of Electrical Generation Costs for Various Engine Options Vs the Second Generation, Coal Burning, Stirling Engine

Engine Option	Cost (¢kWh)
Diesel (Current)	4.6
Adiabatic Turbocompound Diesel	4.2
Gas Turbine (Simple)	6.65
Gas Turbine (Regenerative)	6.30
Stirling Engine (Second Generation)	3.6-4.4

Based on a simple, electrical generation cost comparison of the Stirling engine and various other options, the following conclusions can be drawn:

- The main advantage of the Stirling engine is in its fuel flexibility - especially the ability to burn low-priced coal directly.
- Although the efficiency of the Stirling may be potentially high, this may not be an advantage if oil or gas fuels must be used and capital costs are 20%-50% higher than for Diesel engines.
- Because Diesel and gas turbine engines are well developed and have good-to-excellent reliability, it is doubtful that Stirling engines will be more reliable.
- The good availability of waste heat from the Stirling engine coolers may not be a clear advantage because it is at a relatively low temperature unless engine efficiency is compromised.

- Alternative engine options currently can meet noise, vibration and emissions standards providing little incentive to develop a Stirling for stationary applications, based on these attributes.

Systems studies of a group of residential/commercial communities have essentially confirmed the above conclusions. A large residential/commercial development was studied, and energy systems based on Diesels, gas turbines, and Stirling engines were designed and analyzed. These included:

(1) a community/shopping center which was 100% commercial;
(2) one with 89% residential;
(3) another with 60% residential; and
(4) one with 48% residential occupancy.

Each of these systems, except gas turbines, showed an economic advantage over a conventional system with the coal-using, second-generation Stirling engine being the least expensive on a lifecycle cost basis. In terms of fuel economy, the Stirlings and Diesels were roughly competitive, but it is clear that the main advantage of the Stirling would be its ability to use coal.

4. STIRLING ENGINE DEVELOPMENT GOALS

The research and developmental needs of the Stirling engine include work on: (a) working fluid options including hydrogen, helium, and air; (b) seal design; (c) engine configuration; (d) heater design; (e) combustion system design, especially for coal or coal-derived fuels; (f) air preheater design; (g) regenerator design; and (h) novel engine design studies.

Three overall programmatic goals for a large, stationary Stirling engine include:

1. Development of a Stirling engine that has, at least the efficiency of currently available, medium-speed Diesel engines in the 38-40% range.
2. Development of engines that can use low-cost fuels, such as coal, industrial waste, and municipal waste, as well as coal-derived fuels.
3. Achievement of a capital cost for a alternative fueled, Stirling engine which is not more than twice that of a comparably-sized, medium-speed Diesel engine.

5. STIRLING ENGINE PROGRAM

A program to develop a stationary Stirling engine for use in Total and Integrated Energy Systems is expected to take about 6-7 years from inception to a full demonstration of one or more engines. This program would have six parts, including:

(1) basic research and development;
(2) conceptual engine designs;
(3) preliminary engine designs;
(4) final engine designs;
(5) engine fabrication; and
(6) testing and demonstrations.

The first part will be a continuing ongoing program designed to support the overall engine development and will address the technical problem areas noted in the preview sections. The rest of the program would involve several teams working on engines that show a good chance of success as well as on those of a novel nature that offer some distinct advantages but which could be risky. Phases 2-4 would take about three years; engine fabrication, testing, and demonstration would take about two years each, for a total of seven years. Of course, this schedule could be altered according to the amount of resources devoted to it. Following a successful demonstration, a commercialization program would have to be undertaken to take full advantage of the engine in conserving fuels and using abundant fuel supplies.

1. INTRODUCTION

Given the current emphasis on energy conservation and utilization of non-scarce fuels because of the increased costs of oil and natural gas, the opportunity exists to develop new (and not so new) technologies to accomplish these conservation goals. Technological advances have opened the door to the development of options which only a few years ago, were deemed unsuitable. Paramount among these technologies, are advanced heat engines and energy systems that would not only provide for the electrical needs of a building or community, but also, through the recovery of reject heat, provide for thermal demands such as space heating, cooling and hot water.

The energy systems that generally fulfill the requirements of meeting not only the electrical demands, but also the thermal demands of a building or community, have been referred to as Total Energy Systems (TES). The concept of a TES is not new; in fact, it may well be one of the oldest types of energy systems, dating back to the 19th century when the steam rejected from electrical power generation was used in municipal district heating systems. These systems, or variations thereof, have been used extensively, not only in the residential/commercial sector, but also in the industrial sector. However, the concern of this report is limited to those applications in the residential/commercial sector.

The main component of a viable Total Energy System is the prime-mover. Historically, the emphasis has been on the utilization of technological options that were well developed and readily available commercially. These included (a) Diesel engines, (b) gas turbines, and (c) steam turbines. Generally, the smaller systems use Diesel engines; whereas, progressively larger systems use either gas turbines or steam turbines. Although the heat recovered from the generation of electricity improves the overall efficiency of TES plants, in general they are of lower electrical efficiency than utility systems and generally are restricted to scarce fuel use, i.e., distillate oil or natural gas, although the larger systems based on steam turbines can be coal-fueled.

Technological advances, such as new material developments, have made feasible the development of alternative prime-movers. These options possess attractive characteristics, such as high-thermal efficiency and/or the ability to use a non-scarce fuel, e.g., coal. Among these options are included:

(a) Stirling-cycle engines, (b) externally fired Brayton-cycle engines, (c) coal-using Diesels, and (d) advanced, small steam turbines. Even though these prime-mover alternatives may possess some attractive operational characteristics, they must still compete with currently available technology in terms of reliability and ability to perform economically in a TES.

The objective of the Total Energy Technology Alternative Studies (TETAS) is to address the technological and, to a lesser degree, the institutional problems associated with the introduction of new prime-mover technologies. Specifically, the objectives of this effort include:

- Provide technological and economic evaluations of potentially efficient and fuel flexible, advanced external and internal combustion engines for use in total or integrated energy systems in the residential/commercial sector;
- Compare the technical and economic performance of these engines with those currently available commercially and with which they will have to compete;
- Based on the system studies and technological evaluations, specify general engine performance and cost characteristics that will lead to significant penetration of the expected growth in the TES residential/commercial market; and
- Recommend, in cooperation with the External Combustion Engine Project, a research and development plan for competitive heat engines and components.

These studies, then, are intended, not only to review the state of the art and estimate future performance goals of each of the emerging or advanced heat engines, but also to perform conceptual systems performance and economic studies to discover the projected energy savings and costs of such systems. These will be compared with the performance and costs of systems that are based on currently available technologies to discover the advantages/disadvantages of using alternative, advanced technologies.

In particular, this report is concerned with the development and application of large, Stirling-cycle engines for use in Total Energy Systems. The performance of these engines, using as fuel either distillate oil or coal, will be compared to those systems based on Diesel or gas turbine engines. Diesels and gas turbines are expected to be the main competitors of Stirling-cycle engines in energy system applications.

The general methodology used in the study is as follows:

- Determine the current and expected full-and part-load performance characteristics of each prime-mover technology.
- Determine, in consultation with experts in the field, the current and expected capital and operating costs of each technology; then intercompare each technology on a relatively simple basis.
- Select one or more sites for the application of total, or integrated energy system concepts based on the several prime-movers under consideration. These sites will include a mix of residential and commercial buildings on a community basis. The intent is to address applications with a variety of thermal and electrical power demand profiles.
- Design systems, on a conceptual basis, using several prime-movers. These systems will be sufficiently detailed to evaluate the technical and economic performance of each.
- Intercompare the performance and costs of each system to help define the advantages and disadvantages of each prime-mover and the developmental goals for the advanced technology as they may be affected by TE system requirements.

This report is structured in the following manner:

Chapter 2.0 is a review of Total or Integrated Energy Systems, including an evaluation of their past, present, and future status. This includes estimating the range of prime-mover sizes that would be needed to compete effectively.

Chapters 3.0 and 4.0 are brief reviews of the state of the art of the various prime-movers.

In particular, Chapter 3.0 considers Stirling-cycle engines, the main subject of this report; Chapter 4.0 is concerned with Diesel and gas-turbine engines.

These two chapters are not meant to be exhaustive evaluations, but rather are intended to outline the general characteristics of each prime-mover in terms of performance and costs.

Chapter 5.0, a somewhat simplified comparison of Stirling engines with Diesels and gas turbines, sheds some light on the performance and economic tradeoffs.

Chapter 6.0 describes the systems, studies the intercomparison of the fuel energy consumption of each system and then compares capital and lifecycle costs.

Chapters 7.0 and 8.0 are devoted to the goals of and programs for developing a Stirling-cycle engine for use in Total Energy Systems.

2. TOTAL AND INTEGRATED ENERGY SYSTEMS

2.1 BACKGROUND

Utilizing rejected heat from electrical generation plants is not new. The history of this concept goes back essentially to the early days of electrical power generation when the rejected heat was used to supply district heating systems in the downtown business districts of larger communities. The application of the concept of rejected heat utilization grew in the early part of this century not only in the residential/commercial sector, but also in the industrial sector, mainly as district heating systems or as part of process steam plants. In the 1920s or 1930s, the number of such systems began dropping because of reduced utility prices. Until recently, there were relatively few such applications, aside from those on university campuses or similar institutional complexes and some industrial plants.

In the early 1960s, there was a strong marketing effort by the gas utility companies in Total Energy Systems to help provide an expanded market for gas sales. The systems were based on Diesel engines and gas turbines, with some of the larger systems using gas-fired boilers and steam turbines. Several problems that arose during this period and through the early 1970s caused many of these systems to be decommissioned. These problems included high maintenance costs and low system reliability, both of which made them uneconomic. However, many of the systems were successful and are still in operation. Currently, new systems are being considered and installed, especially in areas where electrical costs are high.

In the early 1970s, the U.S. Department of Housing and Urban Development (HUD) established the Modular Integrated Utility System (MIUS) Program. This effort was aimed at the development of stand-alone energy systems based on current technology - systems that would provide for the electrical, space heating, space cooling, hot water, and waste disposal needs of a community. These systems were much more complete than former Total Energy Systems in that they were designed to provide a wider range of energy related services to the community. In 1974, this program resulted in a demonstration at an apartment complex in Jersey City, New Jersey.

Subsequently, the Integrated Community Energy System (ICES) concept was developed within the U.S. Department of Energy (DOE). The ICES is a general concept that includes all energy systems that provide a multitude of energy-related services to a community. Unlike MIUS, emerging and advanced technologies are to be strongly considered for application in an ICES; and unlike the Total Energy Systems, an ICES does not necessarily have to be a "stand-alone" system, i.e., not connected to the electric utility grid. In fact, grid connection appears to offer operational and economic advantages that a stand-alone system does not have.

Obviously, many variations of systems can be characterized as Total or Integrated Energy Systems. For the purposes of this report, however, we will consider ICES to be stand-alone systems designed to supply the electrical, space heating, space cooling and hot water needs of residential/commercial communities.[1]

In general, the main component of these systems is a prime-mover such as a Diesel engine, gas turbine, or steam turbine. In the case of a Diesel engine, rejected heat is recovered from the exhaust gases, jacket cooling water and lube-oil coolers. This recovered heat is used either directly to supply the community's thermal needs or it may be augmented with a boiler. Typically, the fuel for such a system is either natural gas or oil. Space-cooling requirements can be met, by using the rejected heat in absorption chillers or by motor-driven compressive chillers. Similar arrangements can be obtained with gas-turbine or steam-turbine systems.

Figure 2.1 shows the distribution, by size, of the Total Energy Systems that existed in the United States and Canada in 1974.

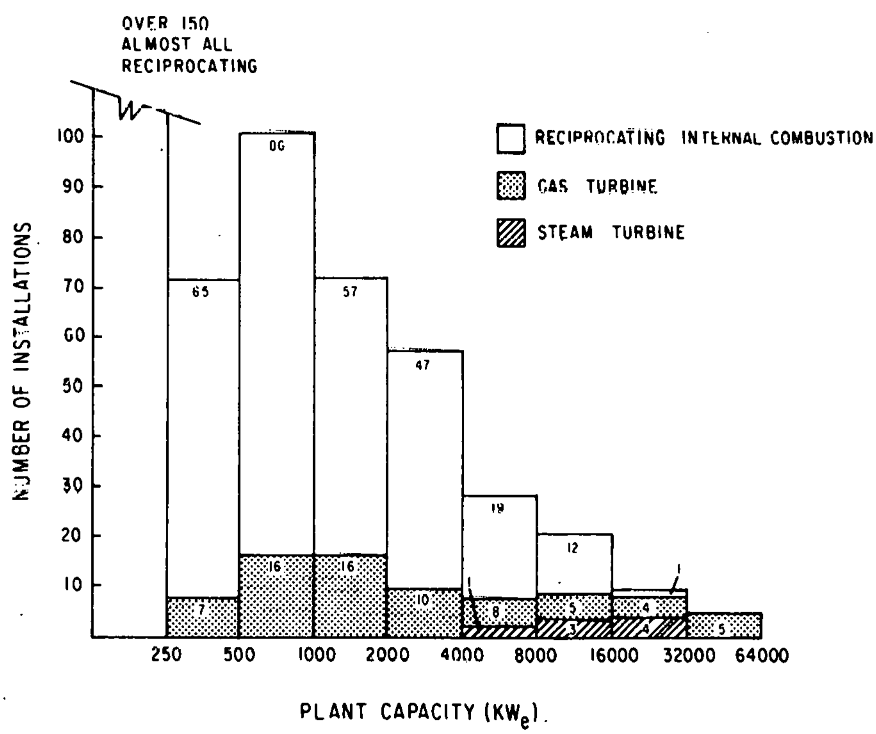

Fig. 2.1 Total Energy Systems Installed in the U.S. and Canada (1974)

Of the more than 500 systems in place and operating at that time, most used reciprocating, internal-combustion engines as prime-movers. The capacity of these systems, in most cases, was less than 4 MWe, which would correspond to about a similar amount of thermal capacity. These data include all the TES applications in existence -- both in the residential/commercial, as well as in the industrial sectors.

Table 2.1 gives the distribution, by engine type, of the systems shown in Fig. 2.1. Reciprocating engines dominate in systems with capacities less than about 8-10 MWe. For larger sizes, the economies of scale inherent in other technologies are apparently more attractive.

Figure 2.2 shows the number of Total Energy Systems in the United States in 1974 as a function of system electrical capacity. Also shown is the breakdown between industrial and residential/commercial applications wherein TES applications are seen to dominate in the residential/commercial sector.

2.2 PRIME-MOVER CHARACTERISTICS

To date, it is apparent that the dominant engine type in use in Total Energy Systems is the reciprocating, compression-ignition, Diesel engine. Furthermore, experience with such systems indicates that the average system capacity is about 3-4 MWe, with some systems as large as 10 MWe and more. Discussion of the future of TES-type systems will be deferred to the next section. Of importance here, in designing a stationary Stirling-cycle engine, is the size range that should be addressed.

Table 2.1 Engine Types Used in Total Energy Systems (1974)

Engine Type	Number	Percent
Diesels	452	85
Gas Turbines	71	13
Steam Turbines	8	2

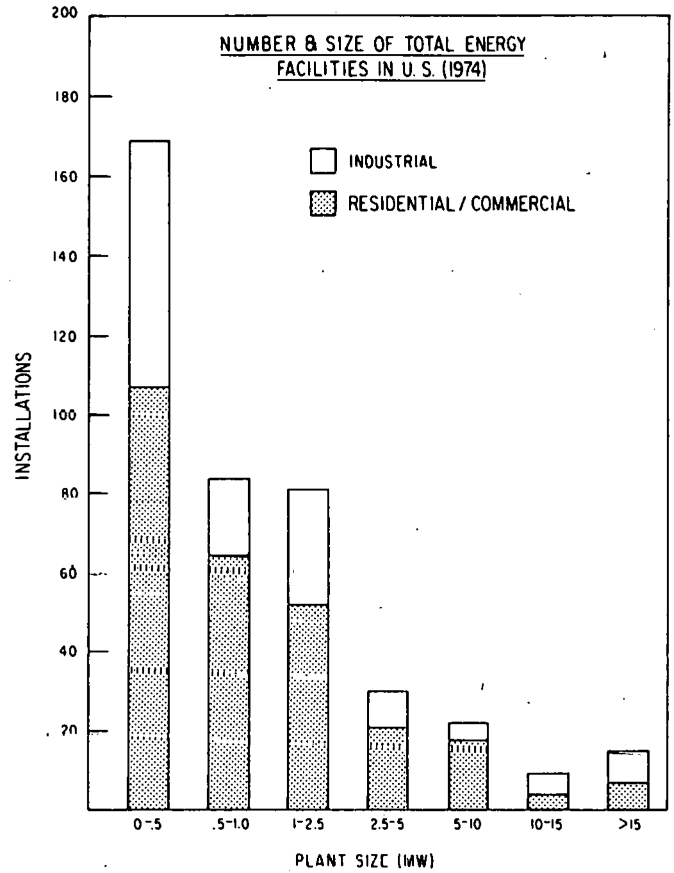

Fig. 2.2 Number and Size of Total Energy Installations in the U.S. (1974)

Data on Total Energy Systems have been examined in somewhat more detail to determine:

(a) the number of prime-movers per installation,
(b) the number of prime-movers as a function of system size, and
(c) the size of prime-movers as a function of system size.

These last data will indicate the target size range for the development of large, stationary Stirling-cycle engines for use in TES.

Figure 2.3 shows the number of installations using reciprocating prime-movers as a function of the number of prime-movers per installation. These data are interesting in that they indicate the "standard practice" in the design of such systems, and they represent, to a degree, the tradeoffs among reliability, performance, and cost inherent in Total Energy Systems. Most of the currently installed systems have 2-4 reciprocating prime-movers per installation. In practice, systems with more than about six engines are somewhat rare.

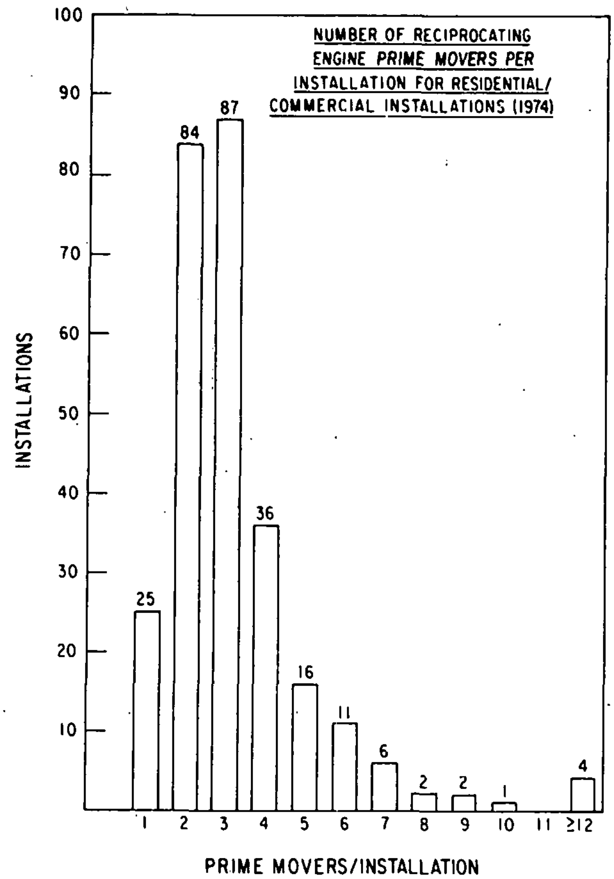

Fig. 2.3 Reciprocating Engine Installations Versus Number of Prime-Movers Per Installations

Figure 2.4 shows the number of reciprocating engines as a function of plant electrical capacity and indicates that the number of prime-movers per installation increases as a function of system size. This is interesting in that it seems to indicate a desire by the system designers to limit the maximum size of individual engines either because of cost considerations or a lack of larger, medium- or low-speed, engines suitable for keeping the number of prime-movers per installation low. Also shown in the figure are the upper and lower numbers of prime-movers in a given installation which gives an idea of the spread in the data.

Figure 2.5 shows the size of each prime-mover as a function of system size and represents fairly well the range of sizes that should be addressed with a mature Stirling-cycle engine. As expected, the size of the engine increases with increasing system size. Thus, the size of the average prime-mover ranges from about 250 kW to 1.8 MW. Reciprocating engines that range in size from 100 kWe to about 3.3 MWe have been used in Total Energy Systems.

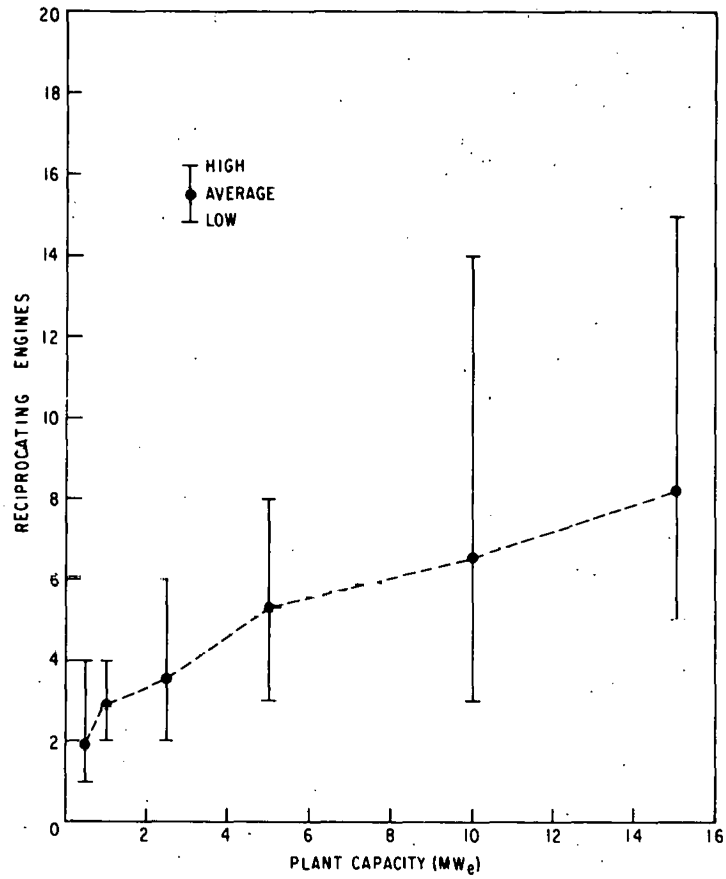

Fig. 2.4 Number of Reciprocation Prime-Movers per Installation as a Function of System Electrical Capacity

Based on the above data the following general conclusions can be drawn:

1. Total Energy Systems, to date, have been designed mainly for single-building applications in the residential/commercial sector (retail stores, shopping centers, office buildings, apartments, townhouses, etc.).

2. The average size of Total Energy Systems to date is about 3-4 MWe, with few applications larger than 10-15 MWe. The larger-capacity systems usually are those serving groups of buildings or users; whereas the smaller systems are usually single-building applications.

3. Generally, there are about 3-4 prime-movers per installation; however, larger-sized systems have been known to use up to 10 or more.

4. The average size range of reciprocating engine prime-movers is from 250 kW to 1.8 MW (335 hp to 2420 hp). The maximum sizes used range up to 3.3 MW.

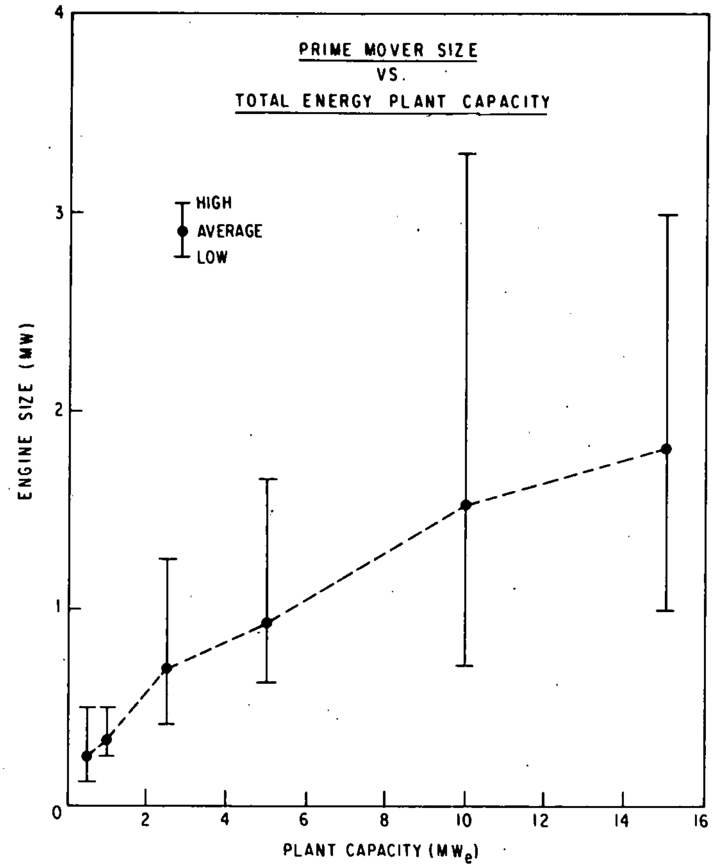

Fig. 2.5 Average Prime-Mover Size Vs Plant Electrical Capacity

Although the above conclusions apply to the Total Energy System experience to date, it does not necessarily follow that the future experience will be identical. In the next section, a brief look will be taken at the future prospects for Integrated Energy Systems which may indicate the trends between now and the year 2000, when Stirling engines could be a force in the engine market.

2.3 FUTURE MARKET DEVELOPMENT

The future of Total Energy Systems, or in a broader sense, Integrated Energy Systems, is promising over a wide range of applications. These systems can be grouped into several categories that are expected to serve varying sized applications. These system types are:

> <u>Total Energy Systems</u> -- Designed primarily to meet the community electrical demand with thermal requirements met by heat recovery from prime-movers or augmented with boilers.

Selective Energy Systems -- Designed to meet the thermal load with some electrical production in the form of topping or bottoming cycles. Electrical demand is met mainly from the electrical utility grid in a buy-only arrangement.

Grid-Connected Systems -- Designed to meet both electrical and thermal demand. The electrical demand is met, however, with a buy-sell arrangement with the grid.

Coal-Using Systems -- Designed to use coal as the primary fuel.

District Heating/Cooling Systems -- Large systems designed specifically to meet thermal demands of high-density areas using rejected heat from existing or new power plants.

Thermal Transport Systems -- Designed for remote generation of thermal energy and transportation into the user community for electrical generation and thermal needs.[2]

The expected range of sizes for each of these Integrated Energy Systems is shown in Fig. 2.6.[3] The Total Energy and Selective Energy Systems are expected to serve the size range from about 0.1 MWe to about 60 MWe. Grid-Connected and Coal-Using Systems are expected to be applicable from about 6 MWe to about 200 MWe; whereas, District Heating/Cooling and Thermal Transport will cover the larger sizes from 20 MWe to 1000 MWe. Some overlap

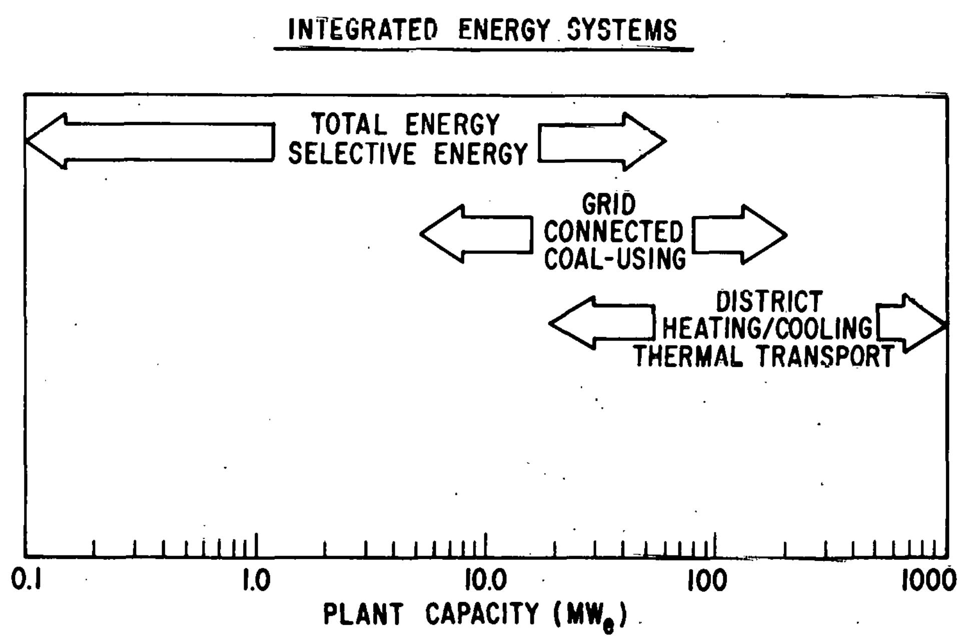

Fig. 2.6 Integrated Energy Systems Concepts and Size Ranges

of system types exists for applications with less than about 100 MWe, indicating that users will have a choice of systems.

Generally, large stationary Stirling engines can be expected to cover the range of systems from about 0.5 MWe up to about 10 or 20 MWe. Thus, they would have applications both in smaller systems where their high efficiency would be an attribute and in larger systems, where their fuel flexibility can be used.

Because a detailed market forecast for ICES has not been made, it is not possible to estimate the market for Diesels and gas turbines in Integrated Energy Systems applications in the residential/commercial sector. However, this problem is being addressed in the Community Systems Program of DOE, and the information will be factored into the subsequent development and commercialization strategy for Stirling-cycle engines as it becomes available. The average size of an Integrated Energy System currently is expected to be about 25 MWe. This is due to the weighting factor of the large systems. About 12,000 systems are expected to be in place in the year 2000. If the average size is only 12.5 MWe, then there will be twice as many systems in place.[3] The demand for Stirling-cycle engines is expected to exist in the smaller sized systems, which could be the dominant force in the overall ICES market between now and the year 2000.

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3. STIRLING ENGINES*

3.1 GENERAL BACKGROUND

Invented in 1816 by Robert Stirling, a Scottish minister, the engine bearing his name is not new. Although its operational principles have been known for over 160 years, it has not been an economically attractive alternative prime-mover technology until recently with the advent of modern technological developments. The Stirling engine can be described as a thermodynamic, shaft power device operating in a closed cycle with gas as the working fluid. It is referred to as an external-combustion engine in which heat is supplied from a source at high temperature and rejected to the environment through a water cooling loop. Thus, the fuel, air, and combustion products never enter the engine; so the gas, the working fluid, operates in a closed cycle.

Stirling's last hot-air engine was taken out of service in 1847 and this type of engine was not again considered seriously until 1938, when the Philips Research Laboratories of N.V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands, decided to develop a small, quiet and reliable heat-driven power source for remote locations.[4] Because of several attractive characteristics of the Stirling engine, it was pursued for development. Subsequently, Philips subjected the Stirling system to many detailed investigations, and over the years many engines were built, ranging from a few kilowatts up to 360 kW. The original intent of the engine as a remote power source was made obsolete with the advent of transistors and batteries, but the experience gained in the development effort indicated the potential of the engine. Since that time, development has centered on Stirling engines which have low noise and vibration levels and potentially high efficiency, but which are currently inhibited by large size, weight and cost relative to Otto, Diesel, and Rankine-cycle engines.

Philips' strong commitment to the early and subsequent development of Stirling engines has resulted in engines for use in boats, buses, and electric power generation.[5-7] Others have entered the field under license from

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*This section is based, in part, on a report prepared by Arthur D. Little, Inc., for Argonne National Laboratory (December 1977).

Philips over the years. United Stirling, a Swedish firm, has been actively pursuing the development of an automotive engine since 1968, while two German firms, MAN* and MWN** have built heavy-duty engines and have demonstrated one in a bus.

In 1958, General Motors became the first Stirling engine licensee in the United States. During the period when GM was actively involved in Stirling development, it acquired over 25,000 hours of engine operating experience. GM's major interest was in the application of Stirlings to cars, trucks, buses, and railroad locomotives, as well as to large, stationary engines. After twelve years of effort, GM's experience led to the conclusion that the Stirling would not offer significant advantages over the already well-developed internal combustion engine. GM cited problems with:

(1) seals (leakage and diffusion of the working fluid around piston rods),

(2) excessive weight (over 14 lbs per horsepower),

(3) excessive bulk (difficulty in vehicle packaging),

(4) low-speed limitation,

(5) large radiator requirement, and

(6) high NO_x levels.[8]

In about 1970, Ford Motor Company conducted an in-house review of Stirling technology, being motivated by the increasing difficulty of achieving low levels of exhaust pollutants in its IC engines and the potential of the external combustion feature of the Stirling engine to accommodate emission regulations. After considerable dialogue with Philips and some in-house testing, Ford management became optimistic about overcoming key problem areas and proceeded to negotiate an agreement with Philips in 1972, as well as another with United Stirling.[8] These agreements gave Ford access to all the relevant technology at Philips and United Stirling, and, subject to some limitations, a license for worldwide application of the technology to passenger cars.

In a joint Ford/United Stirling program, various engineering model versions of a 40 kW (54 hp) engine have been tested, including operation in a Ford Pinto and a Ford Torino. Ford and Philips have cooperated to examine

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*Maschinenfabrik Augsburg-Nuernberg

**Motorenwerke Mannheim

and test a 170 hp Stirling engine alternate to Ford's 351 CID Otto-cycle engine packaged in a Ford Torino. In mid-1975, Ford Motor Company began working under contract to the Department of Energy [8,9] on the "80-100 HP Stirling Engine Feasibility Design Study Program" which was completed in 1977. In October, 1977, the Department of Energy and Ford Motor Co. signed a cost-sharing contract for the development of a Stirling passenger car engine. DOE's share of the development effort will be about $110 million, while Ford will contribute about $50 million over an eight-year period. This program was to have been reviewed jointly each year and funded on an annual basis. However, in October, 1978, Ford Motor Co. notified the Department of Energy and Philips that it would not renew its contract to develop the Stirling engine. As a reason, Ford Motor Co. cited the need to concentrate its research resources to meet government requirements in several areas, especially fuel economy and emissions. DOE plans to continue the Stirling engine development program with a team consisting of United Stirling, American Motors, and Mechanical Technology, Inc.

DOE plans call for a decision whether to develop both the gas turbine and the Stirling engine as successors to the spark-ignition IC engine. The recent funding actions by the federal government are consistent with the recommendations of a study by the Jet Propulsion Laboratory (JPL) completed in July, 1975, which, in part, urged a massive R&D effort leading to the introduction of a Stirling engine-driven car in mid-1985. This report made a case for the Stirling engine to supplant the conventional Otto cycle as a benefit both to consumer and national interests, primarily because of its superior fuel economy and low pollution characteristics. At the same time, the report acknowledged that, because of its relatively infant stage, development would be a high risk venture and would require a substantial resource commitment by both government and industry. JPL estimated a total development cost of $260 million (1974 dollars) for each independent effort. Thereafter, a front-end commitment of $500 million in engineering, tools and plant, and a period of at least five years is generally accepted as necessary for the quantity (400,000 units/year) production of a standardized engine.

Given the level of commitment to the development of Stirling engines for automotive use, it appears that engines for stationary applications are equally feasible. However, such a developmental program would be significantly different because size and weight are not the dominant factors; rather fuel flexibility, especially the ability to burn coal, along with potential high efficiency, make the stationary Stirling engine attractive and unique. Similar to the development of automotive engines, a stationary, Stirling engine in the 500-3000 hp class, could not be available until the mid-to-late 1980s.

3.2 ATTRIBUTES

The primary advantages of the Stirling engine that could make its use attractive in community energy systems are similar to those associated with automotive applications, namely:

- high thermal efficiency,
- good part-load characteristics,
- fuel flexibility,
- low emissions,
- good reliability, and
- low noise.

Of these advantages, those that could be most decisive are:

- the possibility of achieving very high efficiency levels in the 40-50% range, and
- the ability to use a multiplicity of fuel forms including coal, coal-derived fuels, municipal and industrial wastes, and low-Btu gases (from digestor systems).

Although Stirling engines with efficiency levels approaching 40% have been built and tested as part of the Philips development programs, most Stirling engines built to date have efficiency levels of about 32-35%. The ideal efficiency of these engines would be as high at 60-70%; therefore, most present engines achieve about 50% of Carnot efficiency. The rather large divergence between obtained efficiency and the ideal is due, in part, to the restrictions placed on the engines because of their predominant development for use in automotive propulsion systems. This application requires:

- very low first costs (∿$6/hp) which restricts the use of high-temperature materials and elaborate fabrication techniques;
- high power-to-volume (or weight) ratios which result in:
  - high working gas pressure levels that reduce the allowable temperature levels in the heater section,

  - high operating speeds that increase flow losses,
  - high heat flux input rates that increase temperature differences between the heater tubes and the working fluid;
- the requirement for air cooling which, when combined with the frontal area restrictions, leads to relatively high heat rejection temperatures (170°-220°F).

In general, these restrictions do not apply to stationary engine applications. This greatly increases the flexibility in designing Stirling engine systems and allows for maximizing efficiency consistent with achieving a low overall operating cost. Efficiency can be a strong economic driving force because a 5% increase in efficiency is worth about $100/hp in initial costs, assuming $3/10^6$ Btu fuel, 20% capital charges, and a high load factor.

The realistic limit on Stirling engine efficiency is difficult to specify. However, extrapolations of existing data assuming a heat rejection temperature of 100°F, optimum efficiency operation speeds, and heat input temperatures (of the gas) of 1900°F indicate that Stirling engine efficiencies of about 45% are a realistic goal. Even higher efficiency levels may be obtainable if ceramic heat exchangers can be developed that allow higher-temperature operation. These high efficiency levels would be obtainable with engines over a wide power range (a few kilowatts to thousands of kilowatts) which make their use viable for several Integrated Energy System applications. The efficiency potential for the Stirling engine is not matched by the alternative engines considered, particularly at more modest power levels. For example, the most efficient conventional systems would use large, low speed, Diesel engines which have efficiency levels in the 34-38% range.

The second major advantage of the Stirling engine is its ability to use various kinds of fuel forms, in particular, coal, coal-derived fuels, municipal solid wastes, and possibly biomass-derived fuels (wood chips, biogas, etc.).

As an example, Fig. 3.1 indicates a system that would allow for using such a multiplicity of fuels and has been demonstrated by Philips. In this system, the heat is transferred from the fuel combustor to the Stirling engine by a sodium heat pipe. This allows for a uniform, high-flux heat input to the Stirling engine heater without subjecting the heater

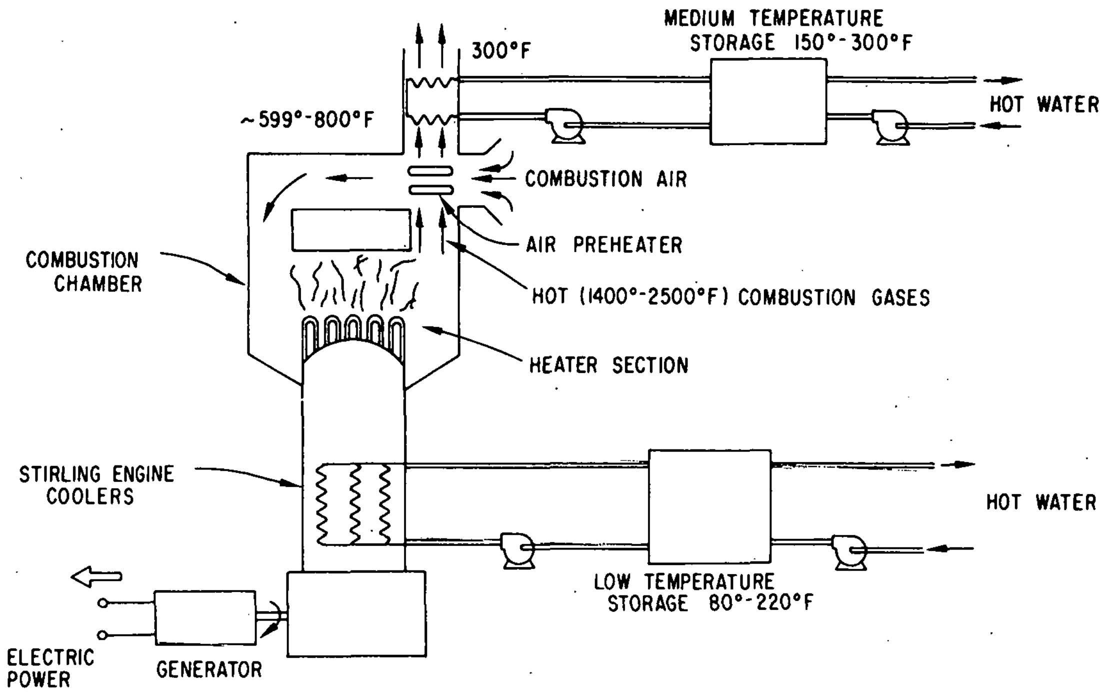


Fig. 3.1 Stirling Engine/Heat Recovery Options

tubes to the potential corrosion and fouling associated with the combustion of many solid fuel forms. The heat input to the heat pipe system can be via heat exchanger configurations (fins, etc.) that are easily cleaned and still have sufficient heat-transfer area to keep gas-to-metal heat fluxes and temperature drops low. This arrangement allows decoupling the combustion gas to metal from the heater tube to engine gas heat transfer processes and makes it possible to optimize both functions. It should be noted that this arrangement is not without its problems; particularly those associated with the safety of liquid metal systems and the choice of containment materials.

The fuel flexibility of the Stirling engine is matched only by the Rankine-cycle engine alternatives. However, small Rankine cycle engines using water or organic working fluids would not have nearly the efficiency of the Stirling engine systems. This will be an increasingly important factor affecting choice of power system options.

3.3 ENERGY SYSTEM APPLICATIONS

As indicated in Fig. 3.1, there are two sources of heat in a Stirling engine which can be used to heat water. These are from the combustor exhaust gas and from the cooling water. The rejected heat can, in turn, be used for a variety of applications including hot water, space heating and the operation of absorption chillers. The two heat sources are:

(1) Heat rejected from the cycle during the compression process. Stirling engines require coolers that should operate at as low a temperature as possible to maximize engine efficiency. This makes preheating domestic hot water or process water particularly attractive because these preheat functions often can be accomplished with water at temperatures of 90°-140°F. However, it is possible to increase cooling water temperature, at a sacrifice in efficiency, to meet heating and cooling needs.

(2) Exhaust gases from the Stirling engine combustor at temperatures above 500°F (even with preheater). A portion of this exhaust gas heat could be used to heat water in a gas-liquid heat exchanger. Because of the relatively high temperature of the exhaust gases, water (or steam) could be easily heated to temperatures above 300°F thereby increasing the range of applications for this heat source. The inclusion of this application in a Stirling engine system concept would reduce the incentive to achieve very high effectiveness on the air preheater system because the exhaust heat would not be wasted. Gas-to-liquid heat exchangers are less expensive than gas-to-gas recuperators (because of higher average heat-transfer coefficients of liquids as compared to gases), so that relaxing the effectiveness requirements of the recuperator could result in an overall cost reduction.

In the system of Fig. 3.1, heat is stored at two different temperature ranges to provide maximum system flexibility in meeting thermal loads. Figures 3.2 and 3.3 show two applications for Stirling engines within a Community Energy System context.

In the system of Fig. 3.2, which might be typical of a hospital complex in northern climates, both hot water and space heating needs are satisfied by:

(1) preheating the water at modest temperatures with heat provided by the coolers, and

(2) "topping off" the temperature with higher temperature heat provided by warm water from the coolers in a coil placed in the air distribution system.

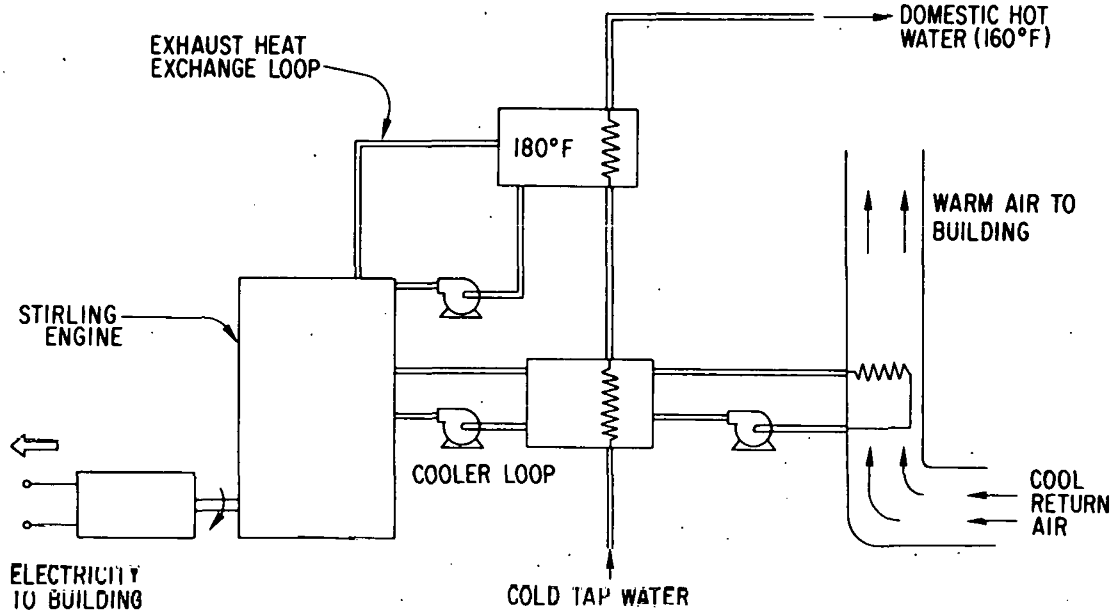


Fig. 3.2 Combined Power/Heating Energy System Using a Stirling Engine

One advantage of this system arrangement is that the coolers are operated at a relatively low temperature conducive to high engine efficiency while supplying a major portion of the water and space heating loads.

In the system of Fig. 3.3, which might be applicable to a large shopping center, the heat energy is stored at temperatures consistent with operation of an absorption air conditioning system (190°-230°F). This arrangement requires operating the engine coolers at relatively high temperatures which results in degradation of engine performance. The appropriate tradeoffs between engine efficiency and the temperature availability of reject heat from the coolers will require study of specific applications.

The application of Stirling engines in a Community Energy System context is, of course, not unique to this engine concept. Fig. 3.4 shows the availability of waste energy from alternative engine systems under consideration.

As indicated, the waste heat availability from the Stirling engine is primarily at low temperatures from the cooler systems. In contrast, heat availability from Diesel and gas turbine engines is primarily at higher temperatures in the exhaust gases. Fortunately, most of the heating functions in a residential/commercial community can be performed at relatively low temperatures, so that the performance of the Stirling engine is not significantly degraded. However, the operation of absorption air conditioning

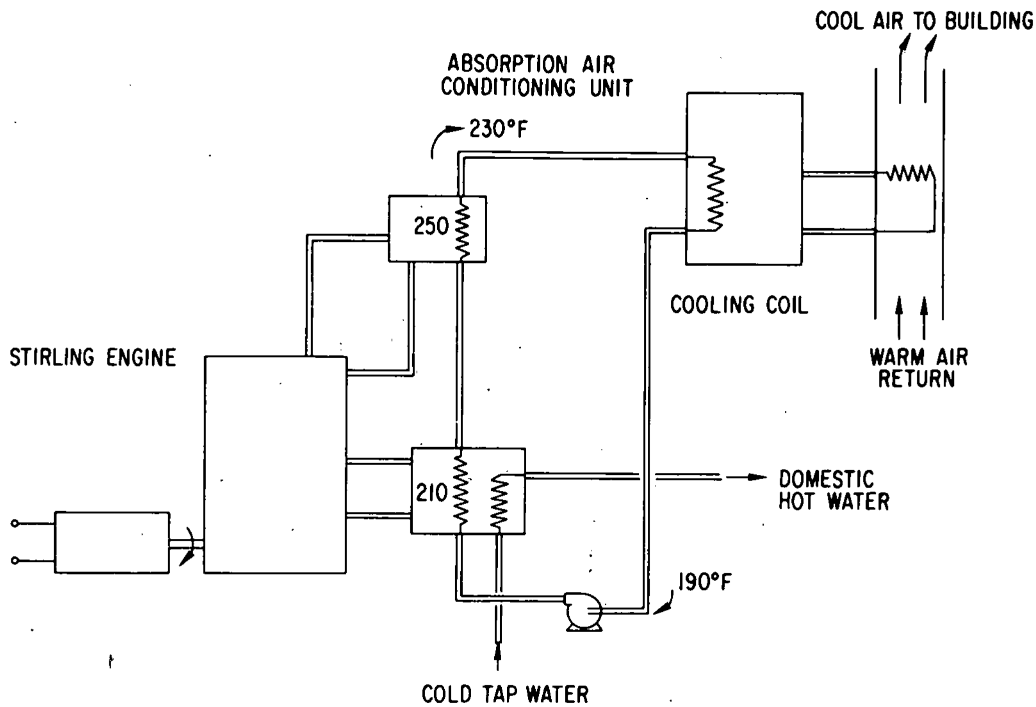


Fig. 3.3 Combined Power/Air Conditioning Energy Using a Stirling Engine

units could decrease engine performance as much as 20% if absorption units designed to operate at 180°-200°F are utilized.

One advantage of the Stirling engine in an Integrated Energy System context is that the heat can be extracted from the coolers in the form of hot water at little, or no, additional cost (i.e., the coolers must be provided with water cooling even if the only function of the engine is electric power production). This is in contrast with the situation of Diesel or gas turbine engines, in which most, or all, of the heat must be extracted by placing waste-heat boilers in the hot exhaust gas streams. These heat exchangers represent a substantial cost factor in the overall total energy system, and the Stirling is at an advantage in this case.

The above advantage (i.e., ease of extracting heat) is somewhat counterbalanced by the fact that this heat will be primarily at lower temperature levels (200°F) unless significant degradations in engine efficiency are acceptable. This may increase the cost of the energy distribution and storage systems as compared with the Diesel and gas turbine options, where heat can be generated readily in the form of steam or pressurized hot water in the waste-heat boilers.

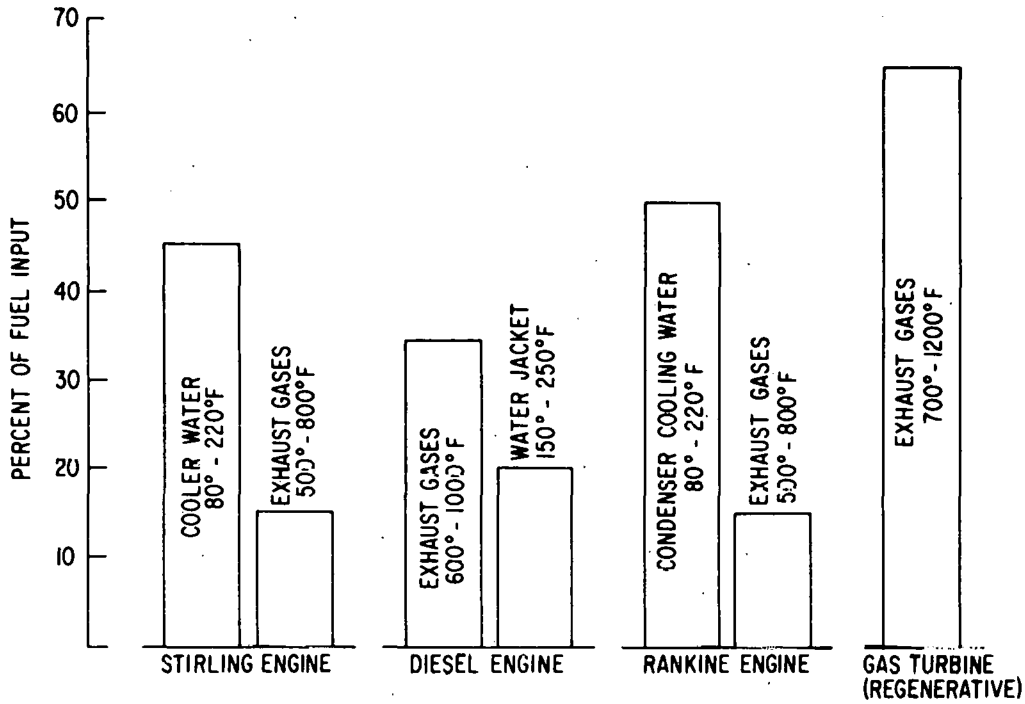


Fig. 3.4 Availability of Waste Heat from Various Engine Options

3.4 PERFORMANCE CHARACTERISTICS

To have sufficient data to perform systems analysis, it is necessary to know the characteristics of Stirling engine performances at full and part load. Furthermore, correction factors would be needed to determine the effect of variations in heater head temperature and coolant temperature on Stirling engine efficiency and power output. These data were gathered from the literature and are based, where possible, on actual engine experimental data.

Performance characteristics of advanced Stirling engines are estimated, based on expected system efficiency for the fully developed, mature technology.

Figure 3.5 shows the part-load performance characteristics of a Stirling engine, including recoverable heat at 80°C. These curves were developed from a study by Philips of Total Energy Systems for single buildings.[12] The shaft work is strictly the mechanical output and must be multiplied by the generator efficiency to get the electrical output. The cooling water temperature is 80°C (176°F). Figure 3.6 shows the same engine with the cooling-water temperature at 120°C (248°F). In each of these cases, the total amount of usable fuel energy is almost identical at about 85-90%. This will be considered as a generally fixed percentage so that variations in engine efficiency will result in opposite changes in recoverable heat.

Figure 3.7 shows the variation of engine shaft work efficiency for the current and advanced technology. Stirling engines can now be operated at about 30-34% efficiency. The expected advanced full-load efficiency is about 46%, although there is some uncertainty in this estimate. The shape of this curve generally conforms to data given by both Philips[9] and Amtech.[13]

Figures 3.8 and 3.9 give the correction factors on engine efficiency and power output as a function of heater head temperature and cooling water temperature, respectively. These data are needed for adapting Stirling engines to specific system designs.[13]

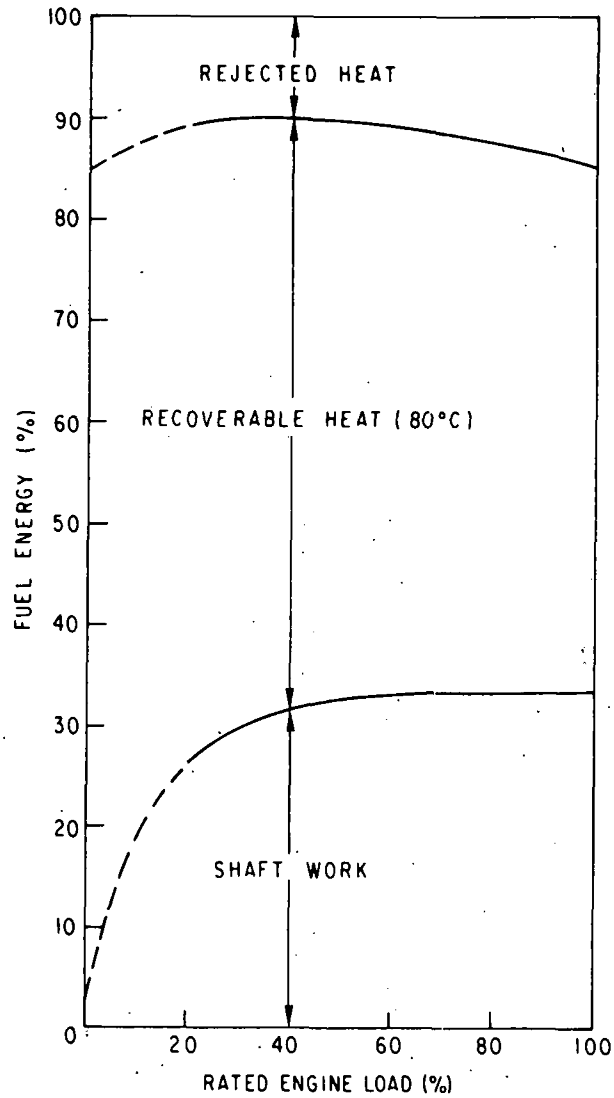


Fig. 3.5 Stirling Engine Heat Balance with 80°F Cooling Water Temperatures

3.5 COSTS

Expected costs of a mature Stirling engine technology, are difficult to estimate, especially in the early stages of development. In this case, recourse must be taken to expert opinion while acknowledging that the numbers will change as more information is gained during development.

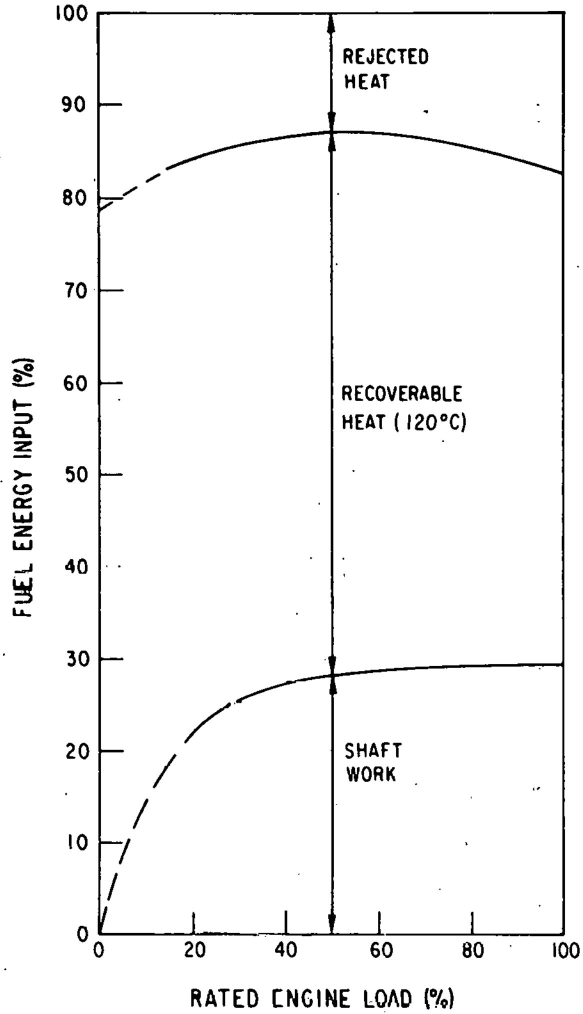


Fig. 3.6 Stirling Engine Heat Balance with 120°C Cooling Water Temperature

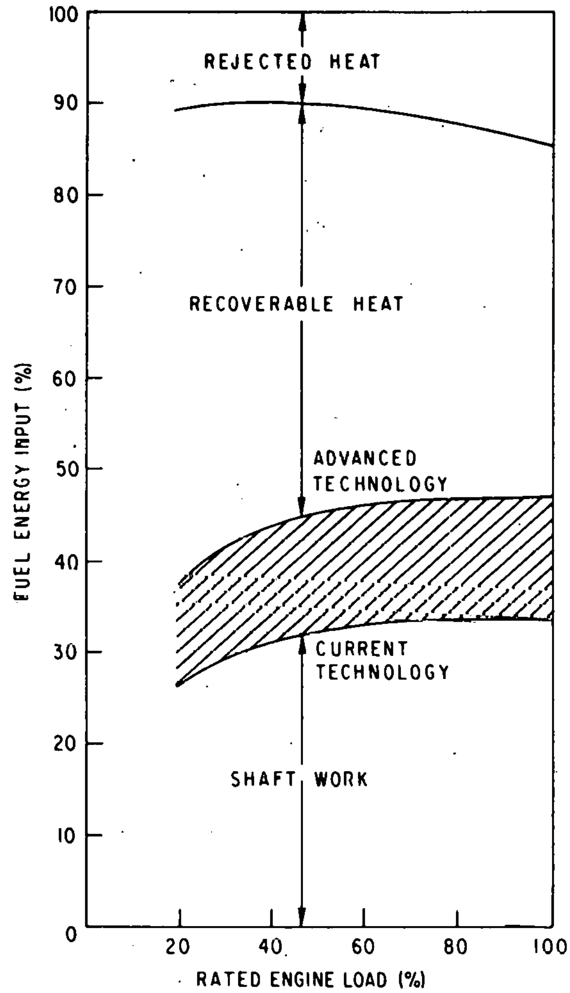
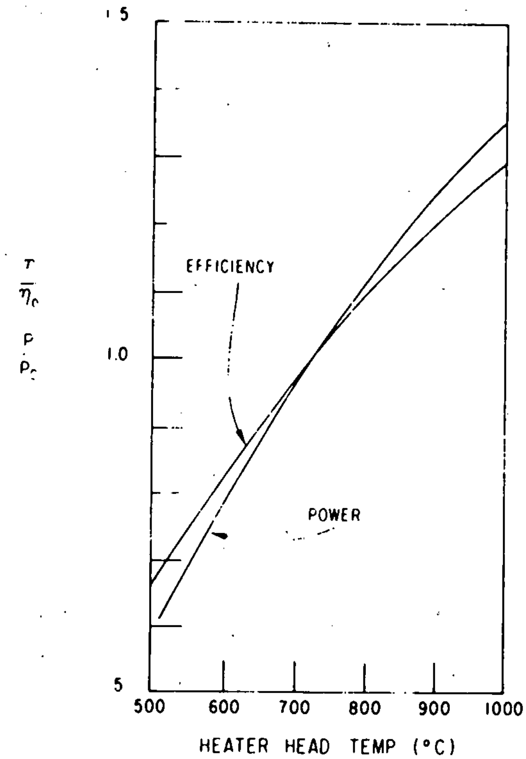


Fig. 3.7 Generalized Stirling Engine Heat Balance

Generally, Stirling-engine construction, installation, and operation are expected to be very similar to those of Diesel engines. In the Philips report,[12] the cost of the Stirling engine was assumed to be twice that of a similar-sized Diesel engine when the technology is mature. However, we are really considering essentially two Stirling engine developments:

1) Advanced Engine - First Generation: A large, stationary engine with high efficiency using distillate fuels; and

2) Advanced Engine - Second Generation: A large, stationary, high-efficiency engine using coal or coal-derived fuels.



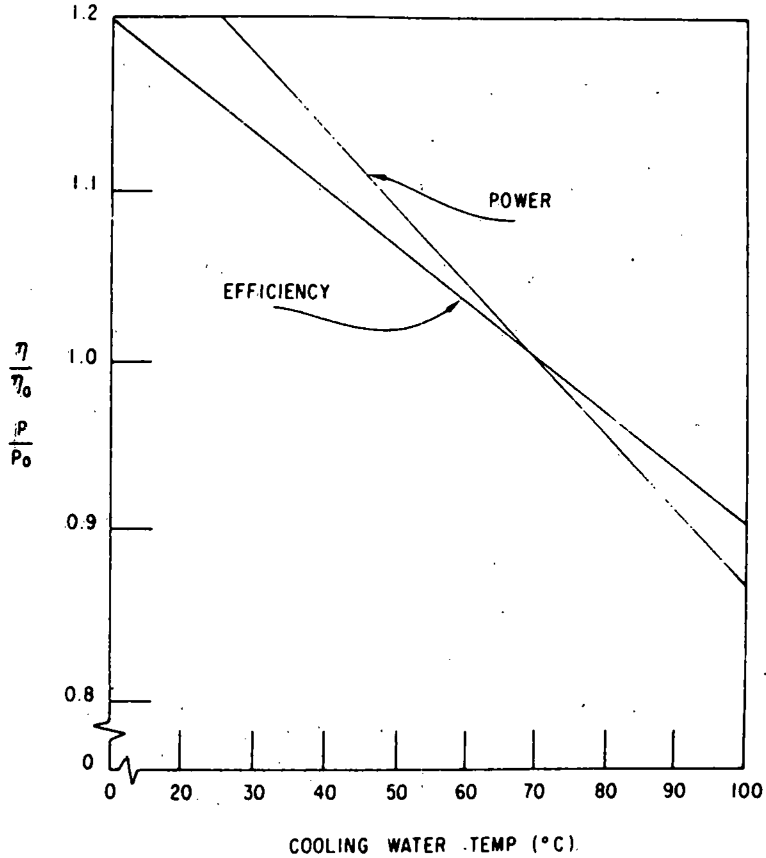


Fig. 3.8 Effect of Heater Head Temperature on Power and Efficiency in Stirling Engines

Fig. 3.9 Effect of Cooling Water Temperature on Power and Efficiency in a Stirling Engine

(courtesy United Stirling)

Amtech considered each of these options[13] and estimated the cost of a first-generation engine to be 20-50% more expensive than a similarly sized Diesel engine. For a second-generation Stirling engine burning coal, it was estimated that the cost of such an engine would be 50-80% more expensive than a similarly sized Diesel engine. With this in mind, the cost of a Stirling engine in a Total, or Integrated Energy System can be estimated.

The uninstalled capital cost of a Diesel engine is given by[7]

$$I_{ED} = 731.91\ Q^{-.171} \tag{3.1}$$

where:

I_{ED} = Capital Cost (\$/kW), and
Q = Engine Capacity (kW).

Generally, the rest of the installation costs about \$150/kW and is comprised of the costs of: (a) the generator, (b) installation, (c) controls, and (d) heat recovery equipment. Therefore, the cost of a Diesel engine installed in a Total Energy Plant is given as:

$$I_{ED} = 150 + 731.91\ Q^{-.171} \quad (\$/kW) \tag{3.2}$$

Likewise, the total installed cost of an advanced Stirling engine would be:

$$I_{ST} = 150 + 731.91\ C_S\ Q^{-.171} \tag{3.3}$$

where:

C_S = Correction factor
C_S = 1.2-1.5 first generation
C_S = 1.5-1.8 second generation

The maintenance costs of the Stirling engine will be considered to be equal to those of a similarly sized Diesel engine and are given in Sect. 4.2.3.

4.0 ALTERNATIVE PRIME-MOVERS

4.1 GENERAL

One of the main objectives of this study is to compare the performance of Stirling engines with that of the main technological competitors it will face in penetrating the Total , or Integrated, Energy System market. Competition in systems applications will include:

(a) internal-combustion piston engines,
(b) Brayton-cycle gas turbines, and
(c) steam turbines.

The most important competitors in the system sizes of interest here will be the first two, while the third is expected to be, not only competitive in large systems, but also able to offer the fuel flexibility at a higher thermal efficiency which is a strong attribute of the Stirling engine.

The intent here is not to provide an exhaustive review of internal combustion piston engines (Diesels in this case) and gas turbines, but only to present enough detail to provide a base for comparing systems designs and simple performance/cost evaluations. More detail on various engine options and their application in Integrated Energy Systems can be found elsewhere.[15-17]

4.2 DIESEL ENGINES

Of the internal combustion piston engines currently available for use in Total Energy Systems, the compression ignition Diesel engine is the most widely used. This engine, which has been developed over the past 40 or more years, has gained wide acceptance in transportation as well as stationary, power generation applications. Thus, the concern here will be with Diesel engines, although spark ignition engines are available for use in stationary applications in many of the same engine sizes.

4.2.1 Current Status

The Diesel engine is a highly accepted, mature technology, that embodies relatively low cost, good efficiency, and high reliability thus making it attractive for applications of relatively small power generation. The size range covered by Diesels is from a few hundred horsepower in high speed automotive application to low-speed marine engines with horsepower ratings in excess of 10,000. The size distribution of stationary engines is shown in Fig. 4.1. Many engines are installed in the 500 -- 1000 hp class with a significant number also in the 3000 -- 4000 hp range. The projection through 1982 shows significant growth in these markets.

The Diesel engine, especially the low-to-medium speed engines, is especially suitable for application in energy systems in the residential/commercial sector, not only because of its relatively low installation and maintenance costs and high reliability, but also because of its good efficiency and the availability of recoverable heat to meet thermal demands.

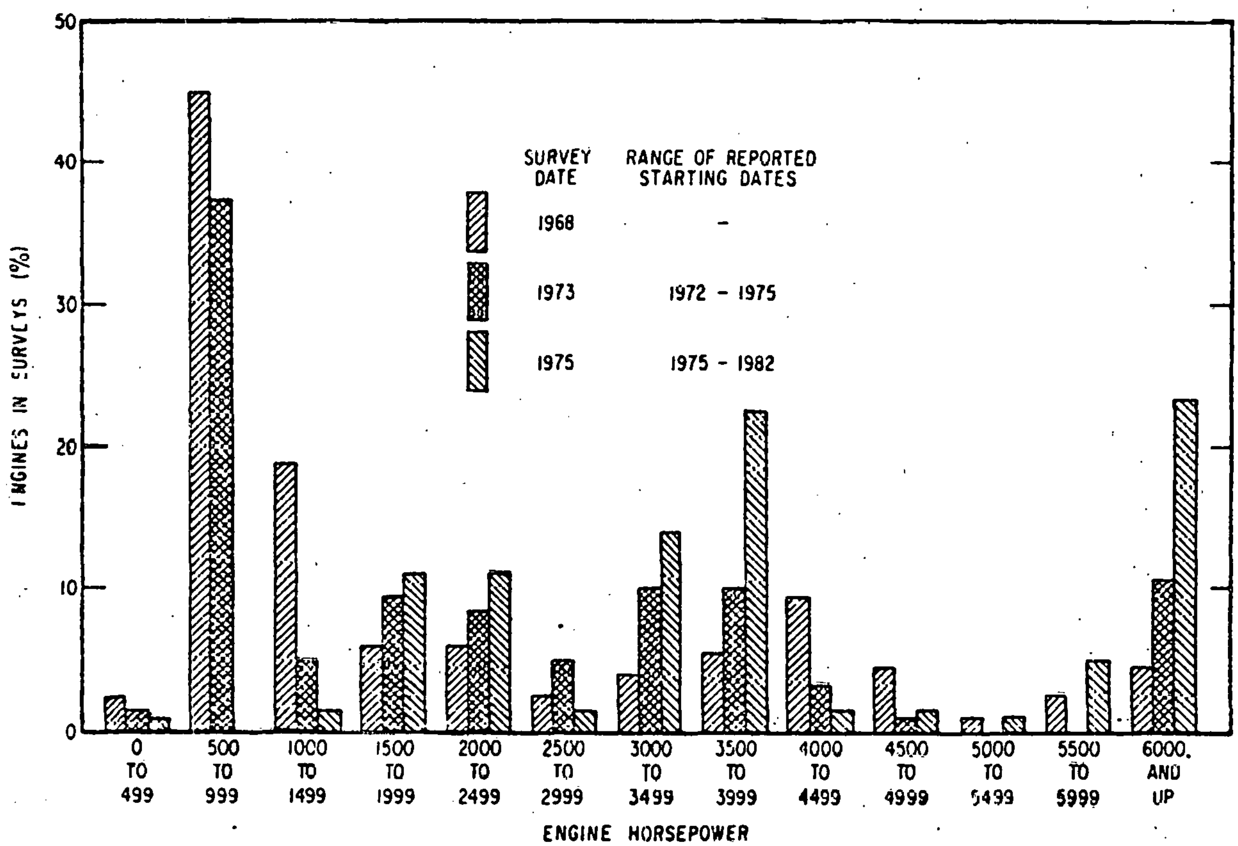


Fig. 4.1 Size Distribution of Oil and Gas Engine Installations Reported in 1968, 1973, and 1975 Surveys[14]

Figure 4.2 shows the general heat balance of a typical Diesel engine. Not only is shaft work available to drive electric generators, compressors, or pumps, but heat may be recovered from the: (a) exhaust gas, (b) jacket cooling water, (c) lube oil and (d) intercooler. The temperatures which this usable heat covers range over the entire spectrum of these needed in residential and commercial applications.

An expense, associated with the use of rejected waste heat from Diesel engines, is usually related to costs of the heat exchangers, controls, and extra piping and installation. These costs will be addressed later.

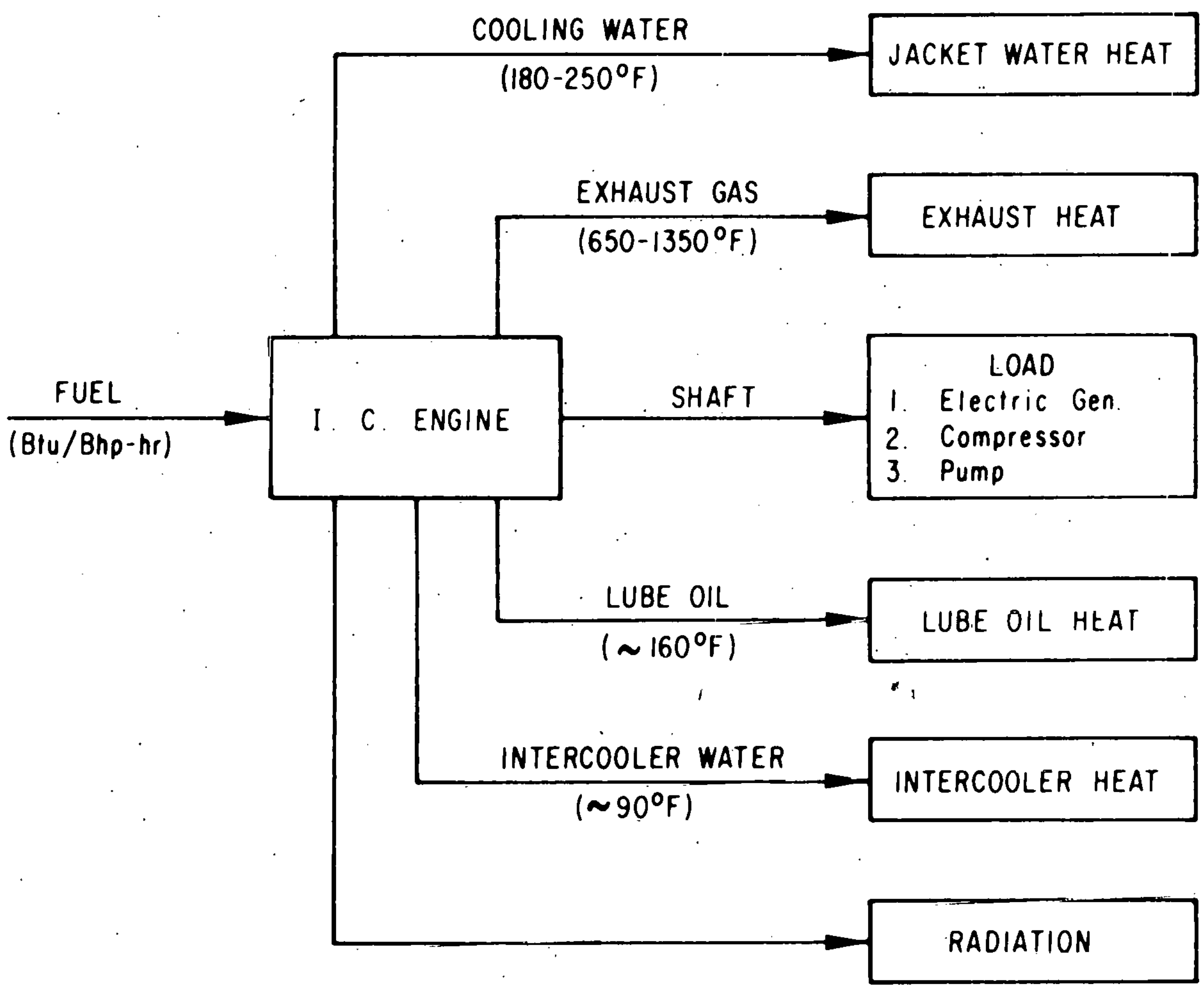


Fig. 4.2 Energy Distribution Diagram for a Diesel Engine

4.2.2 Performance

As the basis for evaluating the performance characteristics of the Diesel engine, the heat balance at full- and part-load of a low-to-medium-speed engine was selected. This heat balance is shown in Fig. 4.3. The net work output of the Diesel and Stirling engine are remarkably similar and show little loss of efficiency down to about 50% of full load. Unlike the Stirling, however, heat is rejected from several points as shown. Most of the rejected heat leaves the engine through the high temperature (650°F to 1000°F) exhaust gases.

The peak efficiency at full load of the Diesel is about 36 -- 38%. This is assumed to apply down to about 50% of full load. Of the heat rejected through the exhaust gases, cooling water and lube oil, only part of it is recoverable as useful energy. For example, to avoid condensation of harmful acids which would destroy the heat exchanger, exhaust gases are not cooled to less than 300-325°F. Cooling to lower temperatures would require a larger heat exchanger, and more expensive materials would have to be used. Forty-two percent of the fuel energy is recoverable as useful thermal energy. Some 22% is rejected to the environment, for a net thermal efficiency of about 78%.

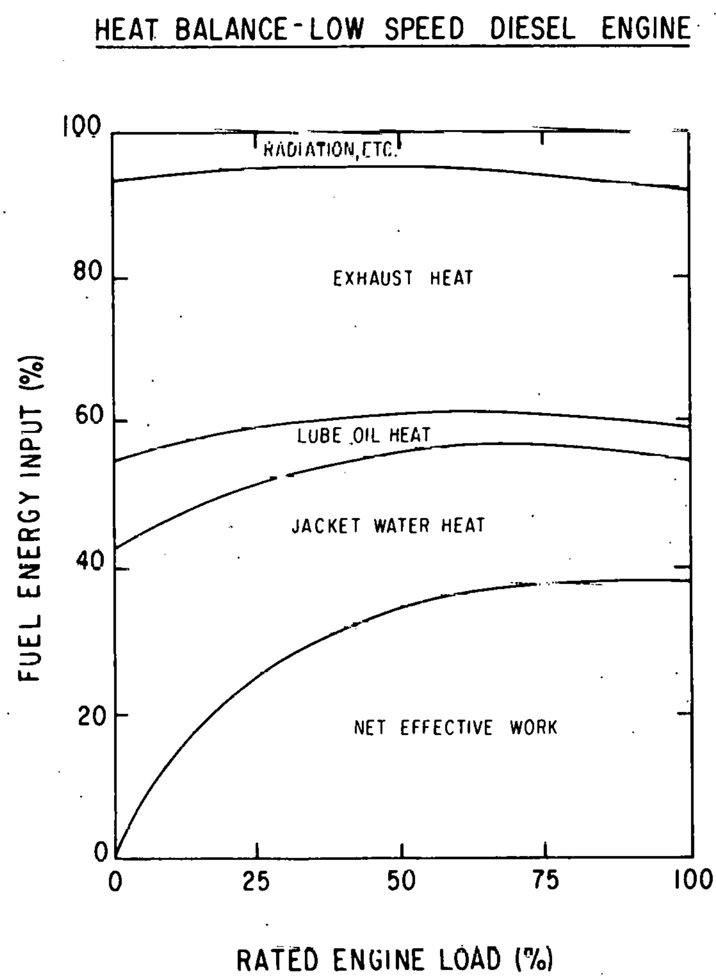


Fig. 4.3 Low-Speed Diesel Heat Balance

4.2.3 Costs

The uninstalled capital cost of a Diesel engine is given by:

$$I_{ED} = 731.91\ Q^{-.171} \qquad (4.1)$$

where:

I_{ED} = Capital Cost (\$/kW), and
Q = Engine Capacity (kW).

The total investment, when the engine is in place for use in a Total Energy System, also must include the installation cost, generator cost, controls cost, and heat-recovery equipment cost. In general, on a cost/unit of power output, this amounts to about \$150/kW of installed engine capacity. Thus, the total investment cost for a Diesel engine is given as:

$$I_{ED}^{T} = 150 + 731.91\ Q^{-.171} \qquad (4.2)$$

For example, the total installed cost (in 1977\$) of a 1000 kW machine would be \$375/kW.

The operating costs of a Diesel in mills/Bhp-h are given as:[16]

$$C_o = 10.644-4.031\cdot 10^{-3}\ X + 6.659\cdot 10^{-7}\ X^2 - 3.870\cdot 10^{-11}\ X^3 \qquad (4.3)$$

where:

X = Engine Capacity (Bhp).

Similarly, the maintenance costs (\$/Bhp-yr) are:[2]

$$C_M = 4.9633-1.9709\cdot 10^{-3}\ X + 3.2972\cdot 10^{-7}\ X^2 - 1.8839\cdot 10^{-11}\ X^3 \qquad (4.4)$$

In practice, most of this can be reduced to a constant of about \$.05/kWh.

4.2.4 Future Development

The future development of the Diesel engine is somewhat uncertain. With normal improvements in technology, the efficiency of today's engines may be expected to improve. The main technological "breakthrough" areas are seen in the development of: (a) coal-using Diesels, and (b) adiabatic Diesels.

The first development, if successful, will result in Diesel engines able to use a non-scarce fuel, such as coal, in either a coal-oil slurry or as a finely ground powder. Currently, the Department of Energy is in the early stages of a program aimed at determining the feasibility of burning such fuels in modified engines. If this program is successful, and such an engine is developed, it would possibly be in the same time scale as the Stirling engine development. Thus, a competitor would be created for the Stirling engine, which not only would have good efficiency, but also would use non-scarce fuels.

A most interesting developmental program is that of the adiabatic Diesel,[18,19] the initial impetus of which is to develop an engine for use in U.S. Army tanks. The program is sponsored by the U.S. Army Tank - Automotive Research and Development Command along with the Cummins Engine Co. Using ceramic materials on the upper cylinder walls, piston, and head, the adiabatic Diesel is designed so that little or no heat is rejected through the cooling water. This, in itself, increases the efficiency of the basic engine by about two percentage points. Exhaust gases now carry away the rejected heat and are passed through a turbine or Rankine-cycle engine where more work is done. The overall efficiency of this engine is not expected to approach 50%. Current plans call for the construction and testing of a prototype engine for automotive application in 1979. The developers feel that this engine, if successful, will be easily adaptable to stationary engine applications. Costs are expected to be the same, or slightly higher than a similarly sized, conventional Diesel engine.

4.3 GAS TURBINES

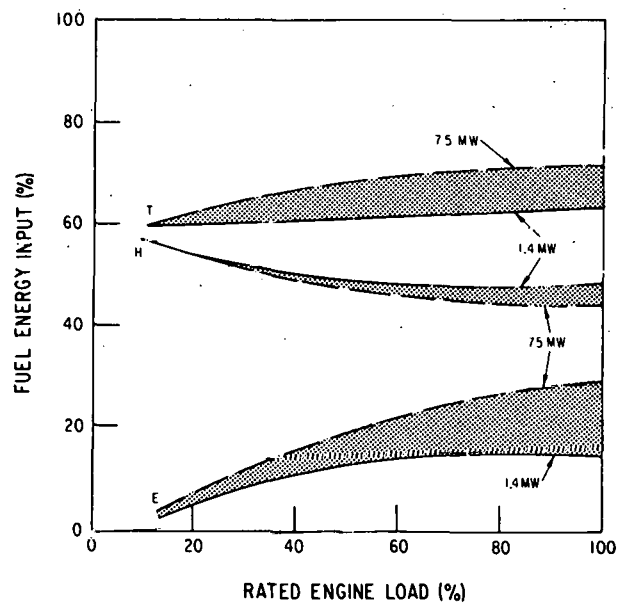
4.3.1 Current Status

Gas turbines constitute the second most popular prime-mover used in today's Total Energy Systems. They have a very low initial cost, small maintenance costs, and high reliability. Modern gas turbines are manufactured with a much larger size range than that of Diesels. Currently available engines range from about 80 to well over 100,000 hp. These include several different subtypes, such as: simple, regenerative, intercooled, reheat, and compound cycles. Of interest here will be the simple-cycle and regenerative-cycle turbines because they represent some interesting tradeoffs for energy system design. A detailed review of gas turbines and their current status can be found elsewhere.[15,17]

The smaller size, simple-cycle gas turbines have relatively low thermal efficiencies ranging from about 11 to about 25%. Although the larger sizes can reach efficiencies of about 30-33%, they are, in general, too large and noisy to use in residential/commercial energy system applications. Regenerative cycle engines are available in larger sizes, ranging from 12,000 to 50,000 hp and can attain efficiencies of up to 35%.

4.3.2 Performance

Figure 4.4 shows the heat balance of simple-cycle gas turbines.[20] Gas turbines offer the significant advantage in that almost all of their rejected heat is through the high-temperature exhaust gases. Figure 4.4 shows that the range of efficiency varies as a function of engine size from about 15-30%. The recoverable heat ranges from about 40-45%, so that the total usable heat is about 60-70%.



T = TOTAL EFFICIENCY
E = ELECTRIC EFFICIENCY
H = RECOVERED HEAT EFFICIENCY

Fig. 4.4 Heat Balance of Simple Cycle Gas Turbines[6]

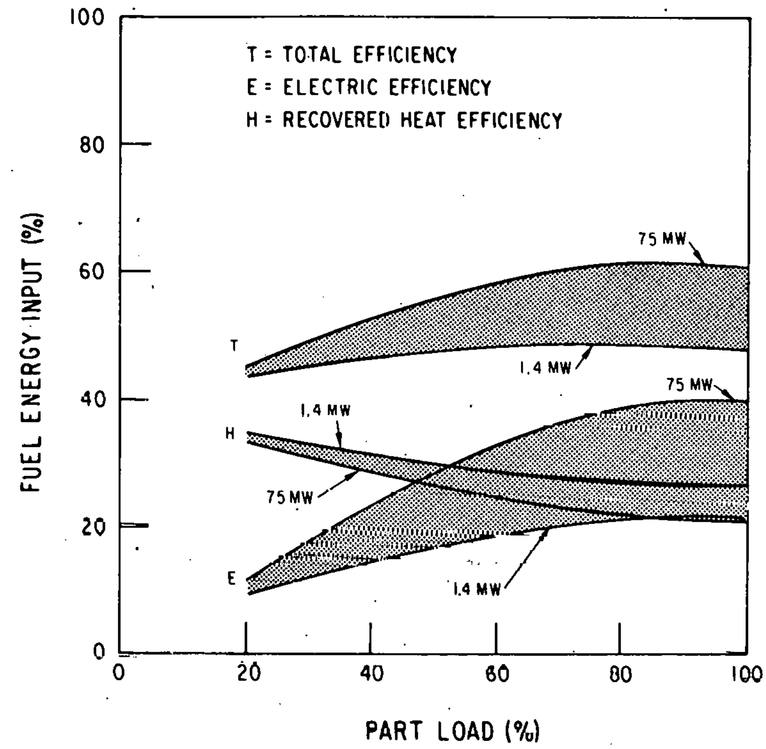


Fig. 4.5 Heat Balance for Regenerative-Cycle Gas Turbines

The heat balance for regenerative cycle gas turbines is shown in Fig. 4.5. Here, the thermal efficiency varies from 20-40% with recoverable heat varying from 20-25%. Thus, about 45-55% of the input fuel energy can be used.

Table 4.1 lists the general characteristics of gas turbines that will be used in the systems studies. Gas turbines do not have the good part-load characteristics of Diesels and Stirlings, but it will be assumed that the systems can be designed such that the engines are used at or near full load at all times.

Table 4.1 Nominal Gas Turbine Heat Balances

Engine Type	Work (%)	Recoverable Heat (%)	Rejected Heat (%)
Simple Cycle	25	45	30
Regenerative Cycle	38	22	40

4.3.3 Costs

As in the case of Stirling engines and Diesels, \$150/kW will be allocated for the cost of installation, controls, heat recovery equipment, and electric generator. Including these costs, and the cost of the simple-cycle gas turbine engine itself, the total investment per kW is given as:[17]

$$I_T^{GT} = 150 + 8861\ Q^{-.46} \tag{4.5}$$

where:

I_T^{GTS} = Total Capital Cost (\$/kW), and
Q = Engine size (kW).

For the regenerative cycle engine, the total capital cost is given by

$$I_T^{GTR} = 150 + 11731\ Q^{-.434} \tag{4.6}$$

The operating and maintenance costs are about \$1.50/hr of operation, based on 8,000 hr/yr.

4.3.4 Future Development[17]

Several companies recently have opened multimillion dollar research facilities[21-24] dedicated to gas-turbine technologies. The greatest efforts are concentrated on improving thermal efficiency. Because the theoretical limit of efficiency is a function of maximum temperature, research is being done to increase the allowable turbine inlet temperature and is proceeding in two directions. The first-stage blades of multi-stage turbines are cooled by compressed air which is admitted to the hollow center of the blade and then passed into the flow stream through a porous-mesh blade surface material. Currently, this allows turbine inlet temperatures of up to 2,500°F and thermal efficiencies of 38% for smaller size turbines. Allowable temperatures may be further increased by using ceramics. If the combustor, nozzles, and turbine blades were made of high-temperature ceramic, the theoretical stoichiometric temperature limits could be approached. However, this would cause problems, such as emissions, in other areas.

Fuel also is an important area of development, and the design of a gas turbine allows it potentially to burn almost any fuel. The advantages of burning solid waste, crude and residual oils, pulverized coal, and high-sulfur fuels are many, so research in these areas would be valuable in view of present energy problems.

Another area of gas-turbine development concerns maintenance. Many components of industrial gas turbines are undergoing design evaluation and are subject to future improvements in maintenance intervals, procedures, and control. The classical, aircraft-engine approach is to schedule maintenance at very short intervals to protect passengers and planes. However, because industrial-type gas turbine reliability is not as critical, maintenance is subject to other constraints.

5. COMPARISONS OF ALTERNATIVE PRIME-MOVERS*

5.1 PERFORMANCE

The primary engine/generator systems with which the Stirling engine must compete in community system applications are:

Diesels,
gas turbines, and
Rankine cycle turbines.

Of these options, the first two are seen as the only competitors for the relatively small systems of less than about 5 MWe since small steam turbine costs increase and efficiency decreases rapidly. With the possible exception of organic Rankine-cycle engines, all of these competitive prime-mover options are in a more advanced state of development than are Stirling engines and have been used in Total Energy Systems. Therefore, the Stirling engine must show significant potential advantages over the alternatives to justify a large research and development effort.

The most important characteristics for comparing engine options include:

thermal efficiency
fuel flexibility
emission
noise and vibration
capital costs
operational and maintenance costs

The first four of these will be discussed in this section; the last two will be covered in Sect. 5.2.

5.1.1 Thermal Efficiency[25]

Thermal efficiency, η_t, is defined as:

$$\eta_t = \frac{\text{electric output}}{\text{energy content of fuel consumed}}$$

*Parts of this section were adapted from a report by Arthur D. Little, Inc., for Argonne National Laboratory.

With fuel costs currently at about 45¢/gal (3.20/10^6 Btu) fuel alone contributes about 3.1¢/kWh to the operation of a 35% engine-generator. This cost increases to 4.4¢/kWh if the engine-generator is only 25% efficient. For larger engine/generator systems, with high load factors, the cost of fuel indicated above is the largest, single, operating cost. If the cost of fuel increases to 90¢/gal ($6.40/$10^6$ Btu) fuel costs would predominate by a wide margin over other operating costs. This sensitivity of power costs to efficiency allows a significant premium to be paid for a highly efficient engine. For example, increasing engine-generator efficiency from 30% to 35% can be worth about $100/kW in additional capital expenditures assuming capital costs of about 20% and a high- load factor.

The above arguments certainly are valid for an engine-generator where the only output is electric energy. However, there are complications when using engine-generators within a Community Energy System context because the waste heat resulting from the engine operation often can be utilized. In those systems where there is not sufficient waste heat available, the above arguments for high efficiency would have to be reevaluated. Even here, however, it may be more advantageous to: (1) operate a highly efficient power cycle that drives a heat-pump system rather than compromise the efficiency of the basic power generation unit, or (2) use solar energy to supply a portion of low temperature heat needs.

In the systems studied in this chapter, the thermal efficiency, recoverable heat, and rejected waste heat for each engine option are given in Table 5.1. Included in this table are nominal values for each engine type.

Table 5.1 Nominal Heat Balances of Prime-Movers as a Percentage of Fuel Input

Engine Type	Work	Recoverable Heat	Rejected Heat
Diesel	36	42	22
Adiabatic Turbo-Compound Diesel	47	36	17
Gas Turbine (Simple)	25	45	30
Gas Turbine (Regenerative)	38	22	40
Stirling (Current)	34	54	12
Stirling (Advanced)	46	41	13

The adiabatic, turbocharged Diesel is included here, but is not considered in the systems studied. Table 5.1 notes that, with the possible exception of the adiabatic Diesel, the Stirling engine offers an option that, not only has high efficiency, but also has high recoverable heat. This particular attribute makes the Stirling very attractive for Community Energy System applications.

5.1.2 Fuel Flexibility

One of the major thrusts of the present National Energy Policy is to develop power systems that can use a variety of liquid, gaseous, and solid fuels. In particular, those systems that can utilize coal, municipal solid wastes, and biomass derivatives (wood chips, etc.) have a great long term advantage over those systems that require highly refined liquid or gaseous fuels for their operation. Of the systems considered, only the Stirling engine and Rankine engines have a high degree of fuel flexibility. High and medium speed, Diesel engines require refined Diesel fuel*; gas turbines are highly restrictive in their acceptable fuel types to refined petroleum products and gaseous fuel types.

Although programs to liquify and/or gasify coal into easily used fuel forms have a high priority, the resultant fuel forms appear to have high projected costs at this time as compared to direct coal combustion, and may have problems with fuel-bound nitrogen as well.

5.1.3 Emissions

All engine systems will have to satisfy EPA-imposed emission standards. When burning refined liquid fuels or gas, all the systems can satisfy these requirements, although the Diesel engines have lingering NO_x, smoke, and odor problems, which have not yet been resolved. However, both Stirling and Rankine can burn any given fuel cleaner than their internal combustion counterparts because they use steady-state, external-combustion processes. Moreover, the Stirling and Rankine engines probably can satisfy these requirements by burning a wide range of solid or unrefined fuels and using proper combustion technology (exhaust gas recirculation, fluidized beds,

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*Coal-driven Diesel engines are under active investigation, and currently available low-speed, marine engines have been run in residual fuel.

etc.). However, each fuel type/combustor system arrangement would have to be considered separately as is now the case for large steam power plants.

5.1.4 Noise and Vibration

The operation of all mechanical and combustion systems causes some level of noise and vibration. Such noise and vibration problems are particularly severe for Diesel engines because of the periodic nature of the combustion and mechanical motion processes. Even with Diesel engines, however, noise levels can be made consistent with OSHA standards with careful acoustic design (mufflers, sound-proof enclosures, etc.) and with mechanical isolation. However, the requirements to lower noise levels to the OSHA standard could significantly (15-25%) increase the installed cost of Diesel generators in a Community Energy System application.

Gas-turbine generators can meet OSHA noise standards by using inlet and exhaust* mufflers, but at significant cost increases over the baseline engine costs.

Stirling engines can be made completely mechanically balanced thus eliminating the mechanical vibration problems. Noise would result primarily from the combustion system which can readily be made acceptably quiet with proper combustion chamber design (again, because of the continuous nature of the combustion chamber) as well as by operating at near atmospheric pressure.

Rankine cycle engines also should have little problem meeting OSHA noise standards.

The main characteristics of the engine alternatives are summarized in Table 5.2. The uncertainty of the figures relating to Stirling engines is greater than for those relating to the gas turbine which, in turn, is greater than for the Diesel as reflective of their relative states of development.

The Diesel engine characteristics are consistent with a four-stroke, turbo-supercharged, IC engine with exhaust gas recirculation for pollution control. The gas turbine for applications in the 100-kW, or better, range (following an extrapolation of current development trends) is taken to be of

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*The exhaust muffler can often be incorporated into the waste heat boiler system in a Total Energy System arrangement.

Table 5.2 Comparison of Prime-Mover Options

	Stirling	Diesel	Gas Turbine
Efficiency			
Near Term	30-37	30-36	30-34
Developmental	40-48	40-50	35-38
Fuel Flexibility	All Fuels	Diesel, Natural Gas, Possible Coal	Specified liquid and Gaseous Fuels
Waste Heat Availability	Primarily at Low Temperatures (80-220°F)	High Temperature Exhaust, Water Jacket, Lube Oil	High Temperature Exhausts (>300°F)
Life (MTBO) Hours	20,000-30,000	20,000-30,000	10,000-50,000
Relative Cost of Maintenance	1.0	1.0	0.8
Ability to Meet 1976 Emission Standards	Yes	No (smoke and odor problem)	Yes
Can Meet OSHA Noise	Yes	Yes	Yes
Weight (lb/Hp)	6-30	6-30	4-6
Box Volume (ft^3/Hp)	0.15-0.3	0.12-0.25	0.05-0.2

the internal combustion, (4:1) pressure ratio, highly (85%) regenerative, single or two-shaft open-cycle, type. To meet top temperature conditions best, it will have blade cooling and ceramic parts in some combination to be determined by future developments. Also, it will have a pre-vaporizing combustor for NO_x control. For applications in the 1,000 kW range (again extrapolating current development trends), a similar technology is assumed and applied to a simple-cycle engine having an 18:1 pressure ratio with regenerator option.

The base-line Stirling engine (for applications in the 100 kW range) is taken to have a Philips/Rinia arrangement of double-acting pistons with swashplate drive, hydrogen working fluid, and mean pressure level power control. For applications in the 1,000 kW range, a "V"-type double-acting piston arrangement with a conventional crankshaft may be substituted.

Most of our electricity is now produced by modern, large steam power systems. In larger sizes (>500 MW) they are quite efficient (30-36%), relatively low in cost, and highly reliable. Some central facilities use back pressure turbines and supply hot water or low pressure steam for district heating and cooling and are, therefore, already being used in a rudimentary form of a Community Energy System.

However, because steam power systems do not scale down well into smaller power units, their flexibility is limited in a Community System application. The smallest steam power systems commercially available have an output of 1 MW power range, and these have relatively low efficiency (15-25%), and relatively high costs. This reduced technical/economic performance of smaller outputs results from several factors, including higher optimum turbine speeds, inability to justify the complexities of feedwater heating via interturbine stage extraction, costs of water control, etc.

5.1.5 Advantages of the Stirling Engine

Based on the above comments, it appears that the Stirling engine has relatively limited advantages over one or more alternative systems based on:

noise level,
emissions,
size,
weight,
reliability, and
waste heat availability.

In these areas, alternative systems can do as well (or nearly as well) as is projected for Stirling engines, thereby providing little incentive for Stirling development. However, two important advantages exist for a properly developed Stirling engine system over any single alternative:

Fuel flexibility, and
High efficiency.

These two areas are critical in justifying the development of a Stirling engine for use in Total Energy System applications and thus are discussed in more detail below.

Current efficiency of Stirling engines is about 30-35%, a range already as high as that for Diesel engines and considerably better than that obtained with gas turbines. Only large, central station steam power plants can attain the higher end of this efficiency range.

It is doubtful whether the efficiency of Diesel power systems will improve significantly beyond that now obtained. Development of higher temperature gas turbine materials indicates that gas turbines may attain efficiency levels in the 35-38% range.

For stationary applications, particularly, there is a good possibility that the efficiency of Stirling engines could be pushed into the 45% range, with overall efficiency of 85%, thus making Stirling engines significantly more efficient than most alternatives. Even in many Community Energy Systems applications, power generation efficiency could be an important parameter.

The only two systems that currently have a high degree of fuel flexibility are the Rankine-cycle engines and Stirling engines. High performance (and efficiency) Diesel engines require refined petroleum products with a cetane number of about 50. However, large, low-speed, Diesel engines can operate with a range of partly refined or unrefined liquid fuels (such as bunker C for marine Diesels). Gas turbines must operate within a relatively narrow range of liquid distillates and gaseous fuels. These fuel restrictions may be reduced in the future.

Fuel flexibility may become paramount, assuming that the major thrust of an overall energy policy is to put increasing reliance on coal. Moreover, the ability to use municipal solid wastes and biomass-derived fuels could be of particular importance within the context of a Total Energy System.

Although it will be possible to operate Diesel and gas turbines on synthetic liquid and gaseous fuels derived from coal, present indications are that these fuel forms will be expensive; certainly more so than burning coal directly.

Presently it is difficult to attach a quantitative value to the fuel flexibility advantage of the Stirling engine. Based on the above considerations, however, it appears that this advantage may be the most important of all.

5.2 COST AND ECONOMICS

The costs, including those for initial capital, operation, and maintenance, were discussed in Chapter 3.0 for Stirling engines and in Chapter 4.0 for Diesels and gas turbines. The purpose of this section is to give some indication of the relative economics of each technological option for electrical generation only. This analysis is only a simplified version of the systems studies of Chapter 6, but it helps to indicate the tradeoffs in capital cost and efficiency when a new engine option is being developed.

The cost of generating electrical energy, given only technological options, is given by:

$$C_e = C_c + C_F + C_o + C_M \tag{5.1}$$

where:

C_e = total cost of electricity generation (¢/kWh),
C_c = capital costs,
C_F = fuel costs,
C_o = operation costs, and
C_M = maintenance costs.

Filling in the terms for each of these costs can be involved and must take into account the debt/equity split, interest rates for debt and equity, tax rates, etc. Equation 5.1 can be rewritten as:

$$C_e = \frac{I_c \, r_c}{8760 \; L} + \frac{C_f}{N_e} + \frac{M}{8760 \; P \; L} \tag{5.2}$$

when

I_c = installed cost of plant (\$/kW)
r_c = annual capital charge rate
L = load factor
C_f = cost of fuel
N_e = thermal efficiency
M = annual operating and maintenance costs
P = plant capacity.

Although this analysis could apply also to the thermal energy generated at a plant, here we will be concerned only with the electrical costs. For this analysis, it will be assumed that (1) the annual capital recovery rate is 0.25, which takes into account the interest and tax rates that would apply to a utility, and (2) for a Total Energy System, the load factor, L, is 0.6.

The efficiencies assumed for each engine option were given in Table 5.1.

The comparison will consist mainly of two parts: (1) a comparison based on the first-generation Stirling engine, i.e., a stationary engine using distillate fuels, and (2) a comparison of the costs of alternative technologies to the second-generation Stirling engine, i.e., the coal burning version. Throughout, we will assume a scarce-fuel oil cost of $3/10^6$ Btu and a coal cost of $1.70/10^6$ Btu. These costs are based on a cost of oil of $0.44/gal and $40/ton for coal. These are the costs used in Chapter 6. All comparisons are based on 1.0 MW engines.

5.2.1 First Generation Stirling Engine

Assuming the data and model presented above, the cost of electrical generation may be plotted as a function of fuel cost.

Figure 5.1 shows the comparison of Stirling engines with current technology Diesel engines. The shaded area for the Stirling engine option shows essentially the range of variation between what is possible in terms of efficiency and capital cost uncertainties. The Stirling engine becomes cost competitive with Diesel engines when the fuel cost exceeds $1.75/10^6$ Btu, provided that a target efficiency of 46% is reached by the Stirling and that the cost of the Stirling is only 20% greater than that of a similar Diesel. If the cost and efficiency targets are not met, then this break-even point will shift to the right, and, in the extreme, the Stirling

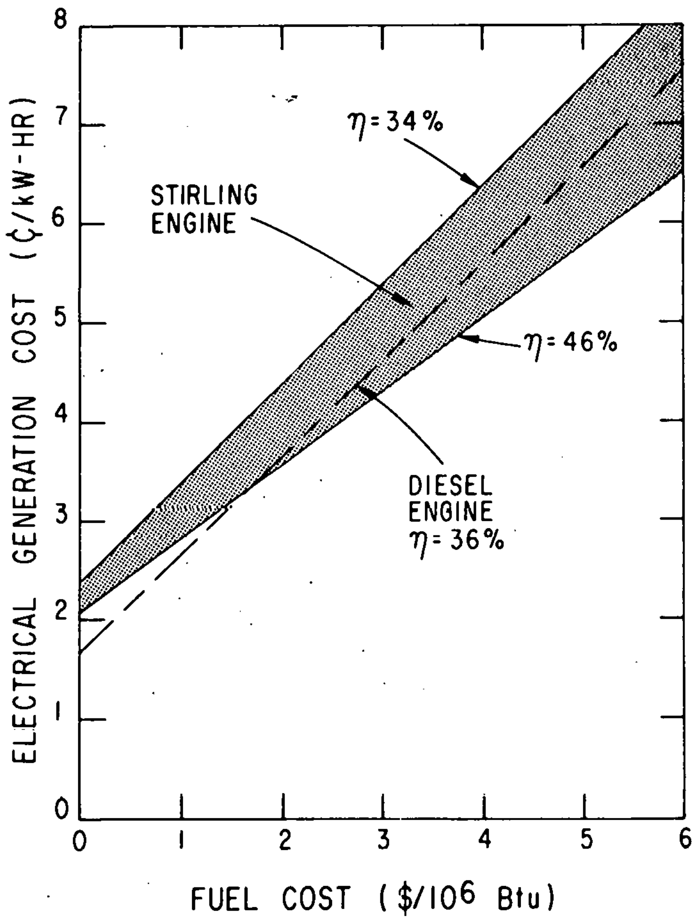

Fig. 5.1 Comparison of Costs for First-Generation Stirling Engines and Current Diesel Engine (1000 kW)

will never be cost competitive. If the Stirling meets minimum cost and maximum efficiency targets, then at $3/10^6$ Btu, the cost of electrical generation will be 0.3¢/kWh lower than that of the Diesel.

Figure 5.2 shows a comparison of the Stirling with the adiabatic, turbocompound Diesel engine. Admittedly, there is at least as great a risk in the development of this engine as with the Stirling, but it gives an indication of the tradeoffs to be considered when looking at alternative technology options. In this case, the current prediction is that the adiabatic, turbocompound engine will have an efficiency similar to that of the fully developed Stirling, and its cost will be comparable to that of a Diesel. If this were true, then the cost of operating the Stirling would be always greater than that of the adiabatic engine, and there might not be an incentive to develop the Stirling. However, in this case, the capital costs of each option are still uncertain, and this uncertainty has a strong influence on system economics.

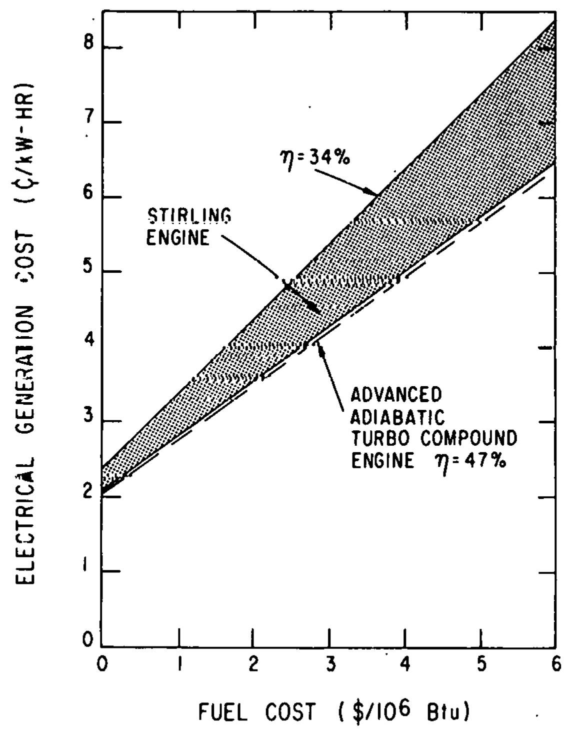

Fig. 5.2 Comparison of Electrical Generation Costs of First-Generation Stirling Engines and Advanced Adiabatic Turbo Compound Engines (1000 kW)

A comparison of gas turbines with the first-generation Stirling in Fig. 5.3 shows that the Stirling offers overwhelming advantages within the projections of cost and efficiency. Table 5.3 summarizes the costs of electrical generation for various options at a fuel cost of $3.00/10^6$ Btu.

5.2.2 Second Generation Stirling Engines

The second-generation advanced Stirling engine is expected to be the next step in the development that will ultimately allow direct coal combustion. This option is expected to cost 50 to 80% more than a similar-sized Diesel engine. Nevertheless, we are comparing a Stirling engine that uses coal costing $1.70/10^6$ Btu against engines with fuel costs of $3.00/10^6$ Btu. A significant economic advantage accrues to the second generation advanced Stirling.

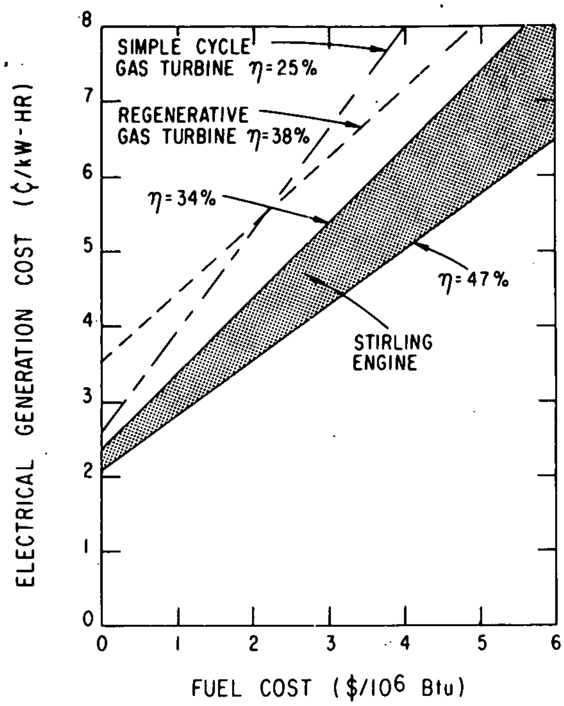

Fig. 5.3 Comparison of Electric Generation Costs of First Generation Stirling Engines and Simple and Regenerative Gas Turbines (1000 kW)

Table 5.3 Summary of Electrical Generation Costs for Various Options at a Fuel Cost of $3/10^6$ Btu (1,000 kW capacity)

Engine Option	Cost (¢/kWh)
Diesel (Current)	4.6
Diesel (Adiabatic)	4.2
Gas Turbine (Simple)	6.65
Gas Turbine (Regenerative)	6.30
Stirling Engine (First Generation)	4.3-5.4

Figure 5.4 compares Stirlings against both the current Diesel and adiabatic, turbocompound engines. At a fuel price of $3.00/10^6 Btu, the electric generation costs of the Diesel options are 4.6¢/kWh and 4.2¢/kWh. The Stirling engine, however, uses coal at $1.70/10^6 Btu, and, given the uncertainties in cost and efficiency, the generation cost would be 3.6-4.4¢/kWh. This makes the Stirling a very attractive option, especially if the efficiency target is met.

In Figure 5.5, the second generation Stirling is compared with the gas turbine options. Here, the cost advantage of the Stirling is even more dramatic than previously shown for the first generation option. The simple and regenerative gas turbines have costs of 6.7¢/kWh and 6.3¢/kWh, respectively; whereas, the Stirling cost is 3.6-4.4¢/kWh.

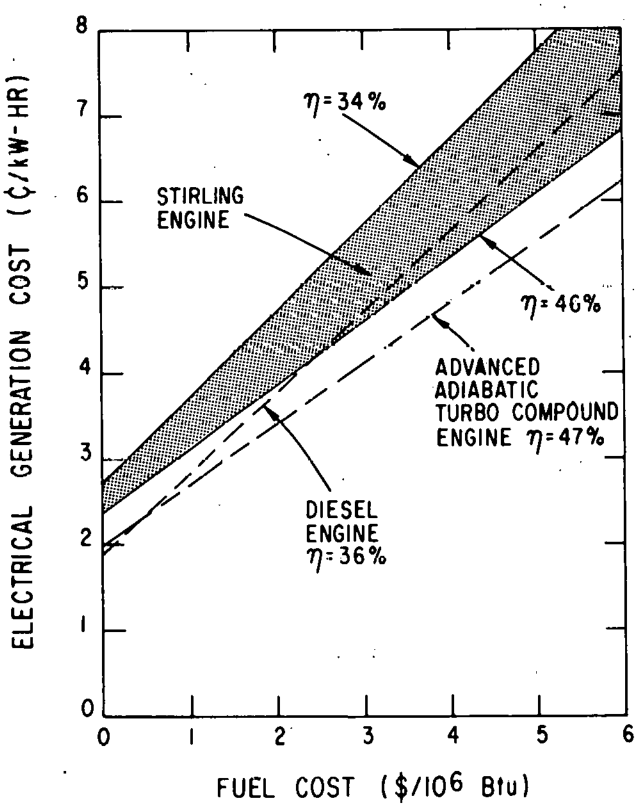

Fig. 5.4 Comparison of Electrical Generation Costs of Second Generation Stirling Engines and Diesel Engines (1000 kW)

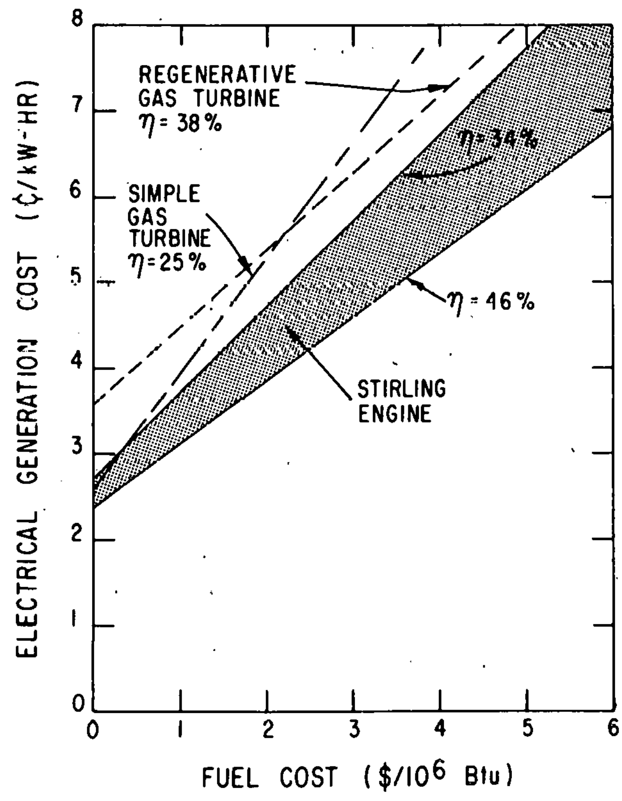

Fig. 5.5 Comparison of Electrical Generation Costs of Second Generation Stirling Engines and Gas Turbines (1000 kW)

Table 5.4 summarizes these costs:

Table 5.4 Summary of Electrical Generation Costs for Various Options vs Costs of Second-Generation Stirling Engine

Engine Option	Cost (¢/kWh)
Diesel (Current)	4.6
Diesel (Adiabatic)	4.2
Gas Turbine (Simple)	6.65
Gas Turbine (Regenerative)	6.30
Stirling Engine (Second Generation)	3.6-4.4

5.3 CONCLUSION

Based on the above discussion and comparisons, the following conclusions may be drawn concerning the several options considered with respect to Stirling engines:

- The main advantage of the Stirling engine lies in its potential ability to use non-scarce, relatively cheap fuels, such as coal. However, to realize this advantage, the engine should use coal directly and not depend on coal-derived fuels. This advantage could be negated if coal-using Diesels are developed.

- Although the efficiency of the Stirling is potentially higher than that of the alternatives, this factor may not be as strong an advantage if the capital costs are high. The potential exists for developing adiabatic Diesels that could have at least as good an efficiency, and have lower capital costs.

- The Diesel and gas turbine power systems are all well developed and highly reliable in stationary applications. Thus, it is doubtful that the Stirling engine will be significantly superior to the conventional options in reliability and will probably have similar or only slightly better maintenance requirements than a similar Diesel engine.

- It is not clear that the availability of waste heat from the coolers of a Stirling engine is a particularly significant advantage. This heat is available only at relatively low temperatures, unless engine efficiency is significantly compromised.

- The alternative (and well-proven) engines can satisfy the requirements relative to noise, vibration, and emissions sufficiently well to provide little incentive to develop an alternative engine based on these criteria.

6. TOTAL ENERGY SYSTEMS ANALYSIS

6.1 COMMUNITY DESCRIPTION

To investigate the various alternative technologies to be used in the total energy study, the Fox Valley Center and Villages were chosen. This community is a new development located in Aurora, Illinois. The Fox Valley Center is a two-level, enclosed mall, shopping center that houses four large department stores and some 150 specialty shops, boutiques, and restaurants, having a total floor space of 1,709,000 ft^2. The land area associated with the center is 115 acres. The remaining area of the development - some 725 acres - is subdivided into four zones. Zones B and C consist of offices and commercial space; whereas, D and E include mainly residential buildings. The layout of the community is given in Fig. 6.1 in which Zone A represents the Fox Valley Center. Table 6.1 shows a breakdown of the different zones of the community with the corresponding floor space.

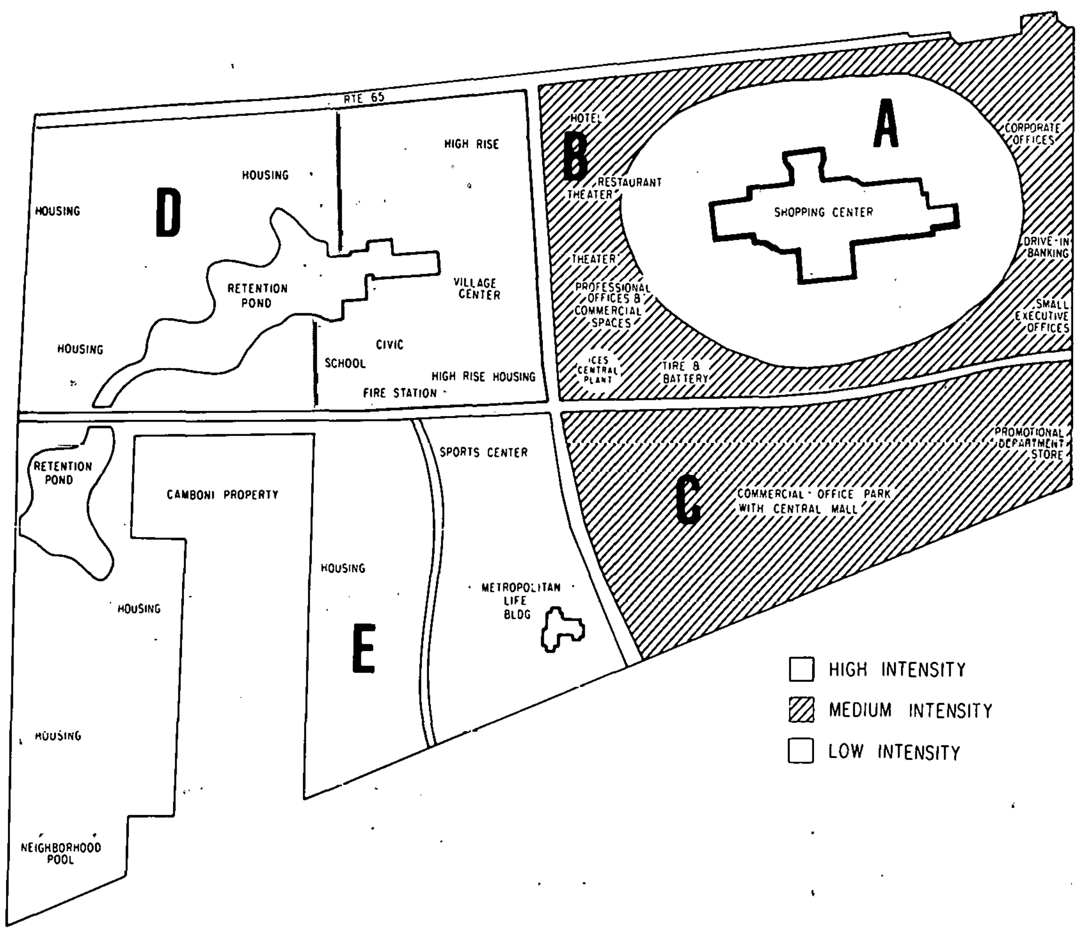

Fig. 6.1 Fox Valley Villages Site Plan

Table 6.1 Fox Valley Villages Development

ZONE		
A	Fox Valley Center	1,709,000 ft^2
B	Office	752,000 ft^2
	Commercial[(a)]	273,000 ft^2
C	Commercial[(a)]	800,000 ft^2
D	Residential	
	Townhouses	750 dwelling units
	Garden Apartments	408 dwelling units
	Mid-Rise Apartments	466 dwelling units
	Town Center Commercial	206,000 ft^2
	School (K-8)	23,000 ft^2
	Fire Station	10,000 ft^2
E	Residential	
	Townhouses	900 dwelling units
	Garden Apartments	702 dwelling units
	Offices[b]	360,000
	Commercial[a]	15,000 ft^2
SUBTOTALS		
	Fox Valley Center	1,709,000 ft^2
	Office	1,112,000 ft^2
	Commercial	1,088,000 ft^2
	Town Center Commercial	206,000 ft^2
	School	23,000 ft^2
	Fire Station	10,000 ft^2
	Residential	3,871,200 ft^2
TOTAL		8,012,200 ft^2

(a) Commercial includes hotel, restaurants, theaters, the Metropolitan Life Insurance Company Building, and similar uses.

(b) Includes future expansion of the Metropolitan Life Insurance Company Building site.

The Fox Valley Center and Villages were selected for this study because they had been the subject of earlier investigations and thus the required information is readily available. Furthermore, by being subdivided into zones, it allows us, through combination of different zones, to construct communities with various proportions of residential and commercial occupancy and various thermal-to-electric demand ratios. For the study, four different groupings of these zones were examined:

(1) Zone A; Fox Valley Center (commercial only);

(2) Zone D; 89% residential, 11% commercial;

(3) Zones A, D, and E; 60% residential, 40% commercial; and

(4) Fox Valley Center and Villages; 48% residential, 52% commercial.

6.2 ENERGY DEMAND

For each of the four groupings chosen, the energy demand was calculated for electricity, cooling, heating, and domestic hot water. Reference 26 was used as a basis for these calculations. Figure 6.2 presents the hourly behavior of the non-HVAC (Heating Ventilating and Air Conditioning) electric demand as well as the heating demand during the winter design day of the Fox Valley Center. The non HVAC electric demand peaks in the evening hours, and consists mainly of the interior and exterior lighting, and includes the parking lot lighting after dark. The maximum heating load occurs in the morning hours because of the temperature setback during the night. In the

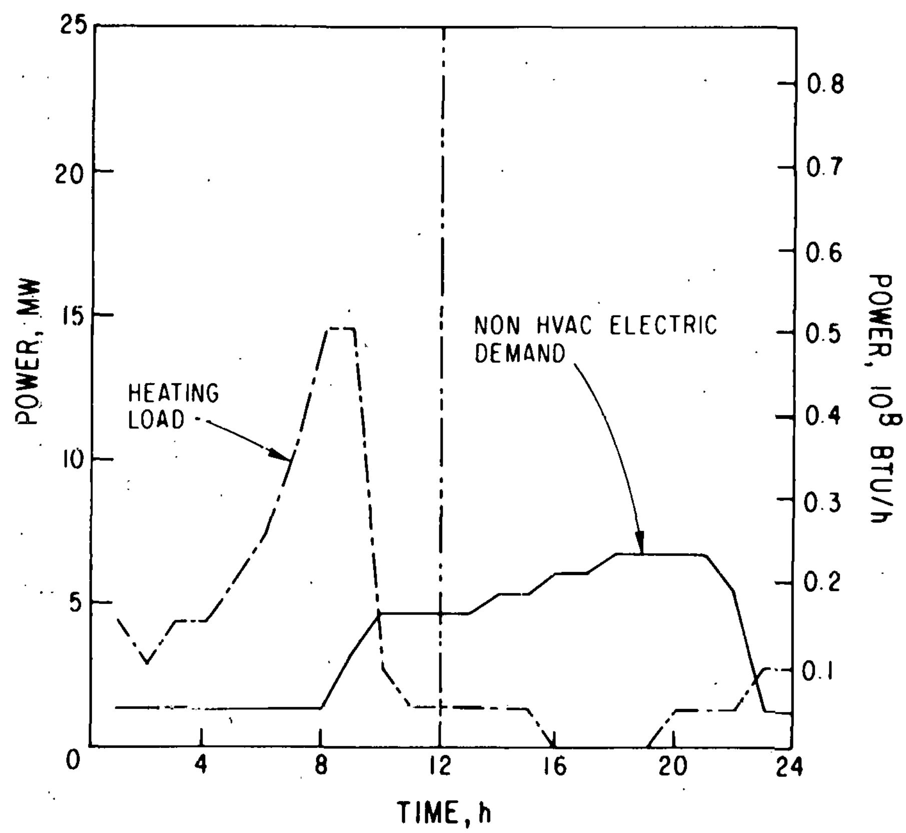

Fig. 6.2 Non-HVAC Electric and Heating Demand Profile of the Fox Valley Center for the Winter Design Day

early evening hours, the heating demand drops to zero because the heat produced by the lighting is sufficient to cover the heat losses of the center. Figure 6.3 graphs the hourly non-HVAC electric demand, as well as the cooling demand during the summer design day of the Fox Valley Center.

In the case of the cooling load, the maximum occurs in the late afternoon hours when the outside temperature reaches its maximum. Similar curves for the winter and summer design days were obtained for the remaining three groupings of zones, and these are given in Appendix A. The demand for domestic hot water has not been included in the figures because of its small magnitude compared to the heating and cooling demands. However, the domestic hot water demand has been taken into account in the design of the system and in the fuel consumption calculations.

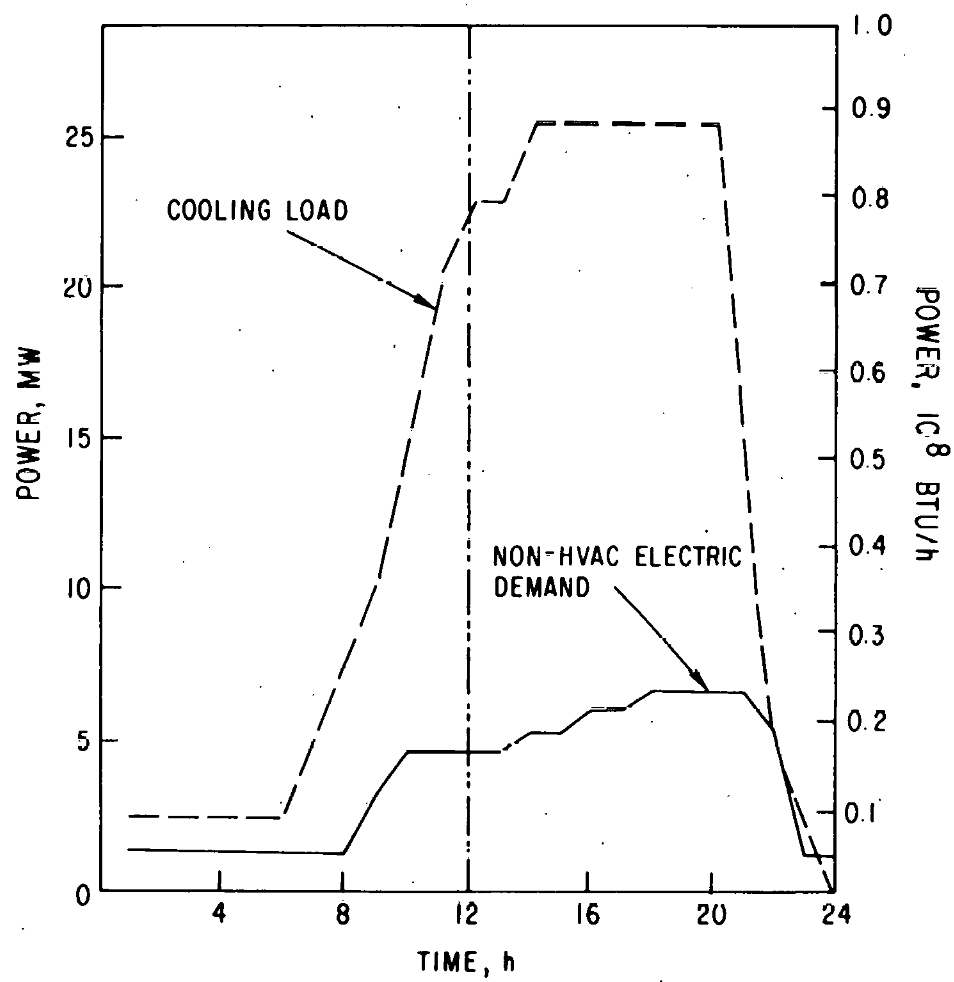

Fig. 6.3 Non-HVAC Electric and Cooling Demand Profile of the Fox Valley Center for the Summer Design Day

6.3 METHODOLOGY

6.3.1 Design

Given the energy demands for the winter and summer design days, the total energy system can be adequately designed. In the following paragraphs, an outline of the design process, common to all prime-movers considered, will be presented. More detailed descriptions will be given in later sections where the systems for each prime-mover are discussed.

The first constraint that has to be satisfied by the Total Energy System is the maximum electric power demand. The prime-mover chosen has to satisfy, not only this peak non-HVAC electric demand, but also the electric load required for driving the pumps and the other auxiliary equipment of the system. This load is only estimated in this study; a detailed calculation of auxiliary equipment was deemed unnecessary for our objectives. For the prime-mover chosen and the electric output required, the amount of recoverable heat can be estimated. If this heat is not sufficient to cover the heating load for the design winter day, the power of the prime-mover is increased. The additional electrical output is used in electric boilers and, together with the recoverable heat, satisfies the heating load. The system thus far can satisfy the electric and heating load; the only constraint left is the cooling load. Recovered heat from the prime-mover is usually insufficient to produce, through absorption chillers, the amount of cooling required. Two design options are available for increasing the amount of cooling produced. In the first option, A, hot water boilers are introduced into the system to increase the hot water available for the absorption chillers, the number of which is also increased accordingly. In the second option, B, the electrical output of the prime-mover is increased, and the additional electric power is used to drive compressive chillers to satisfy the remaining cooling demand.

In the above calculations, hot- and chilled-water storage is included to reduce the peak heating and cooling loads and, therefore, the design power of the equipment and increase the efficiency of the system.

To compare the costs of different designs, an estimate of the annual fuel consumption by the Total Energy System is required. From the demand curves for the design days, the ratio of the average demand to the peak demand is calculated for the electric, heating, and cooling loads. Variations of peak and of the average value over the year are assumed to have a certain profile. Thus, the calculation of the annual fuel consumption becomes rather simple and will be shown in the following sections.

6.3.2 Cost Analysis

After the design process has been completed and the equipment has been sized, the cost of the components is estimated. The cost of the prime-mover is calculated with the formulae presented in Sect. 4. This cost includes, not only the prime-mover, but also the generator, heat recovery equipment, installation, and controls. For the electric heaters with power below 4.6 MW, a constant value of $20/kW (which includes installation) was assumed. For larger units, the formula given in Ref. 27 is utilized, and the installed cost is calculated by assuming that the installation is 80% of the initial equipment cost. The resulting total cost of the electric boiler for units larger than 4.6 MW becomes

$$C\ (\$) = 40{,}000\ Q^{0.52} \tag{6.1}$$

where Q is the power of the boiler in MW.

Cost of the oil-fired, as well as of the coal-fired hot-water boilers, was estimated using Ref. 28. For the range of output capacities considered here, the cost of the oil-fired boilers is given by the relation:

$$C\ (\$) = 92{,}000 + 1{,}870\ Q \tag{6.2}$$

where:

Q, the output capacity of the boiler in 10^6, Btu/h.

For the coal-fired boilers, a cost of $0.0184/(Btu/h) was assumed.

All absorptive chillers used in the various designs are assumed to be single-effect chillers, the cost of which is calculated from Ref. 29. For the compressive chillers, Ref. 30 supplies the equipment F.O.B. cost, as well as the total amount of man-hours required for the installation. Assuming a cost of $50/man-hour, which includes the cost of materials, overhead, etc., the total cost of the compression chillers can be calculated.

The cost of the wet cooling towers used in this study was taken from Ref. 31. For the oil preparation, which includes storage, pumps, piping, etc., a cost of \$1.00/gal of storage was assumed for installations of less than 0.28×10^6 gal and 50¢/gal of storage for installations larger than 3 $\times 10^6$ gal. For capacities in between, a linear interpolation was used. The cost of coal preparation, obtained from Ref. 32, is directly related to the maximum feed rate. For feeding rates from 5 to 30 tons/h, the following formula was used:

$$\text{Cost (\$)} = 750{,}000 \left(\frac{X}{5}\right)^{0.9} \tag{6.3}$$

where:

X is the maximum feed rate in tons/h.

This cost is very approximate, especially when the coal is supplied to Stirling engines. Installations of this nature, on which cost estimates could be based, do not exist; therefore, a large uncertainty dominates the values derived from the above formula. For the cost of the electric distribution system, a price of \$80/kW was assumed. The cost estimate for the chilled- and hot-water distribution system was based on Ref. 33, where the cost of installed piping systems as a function of pipe diameter is given for three different metropolitan areas. In this study, the cost of the piping system in suburban Philadelphia was used. First, the diameter and the length of the main piping systems for the chilled and hot water were estimated. Second, the cost per foot was taken from Ref. 8 for the various pipe diameters, and the costs of the chilled- and hot-water systems were calculated separately. The total cost was estimated to be that of the chilled-water system plus 70% of the cost of the hot-water system, because some of the cost is common to both systems, e.g., excavation and backfill. The piping for the chilled- and hot-water systems in the plant was estimated to have a cost equivalent to 300 ft of installed pipe having a diameter equal to the maximum diameter encountered in the distribution system. Storage of chilled and hot water that is used to reduce the peak demand of cooling and heating was assumed to cost \$0.40/gal.

For the chemical treatment of the water, we assumed that the cost is proportional to the total amount of high- and average-quality water required. The proportionality factor was obtained from a previous study of a plant using 2000 gpm at a cost of $300,000. Estimates of the other costs are best illustrated with the aid of Table 6.2, which presents costs of a Diesel-engine-based energy system for the Fox Valley Center. The costs of the building and land are assumed to be 10% of the sum of the costs down to the chemical treatment, indicated by CD. The cost of instrumentation and controls is assumed to be 15% of the sum CE that includes the oil preparation. An estimate of the operating and maintenance costs for the total energy plant is 6% of the sum CE indicated in Table 6.2.

Table 6.2 Costs of Diesel-Based Total Energy Systems, Option A, for Fox Valley Center

Description	Cost ($ thousand)	
Diesel Engines 4 X 3 MW	4,032	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Hot Water Boilers 4 X 9.6 MW	613	
Absorption Chillers 6 X 1450 tons	1,163	
Cooling Towers 6 X 1450 tons	684	
Chemical Treatment	87	(CD 7,087.)
Oil Preparation (5 + 2.43) X 10^5 gal	676	(CE 7,763.)
Building and Lot 10% CD	709	
Instrumentation and Controls 15% CE	1,164	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	11,778	

O&M 6% CE 466.

fuel 4.53 X 10^6 gal/yr oil

To compare the costs of the various designs for the total energy systems, the present values of the various costs were calculated under the assumption that the useful life of the plant and all components is 20 years. The cost of the plant has been calculated in 1977 dollars. To find the cost in 1978, which will be the year when the plant goes into operation, a price escalator of 6% was assumed. The present value of the operating and maintenance costs, as well as the cost of the fuel, are calculated using a 10% interest rate. For 1978, a fuel oil price of $0.44/gal and a coal price of $40/ton were used. These prices were assumed to escalate at an annual rate of 10%; whereas, the cost of operating and maintenance was assumed to escalate at an annual rate of 6%. When the present values of the operating and maintenance and of the fuel costs over the 20-yr period are added to the cost of the installation, a comparison of the various designs can be made. Uncertainties over the cost of items that are common to the various designs, e.g., thermal distribution system, will not affect the result of this comparison. However, uncertainties in the cost of items that are peculiar to a certain design can affect the comparison.

6.4 DIESEL-ENGINE-BASED SYSTEMS

Two design options are available for each prime-mover, depending on whether the cooling load is satisfied by the addition of fossil-fuel-fired, hot-water boilers, and the corresponding absorption chillers, or by the introduction of compressive chillers. The first design option will be referred to as Option A; the second, as Option B. Each will be discussed in turn in the following paragraphs.

6.4.1 Diesel-Based System with Design Option A

Figure 6.4 presents a schematic diagram of a Diesel-engine-based system with design Option A. The Diesel engines supply the non-HVAC electric power required by the community, while the heat recovered by the cooling water -- together with that recovered from the exhaust gases and lubricating oil -- is used to satisfy the heating needs or, through absorption chillers, the cooling needs. For the Fox Valley Center, for which the load curves of non-HVAC electric, heating, and cooling demand for the design days were presented in Figs. 6.2 and 6.3, the peak non-HVAC electric demand is 5.3 MW. If an estimate of the electric demand for the auxiliary equipment is included, then

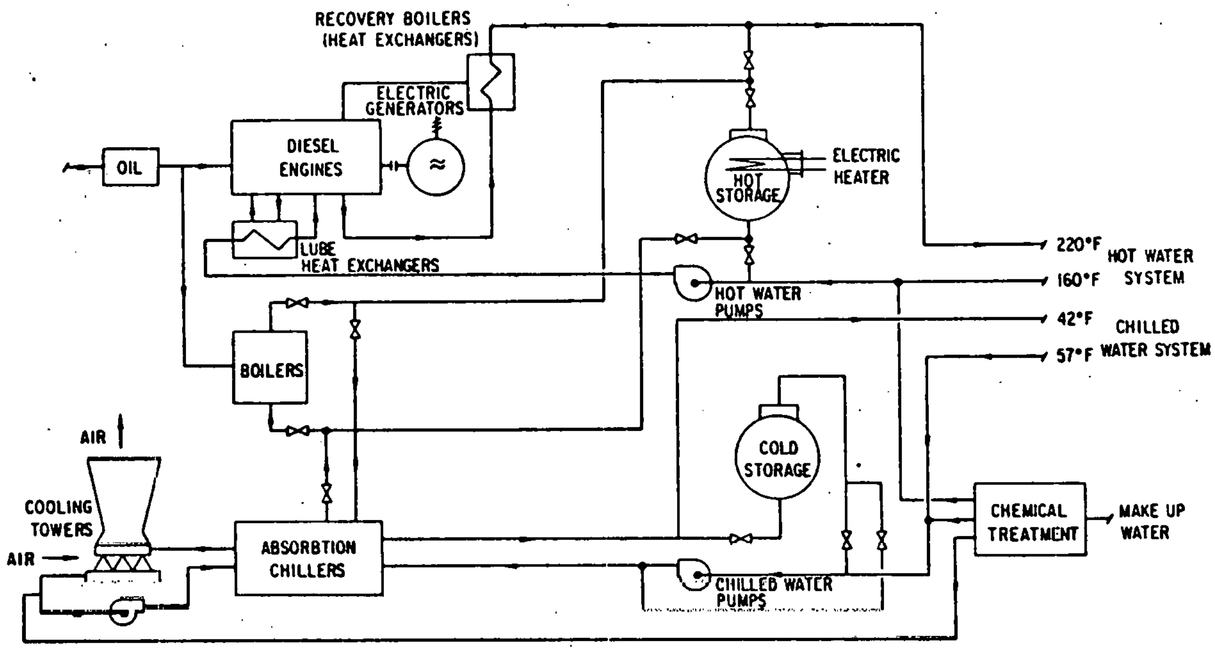

Fig. 6.4 Schematic Diagram of the Diesel-Based System with Design Option A

the peak electric demand is 6.4 MW for the winter and 8.66 MW for the summer. Assuming that the electric efficiency, is 34.2% for the Diesel engine and that 42% of the energy input is recovered as heat, the maximum heat for the heating season is 7.86 MW. The maximum electric heating is chosen as 1.3 MW, where 5.1 MW is the average non-HVAC electric demand plus the electric demand of the auxiliary equipment. Hence, the maximum heating power during the heating season is 7.86 + 1.3 = 9.16 MW.

To calculate the amount of hot water storage, refer to Fig. 6.2, and note that the peak heating demand is 15 MW; whereas, the maximum heating power is 8.78 MW for the total energy system. To satisfy the 15 MW heating demand, 5.84 MW would be required from the hot-water storage. From Fig. 6.2 it can be estimated that this power will be required for two hours, i.e., the hot-water storage must have a capacity of 11.68 MWh. For a 60°F change in temperature of the hot-water storage, a storage volume of approximately 80,000 gal is needed.

The cooling demand calculations also are needed. Figure 6.3 indicates a peak cooling demand of 26 MW or 7,400 tons that is continuous over a period of 6 hr. Assuming a chilled-water storage having an 80,000-gal capacity and a temperature change of 15°F, the peak cooling demand can be reduced to 7,260 tons. For the absorption chillers, given a hot water temperature drop from 220°F to 160°F and a chilled-water temperature change from 57°F to 42°F, manufacturers' data indicate the need for 6.07 kW of heat per one ton of cooling. Because the maximum cooling power is 7,260 tons, the heating power requirement for the absorption chillers is 44.07 MW. The recovered heat from the Diesel engines is 10.64 MW; the electric heat load is then 2.66 MW. Moreover, by utilizing the heat stored in the hot-water storage over a period of six hours, another 1.96 MW are obtained. The remaining heat required by the absorption chillers must be supplied by the oil-fired hot-water boilers, or, in other words, the power of the boilers must be 28.81 MW. Thus, the components of the Diesel-engine-based with Option A have been specified.

The next step is to estimate the annual fuel consumption of this system. From Fig. 6.2, we can obtain the peak and the average electric and heating demand for the winter design day, and from Fig. 6.3, the peak and the average cooling demand for the summer design day. Using these values, Fig. 6.5 is constructed to show the variation of the peak and average values over the whole year.

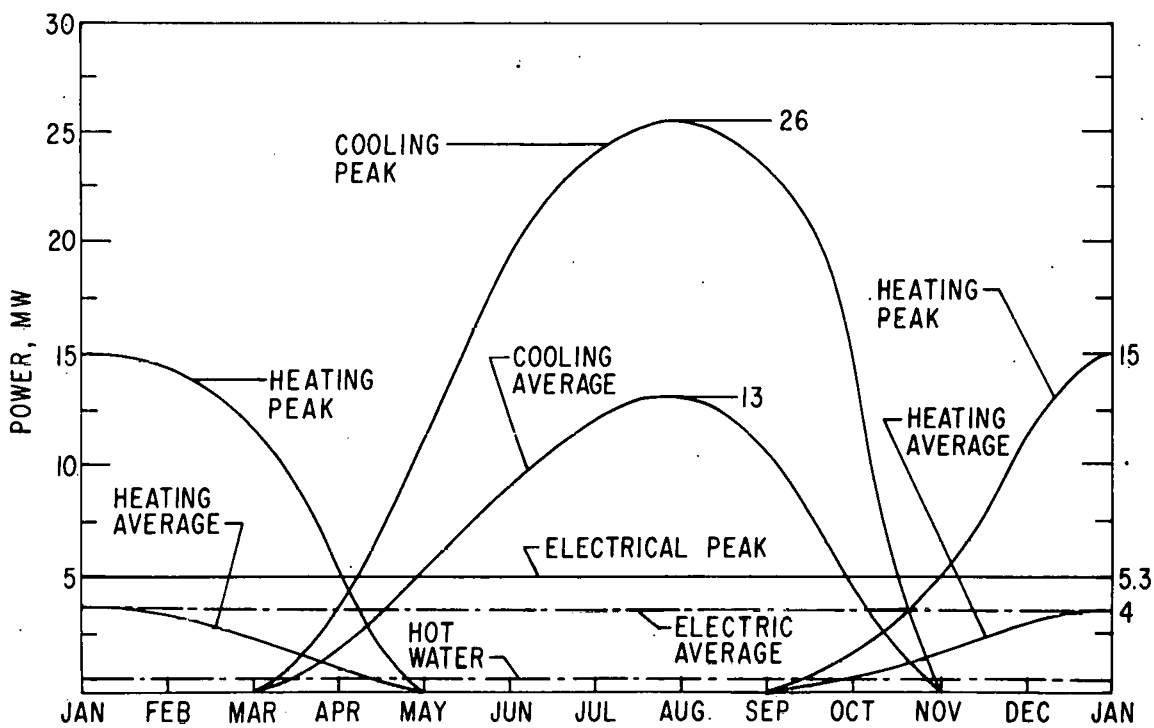

Fig. 6.5 Variation of Peak and Average Values of Non-HVAC Electric, Heating and Cooling Demand for the Fox Valley Center

The variation of the peak values of the electric demand, the heating demand, and the demand for hot water by the absorption chillers is shown in Fig. 6.6. The bottom line marked 8.66 indicates the variation of the peak electric demand; whereas, the top line marked 44.07 indicates the variation of the peak demand for hot water by the absorption chillers. The first three and last three months of the year (a total of 4,368 hours), are the months during which the peak electric demand remains constant; whereas, during the rest of the year, or 4,392 hours, the peak electric demand varies as indicated in Fig. 6.6. The area under this curve can be estimated as 6.11 x 10^4 MWh/yr. This value, multiplied by the ratio of the average to the peak electric demand, derived from Fig. 6.2, yields an annual electric consumption of 4.58 x 10^4 MWh/yr. Using the electric efficiency of 34.2% for the Diesel engine and the heating value of 150,000 Btu/gal for the Diesel fuel, the consumption of fuel by the Diesel engines is found to be 3.05 x 10^6 gal/yr. For the calculation of the fuel consumption by the hot water boilers, the area in Fig. 6.6 between the curve with the 42.11 MW peak and that with the 13.3 MW peak, is estimated. The value found, 9.77 x 10^4 MWh/yr, multiplied by the ratio, 0.5, of the average to the peak cooling demand, that was obtained from Fig. 6.3, yields the annual amount of energy to be supplied by the hot water boilers. Assuming a 75% efficiency for the boiler, the annual fuel demand is found to be 1.48 x 10^6 gal/yr. For the Diesel-engine-based design with Option A,

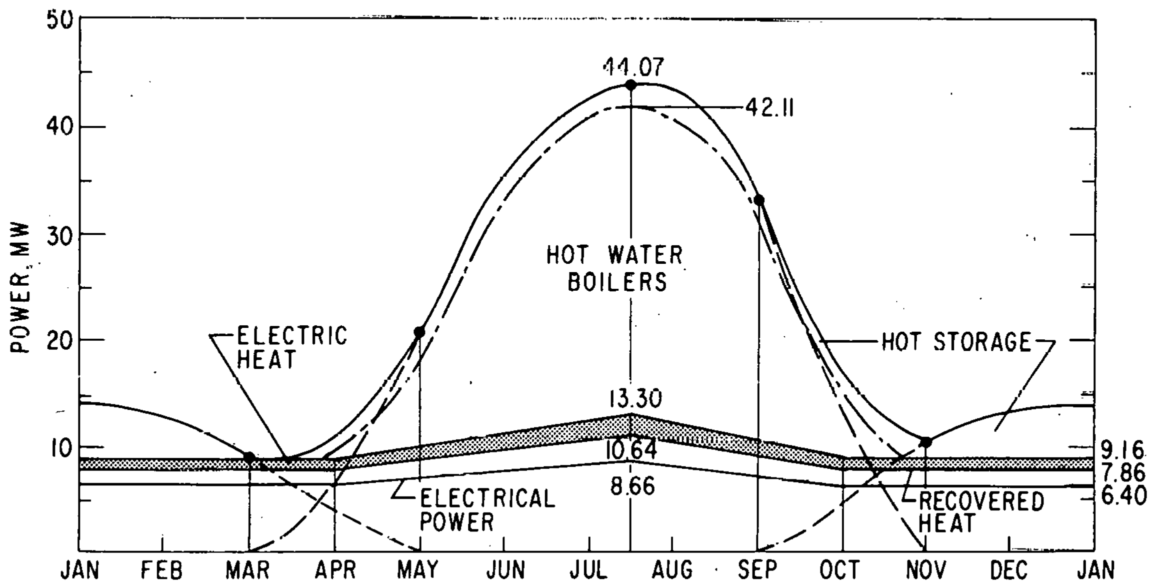

Fig. 6.6 Variation of Peak Values of the Electric, Heating, and Absorption Chiller Demand of the Fox Valley Center for the Diesel Based System with Design Option A

the total annual fuel consumption is 4.53×10^6 gal of oil. Table 6.2 presents the cost of the various components, as well as the operating and maintenance cost and the annual fuel consumption.

6.4.2 Diesel-Based System with Design Option B

Figure 6.7 indicates diagramatically the Diesel-engine-based system with design Option B. The differences between this system and the previous one are the presence of the compression chillers and the absence of oil-fired hot-water boilers. Because the calculation of the peak electric demand is the same as in the previous option, it is not repeated here. Introduction of compressive chillers requires an increase of the Diesel engine power which, in turn, increases the recoverable heat and the amount of cooling supplied by the absorption chillers. Two constraints have to be satisfied:

(1) The amount of cooling supplied by the absorption and the compressive chillers should satisfy the demand, which in this system is 7,260 tons (the effect of chilled-water storage is taken into consideration).

(2) The ratio of the electrical energy produced to satisfy non-HVAC, auxiliary equipment, and compression chiller demand to the amount of heat used in the absorption chillers has to have the same value as the ratio of the Diesel electric efficiency to the recoverable heat efficiency, i.e., 0.342/0.42.

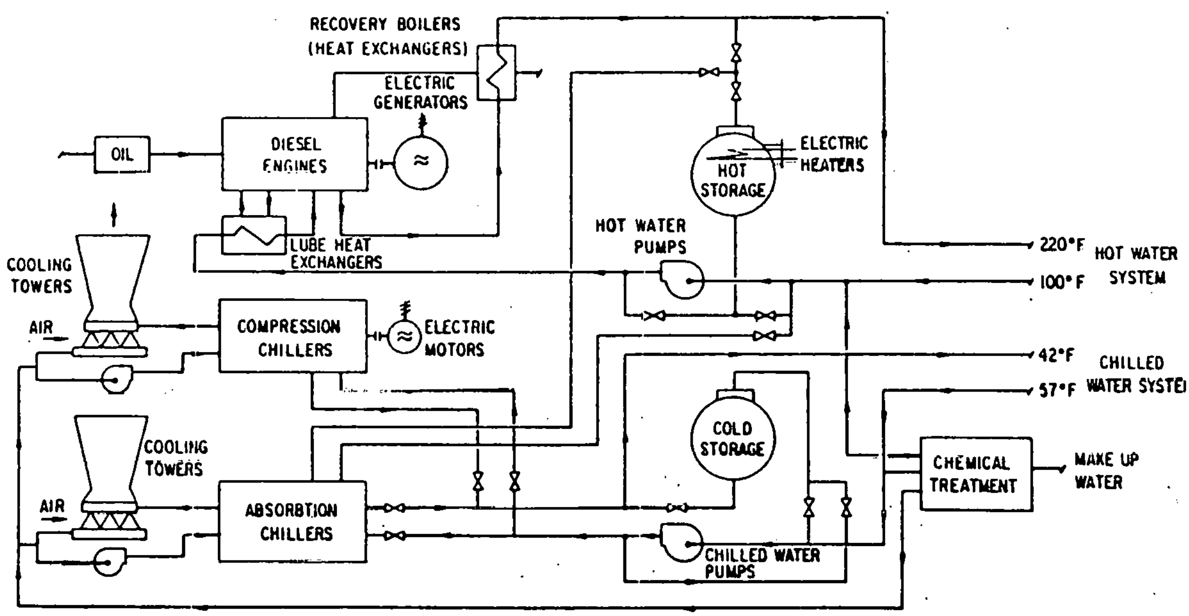

Fig. 6.7 Schematic Diagram of the Diesel-Based System with Design Option B

With these constraints and the value of 1 kW per ton of cooling for the compressive chillers, and 6.07 kW of heat per ton of cooling for the absorption chillers, the capacity of the compression chillers must be 3,500 tons and that of the absorption chiller 3,760 tons.

To calculate the annual fuel consumption, Fig. 6.8 is constructed. The area between the curves having maxima 8.66 and 12.16 MW is related to the electric energy used by the compressive chillers; whereas, the area below the curve with the 12.16-MW maximum is related to the total energy produced by the Diesel engine-generator sets. Using an electric efficiency of 34.2% for the Diesel engines, and a ratio of 0.75 for the average-to-peak electric demand, a fuel oil consumption of 3.12 x 10^6 gal/yr is obtained.

Table 6.3 presents the cost of the various components used in the Diesel-engine-based system, Option B, for the Fox Valley Center. Also presented in Table 6.3 are the cost of operating and maintenance of the plant and the annual amount of fuel consumed by the system. Tables 6.2 and 6.3 were constructed for the other three groupings of zones discussed in Sect. 6.1. These tables are presented in Appendix B.

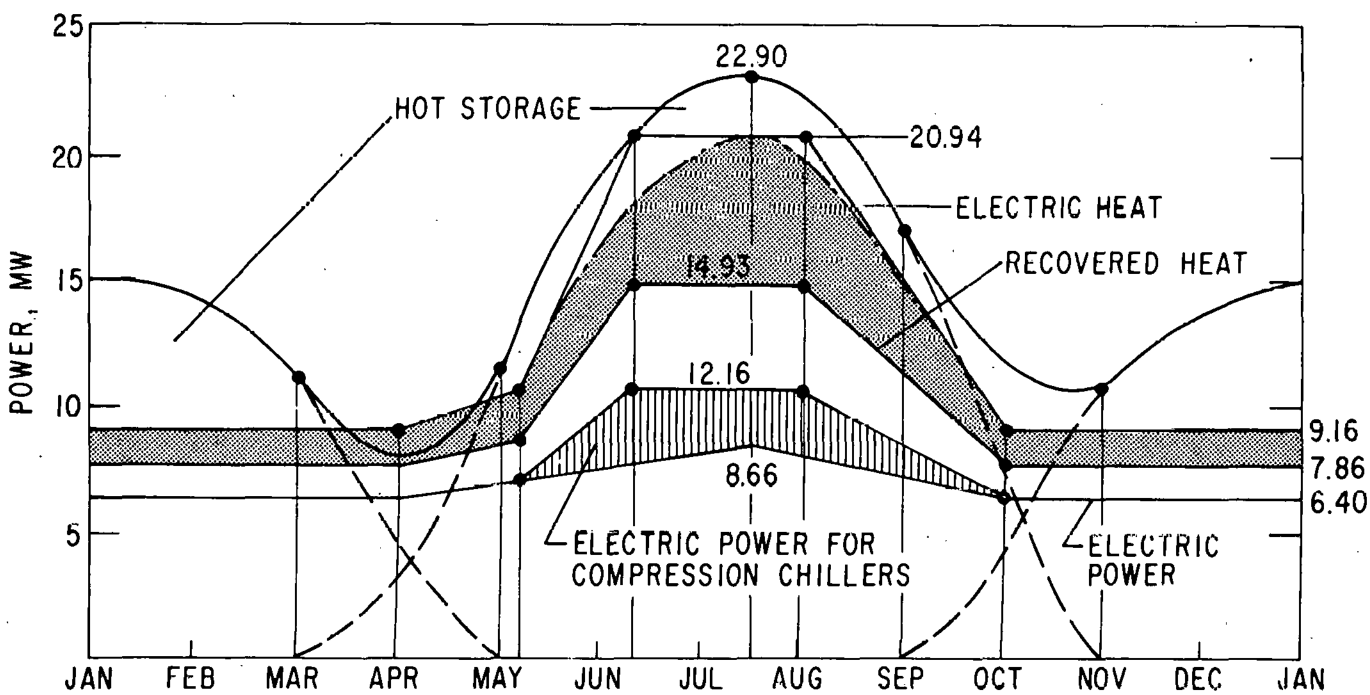

Fig. 6.8 Variation of Peak Values of the Electric, Heating, and Cooling Demand of the Fox Valley Center for the Diesel Based System with Design Option B

Table 6.3 Costs of Diesel-Engine-Based Total Energy System, Option B, for Fox Valley Center

Description	Cost (k$)	
Diesel Engines 4 X 4.1 MW	5,354	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Absorption Chillers 4 X 1253 tons	704	
Cooling Towers 4 X 1253 tons	400	
Compression Chillers 3 X 1750 tons	464	
Cooling Towers 3 X 1750 tons	405	
Chemical Treatment	80	(CD 7,915.)
Oil Preparation 5.12 X 10^5 gal X .95 $/gal	486	(CE 8.401.)
Building and Lot 10% CD	792	
Instrumentation and Controls 15% CE	1,260	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	12,595	

O&M 6% CE 504.

fuel 3.12 X 10^6 gal/yr oil

6.5 GAS-TURBINE-BASED SYSTEMS

As with the Diesel-engine-based system, there are two design options for the Gas-turbine-based system:

(1) Option A that uses fuel-fired, hot-water boilers and only absorption chillers for satisfying the cooling demand, and

(2) Option B that uses compressive chillers to satisfy the cooling demand with no fuel-fired, hot-water boilers in the system.

The main difference between the Diesel-based and gas-turbine-based systems is the smaller electric efficiency and recoverable heat in the turbine system. For the calculations, the electric efficiency of the turbine was assumed to be 22%, and the heat recovered 48% of the energy input. The amount of heat required by the absorption chillers was 5.6 kW of heat per ton of cooling because of the higher temperature of the hot water.

6.5.1 Gas-Turbine-Based System with Option A

Figure 6.9, presents schematically the gas-turbine-system, Option A, for the Fox Valley Center.

Using the same procedure as for the Diesel-engine-based system, the maximum gas turbine power is found to be 8.66 MW for Option A. The required absorption chillers have a power of 7,260 tons and the boilers a rating of 17.15 MW. Estimates of the annual fuel consumption are based on Fig. 6.10, and follow the same procedure explained in Sect. 6.4 for the Diesel-engine-based system. The estimate derived for Option A is 4.72 x 10^6 gal of oil/yr for the gas turbines and 0.69 x 10^6 gal of oil/yr for the boilers. Table 6.4 lists costs of the various components, the cost of operating and maintenance of the plant, and the annual fuel consumption for a gas-turbine-based Total Energy System with Option A.

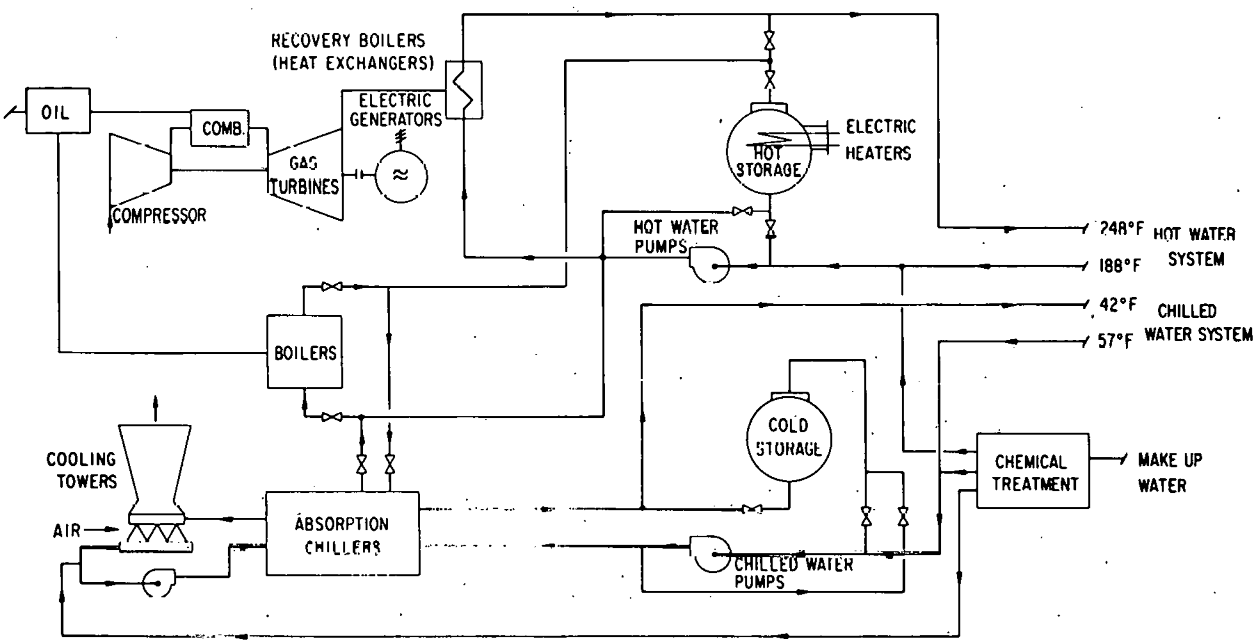

Fig. 6.9 Gas-Turbine-Based Systems with Design Option A

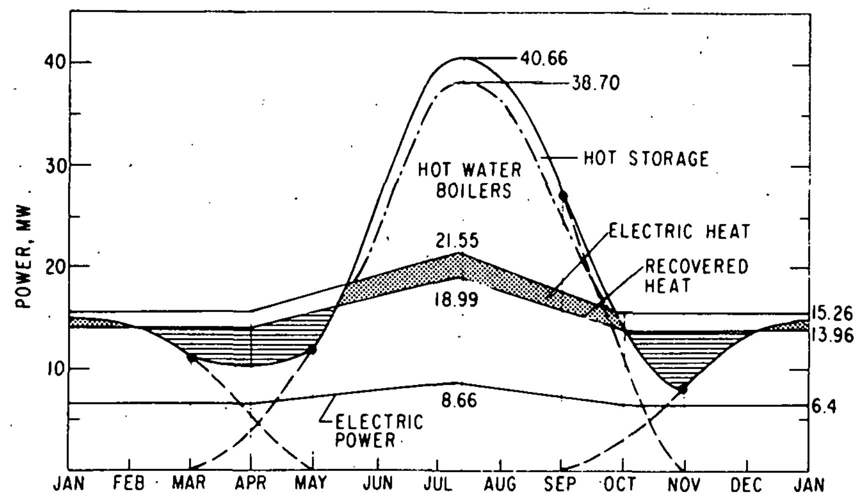

Fig. 6.10 Variation of Peak Values of the Electric, Heating, and Absorption Chiller Demand of the Fox Valley Center for the Gas-Turbine-Based System with Design Option A

Table 6.4 Costs of Gas-Turbine-Based Total Energy System, Option A, for Fox Valley Center

Description	Cost (k$)	
Gas Turbines 4 X 4.5 MW	4,521	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 1.3 MW	52	
Hot Water Boilers 3 X 8.58 MW	478	
Absorption Chillers 6 X 1450 tons	1,163	
Cooling Towers 6 X 1450 tons	684	
Chemical Treatment	86	(CD 7,308)
Oil Preparation $(7.87 \times 1.15)10^5 \times 0.89$ \$/gal	803	(CE 8,111)
Building and Lot 10% CD	730	
Instrumentation and Controls 15% CE	1,217	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	12,200	

O&M 6% CE 487.

fuel 5.41×10^6 gal/yr

6.5.2 Gas-Turbine-Based System with Option B

Turning now to the Option B of the gas-turbine-based system for the Fox Valley Center total energy system, we calculate the gas turbine maximum electric power to be 10.61 MW; compression chillers to be 1,950 tons; and absorption chillers to be 5,310 tons. Figure 6.11 presents a schematic diagram of this system. Based on estimates of the annual fuel consumption shown in Fig. 6.12, a value of 5.41 x 10^6 gal of oil/yr is obtained.

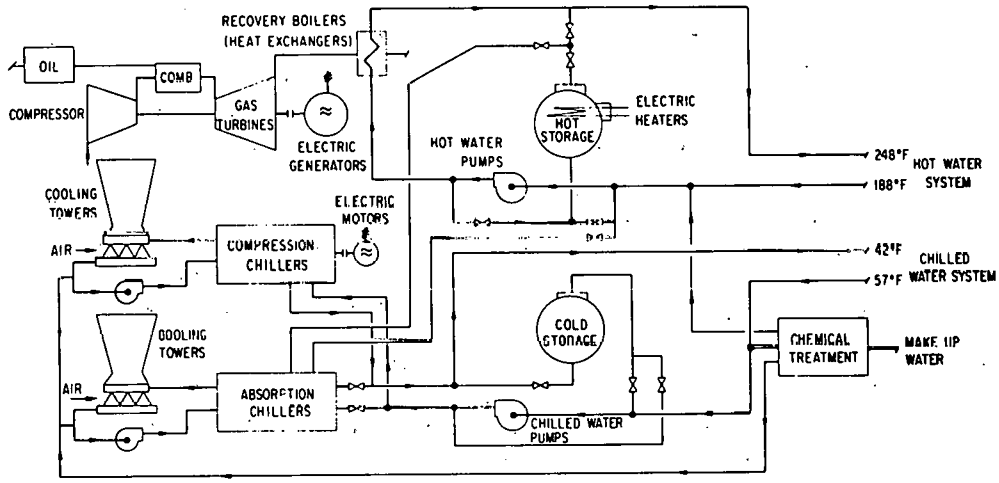

Fig. 6.11 Gas-Turbine-Based System with Design Option B

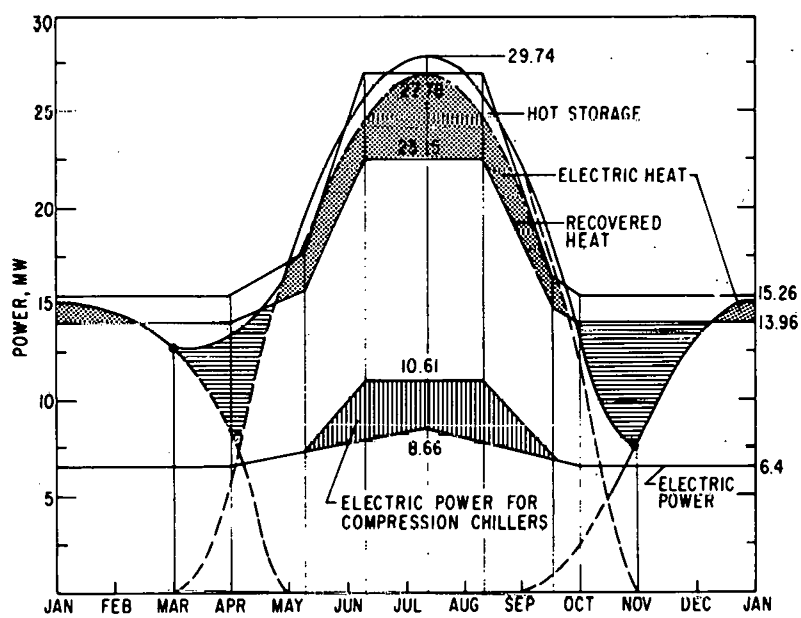

Fig. 6.12 Variation of Peak Values of the Electric, Heating, and Cooling Demand of the Fox Valley Center for the Gas-Turbine-Based System with Design Option B

Table 6.5 lists the costs of the various components, the operating and maintenance costs, and the annual fuel consumption for a gas-turbine-based total energy system with Option B.

6.6 CURRENT STIRLING-ENGINE-BASED SYSTEMS

Stirling engines of current technology are assumed to have an electric efficiency of 32.3% and a heat recovery of 54% of the energy input. Figure 6.13 presents a schematic diagram of a Stirling-engine-based system using the design Option A. The fuel, as indicated in Fig. 6.13, can be either oil or coal. It has been assumed that a second generation of Stirling engines will

Table 6.5 Costs of Gas-Turbine-Based Total Energy System, Option B, for Fox Valley Center

Description	Cost (k$)	
Gas Turbines 3 X 5.3 MW	5,120	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 1.3 MW	52	
Absorption Chillers 5 X 1327 tons	914	
Cooling Towers 5 X 1327 tons	527	
Compression Chillers 2 X 1950 tons	359	
Cooling Towers 2 X 1950 tons	297	
Chemical Treatment	84	(CD 7,677)
Oil Preparation 0.9 X 10^6 gal X 0.89 $/gal	801	(CE 8,478)
Building and Lot 10% CD	768	
Instrumentation and Controls 15% CE	1,272	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	12,660	

O&M 6% CE 509.

fuel 5.41 X 10^6 gal/yr

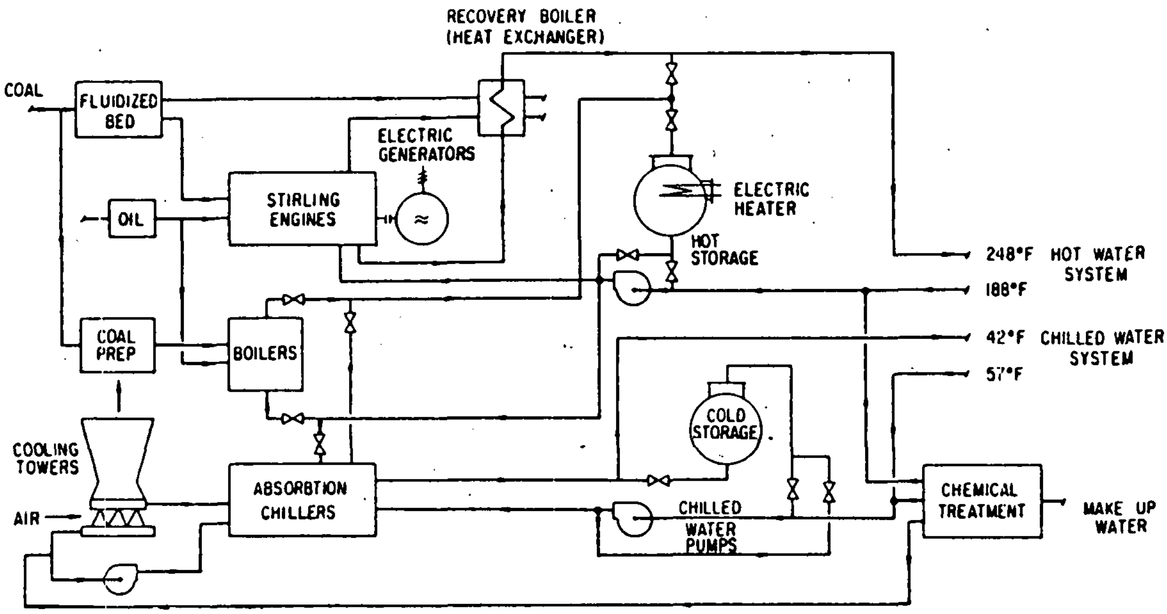

Fig. 6.13 First- and Second-Generation Stirling-Based System with Design Option A

be available in the future and will have the same operating characteristics as the current version but will be able to burn coal. With these assumptions, the calculations proceed as in the case of the Diesel-engine-based system. The maximum engine power required is 8.66 MW; the absorption chillers must have a cooling power of 7,200 tons; the hot-water boilers, a power of 23.14 MW. Figure 6.14 constitutes the basis for calculating the annual fuel consumption for a first- and second-generation, current Stirling system with Design Option A. This consumption expressed, in Btus, is 4.84×10^{11} Btu/yr for the Stirling engines and 1.41×10^{11} Btu/yr for the boilers. Assuming that the boilers use the same fuel as the Stirling engines, a system based on first-generation (i.e., oil-burning) current Stirling engines, will have a total annual fuel consumption of 4.17×10^{6} gal of oil. For the second generation (i.e., coal-burning) current Stirling-engine-based system, the fuel consumption is 26,000 tons of coal/yr.

Tables 6.6 and 6.7 list the cost of the components, the operating and maintenance costs, and the annual fuel consumption for the first- and second-generation current Stirling-engine-based system, respectively.

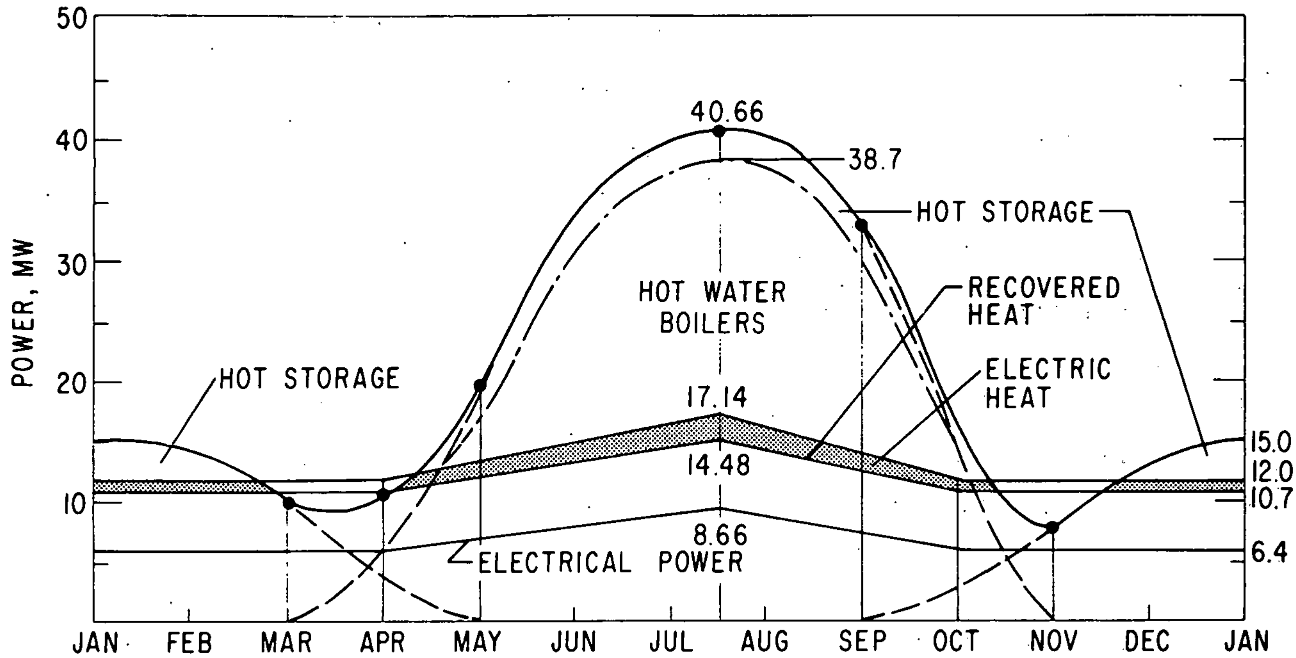

Fig. 6.14 Variation of Peak Values of the Electric, Heating, and Absorption Chiller Demand of the Fox Valley Center for the First- and Second-Generation Current Stirling System with Design Option A

Table 6.6 Costs of First-Generation, Current Stirling-Engine Based System, Option A, for the Fox Valley Center

Description	Cost (k$)	
First Generation Current Stirling Engines 4 X 3 MW ($429/kW)	5,148	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Hot Water Boilers 4 X 7.2 MW	552	
Absorption Chillers 6 X 1450 tons	1,163	
Cooling Towers 6 X 1450 tons	684	
Chemical Treatment	87	(CD 8,142)
Oil Preparation $(5.3 + 1.54)10^5$ gal X 0.92 $/gal	629	(CE 8,771)
Building and Lot 10% CD	814	
Instrumentation and Controls 15% CE	1,316	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	13,043	

O&M 6% CE 526.
fuel 4.17 X 10^6 gal/yr

Table 6.7 Costs of Second Generation, Current Stirling-Engine Based System, Option A, for the Fox Valley Center

Description	Cost (k$)	
Second Generation Current Stirling Engines 4 X 3 MW ($429/kW)	5,820	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Hot Water Boilers 4 X 7.2 MW (coal)	1,809	
Absorption Chillers 6 X 1450 tons	1,163	
Cooling Towers 6 X 1450 tons	684	
Chemical Treatment	87	(CD 10,142)
Oil Preparation 7.06 ton/h	1,023	(CE 11,409)
Building and Lot 10% CD	1,007	
Instrumentation and Controls 15% CE	1,664	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	15,907	

O&M 6% CE 666.

fuel 26,000 ton/yr coal

Turning now to design Option B, which uses compressive chillers but no hot-water boilers, a schematic diagram of this system is presented in Fig. 6.15, which indicates the use of either oil or coal as fuel. The maximum engine power required is found to be 11.26 MW; the needed capacity of the compressive chillers is 2,600 tons; and that of the absorption chillers is 4,460 tons. Figure 6.16 is the basis for calculating the annual fuel consumption which is found to be 3.48 x 10^6 gal of oil for the first-generation, and 21,800 tons of coal for the second-generation current Stirling engines.

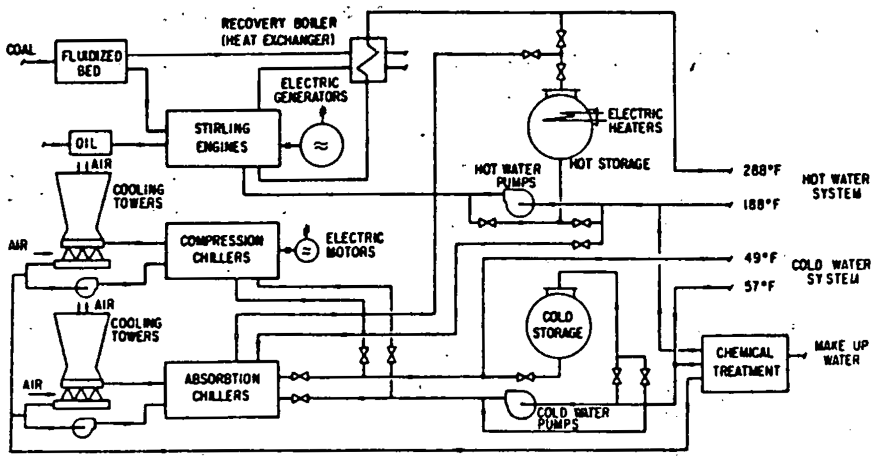

Fig. 6.15 First- and Second-Generation Stirling-Based System with Design Option B

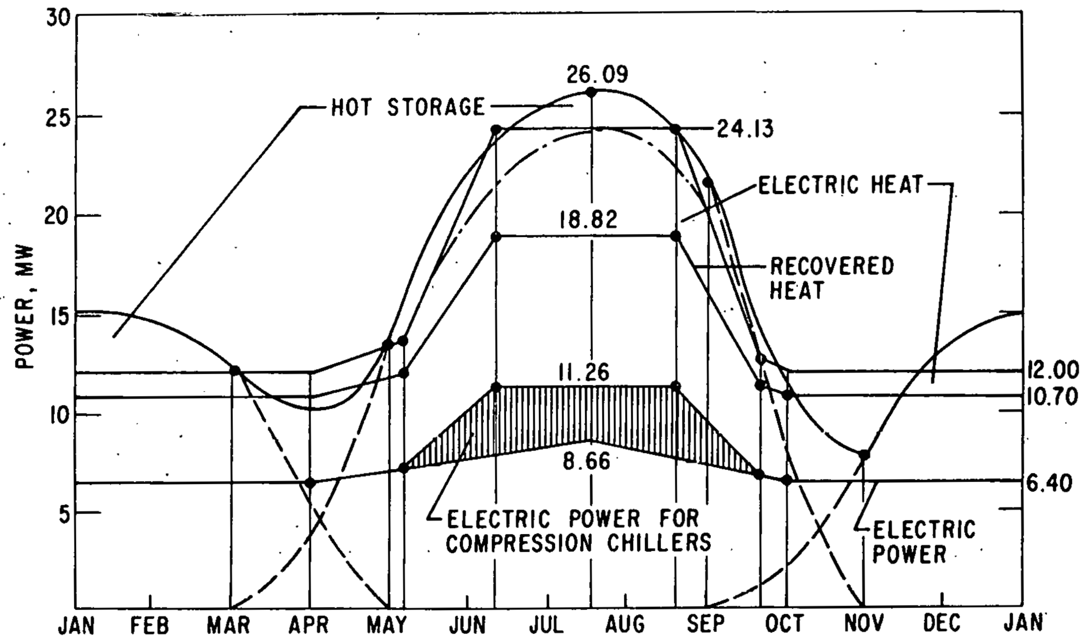

Fig. 6.16 Variation of Peak Values of the Electric, Heating, and Cooling Demand of the Fox Valley Center for the First and Second Generation Current Stirling System with Design Option B

Tables 6.8 and 6.9 list the costs of the components, the operating and maintenance costs, and the annual fuel consumption for the first- and second-generation current Stirling-engine-based design, respectively.

Table 6.8 Costs of First Generation, Current Stirling-Engine-Based System, Option B, for the Fox Valley Center

Description	Cost (k$)	
First Generation Current		
Stirling Engines 4 X 4 MW	6,653	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Absorption Chillers 4 X 1553 tons	812	
Cooling Towers 4 X 1553 tons	484	
Compression Chillers 3 X 1300 tons ($95/ton)	378	
Cooling Towers 3 X 1300 tons	312	
Chemical Treatment	80	(CD 9,227)
Oil Preparation 5.7 X 10^5 gal X 0.94 $/gal	535	(CE 9,762)
Building and Lot 10% CD	922	
Instrumentation and Controls 15% CE	1,464	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	14,290	

O&M 6% CE 586.

fuel 3.48 X 10^6 gal/yr

Table 6.9 Costs of Second Generation, Current Stirling Engine Based System, Option B, for the Fox Valley Center

Description	Cost (k$)	
Second Generation Current Stirling Engines 4 X 4 MW	7,504	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.6 MW	184	
Absorption Chillers 4 X 1553 tons	1,812	
Cooling Towers 4 X 1553 tons	484	
Compression Chillers 3 X 1300 tons	378	
Cooling Towers 3 X 1300 tons	312	
Chemical Treatment	80	(CD 10,078)
Coal Preparation 4.96 ton/h	745	(CE 10,823)
Building and Lot 10% CD	1,008	
Instrumentation and Controls 15% CE	1,623	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	15,596	

O&M 6% CE 649.

fuel 21,800 ton/yr

6.7 ADVANCED STIRLING-ENGINE-BASED SYSTEMS

Stirling engines of advanced technology are assumed to achieve an electric efficiency of 43.7% and to recover 41% of the energy input. Here, as in the case of the current Stirling engines, the first-generation, or oil-burning, advanced Stirling engines, and second-generation, or coal-burning, advanced Stirling engines will be discussed.

6.7.1 Advanced Stirling-Engine-Based System with Design Option A

A system, based on the advanced Stirling and using design Option A, has the same schematic diagram as the current Stirling system shown in Fig. 6.13. With the assumption that 5.6 kW of heat are required for one ton of cooling by the absorption chillers, the calculations proceed as in the previous cases. The maximum required power of the engines is 8.66 MW; the capacity of the chillers is 7,192 tons, and that of the hot-water boilers 26.57 MW. Figure 6.17 can be used to calculate the annual fuel consumption which is found to be 3.7 x 10^6 gal of oil or, for the second-generation engines, 24,300 tons of coal.

Costs of the first and second generation advanced Stirling-engine-based systems with design Option A are shown in Tables 6.10; and 6.11, respectively.

6.7.2 Advanced Stirling-Engine-Based System with Design Option B

For the system with design Option B, the required maximum engine power output is 12.16 MW. The capacity of the compression chillers must be 3,500 tons and that of the absorption chillers, 3,692 tons.

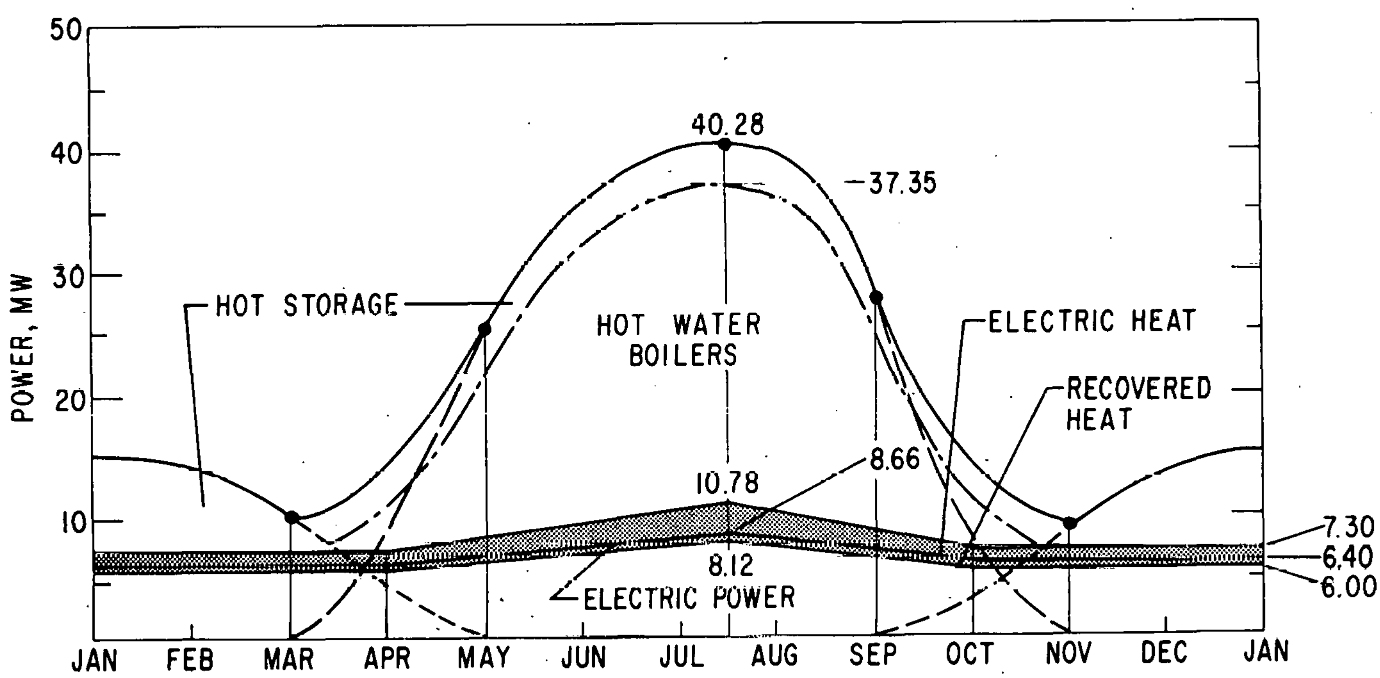

Fig. 6.17 Variation of Peak Values of the Electric, Heating, and Absorption Chiller Demand of the Fox Valley Center for the First- and Second-Generation, Advanced Stirling System with Design Option A

Table 6.10 Costs of First-Generation, Advanced Stirling-Engine-Based System, Option A, for the Fox Valley Center

Description	Cost (k$)	
First Generation Advanced Stirling Engines 4 X 3 MW	5,184	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.6 MW	276	
Hot Water Boilers 4 X 8.86 MW	594	
Absorption Chillers 6 X 1440 tons	1,157	
Cooling Towers 6 X 1440 tons	684	
Chemical Treatment	84	(CD 8,335)
Oil Preparation $(3.92 + 2.48)10^5$ X 0.93 $/gal	595	(CE 8,930)
Building and Lot 10% CD	833	
Instrumentation and Controls 15% CE	1,339	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	13,244	
O&M 6% CE 536.		
fuel 3.9 X 10^6 gal/yr		

Table 6.11 Costs of Second Generation, Advanced Stirling Engine Based System, Option A, for the Fox Valley Center

Description	Cost (k$)	
Second Generation Advanced Stirling Engines 4 X 3 MW	5,820	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.6 MW	276	
Hot Water Boilers 4 X 8.86 MW (coal)	2,226	
Absorption Chillers 6 X 1440 tons	1,157	
Cooling Towers 6 X 1440 tons	684	
Chemical Treatment	84	(CD 10,603)
Coal Preparation 7.86 ton/h	1,127	(CE 11,730)
Building and Lot 10% CD	1,060	
Instrumentation and Controls 15% CE	1,759	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	16,691	
O&M 6% CE 704.		
fuel 24,300 ton/yr		

Using Fig. 6.18, the annual fuel consumption of the system is calculated to be 2.59 x 106 gal of oil for the first-generation and 16,200 tons of coal for the second-generation advanced-Stirling-based system.

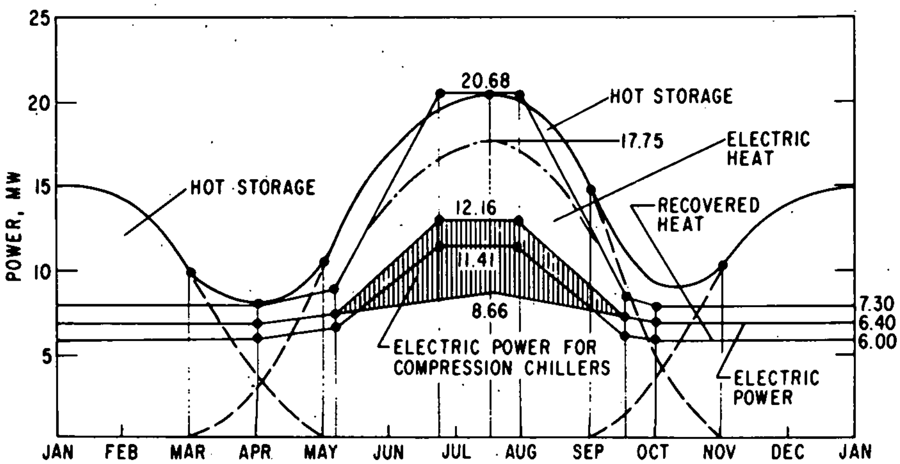

Fig. 6.18 Variation of Peak Values of Electric, Heating, and Cooling Demand of the Fox Valley Center for the First- and Second-Generation, Advanced Stirling System with Design Option B

Tables 6.12 and 6.13 list the costs of components, the operating and maintenance cost, and the annual consumption of the first- and second-generation, advanced Stirling-engine-based systems, respectively.

6.8 CONVENTIONAL SYSTEM

The conventional system will be assumed to be a decentralized, in-building, customer-owned and - maintained building, ventilating, and air conditioning system. For the Fox Valley center and villages, compressive chillers and electric resistance heaters are assumed for the large commercial, office, and apartment building areas. For low-rise commercial and office buildings, rooftop, multizone units with electric cooling and heating are assumed. For garden apartments and townhouses, gas furnaces and central air-conditioning units will be considered.

In cost estimating the various Total Energy Systems examined previously, the cost of the in-building systems was never calculated. This cost is common to all Total Energy Systems and, for this reason, the economic comparisons are not affected when this cost is ignored.

To compare the cost between the conventional system and systems presented earlier, only the cost of components that are not common to these systems have to be considered. For example, in the Total Energy Systems, chilled water is supplied to the office buildings for satisfying the cooling demand. In the conventional system, the chilled water is supplied by in-

Table 6.12 Costs of First Generation, Advanced Stirling-Engine-Based System, Option B, for the Fox Valley Center

Description	Cost (k$)	
First Generation Advanced Stirling Engines 4 X 4.2 MW	6,955	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.6 MW	276	
Absorption Chillers 4 X 1230 tons	696	
Cooling Towers 4 X 1230 tons	394	
Compression Chillers 3 X 1750	463	
Cooling Towers 3 X 1750 tons	405	
Chemical Treatment	84	(CD 9,629)
Oil Preparation 4.25 X 10^5 X 0.97 $/gal	412	(CE 10,041)
Building and Lot 10% CD	963	
Instrumentation and Controls 15% CE	1,506	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	14,652	
O&M 6% CE 602.		
fuel 2.59 X 10^6 gal/yr		

Table 6.13 Costs of Second Generation, Advanced Stirling-Engine-Based System, Option B, for the Fox Valley Center

Description	Cost (k$)	
Second Generation Advanced Stirling Engines 4 X 4.2 MW ($466/kW)	7,829	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.6 MW	276	
Absorption Chillers 4 X 1230 tons	696	
Cooling Towers 4 X 1230 tons	394	
Compression Chillers 3 X 1750 tons	463	
Cooling Towers 3 X 1750 tons	405	
Chemical Treatment	84	(CD 10,503)
Coal Preparation 3.7 ton/h	608	(CE 11,111)
Building and Lot 10% CD	1,050	
Instrumentation and Controls 15% CE	1,667	
Distribution: Heating and Cooling	1,715	
Electric	427	
TOTAL COST	15,970	
O&M 6% CE 667.		
fuel 16,200 ton/yr coal		

building compressive chillers, the cost of which should be included in the cost of the conventional system. The cost of the chilled-water distribution system inside the building is common to all systems and can be ignored in the cost comparisons. Some costs should be charged only to the Total Energy Systems because they are not common to the conventional system. For example, electric baseboard heaters are used in the conventional system and hot-water heating for the Total Energy Systems. Thus, the cost of the electric baseboard heaters should be included only in the conventional system cost, and that of the in-building hot-water distribution system in the Total Energy System cost. For the Fox Valley center, we calculated for the conventional system a cost of $5.53 million, and for the Total Energy System an additional $1.14 million. To simplify the comparisons without revising Tables 6.2 through 6.13, only the differential cost will be charged to the conventional system, with the cost of the Total Energy Systems remaining unchanged. Table 6.14 presents these costs for all four communities considered.

Next, an estimate of the annual energy consumption of the conventional system is made, based on Fig. 6.5, which presents the annual variation of the peak and average values of the non-HVAC electric, heating, and cooling demand for the Fox Valley Center. By integrating the area under the average demand curves, the annual non-HVAC electric demand is 35.04×10^6 kWh; the cooling demand 12.59×10^6 kWh; and the heating demand 12.59×10^6 kWh. Assuming an electricity cost of $0.04/kWh, the cost of the non-HVAC electric demand is $1.4 million. If the coefficient of performance of the compressive chillers is 3, then the electric demand for cooling becomes 14.48×10^6 kWh which, at $0.04/kWh, yields a cost of $580,000.

Table 6.14 Differential Cost between Conventional and Total Energy Systems

Community	Conventional System Cost Not Common To Total Energy System ($$10^6$)	Total Energy System Cost Not Common To Conventional Energy System ($$10^6$)	Differential Cost ($$10^6$)
Fox Valley Center	5.53	1.14	4.39
Zone D	3.45	0.49	2.96
Zones A,D, and E	13.61	2.24	11.37
Fox Valley Center and Villages	19.71	3.20	16.57

Because electric heating has been assumed for the Fox Valley Center, the cost of heating becomes $504,000, and the total cost of energy for the Fox Valley Center amounts to $2.48 million. Similar calculations were made for the remaining three-zone groupings, and the results obtained are summarized in Table 6.15.

To compare the conventional system with the various Total Energy Systems presented earlier, the present value of all costs is required. It will be sufficient to take into account only the differential capital costs for the conventional system. Assuming a 10% annual price escalation for gas and electricity, a 6% escalation of the operating and maintenance cost, a rate of return equal to 10%, and a system life span of 20 years, the present value of the costs is calculated. Table 6.16 presents the results for all four zone groupings considered.

6.9 SYSTEM PERFORMANCE AND COST COMPARISONS

After the capital cost, the operating and maintenance cost, and the annual fuel consumption were estimated, the Net Present Value (NPV) of the

Table 6.15 Annual Energy Consumption and Cost of the Conventional System

Community	Description	Non-HVAC Electric[a]	Cooling[b]	Heating	Total
Fox Valley Center	Energy, 10^6 kWh	35.04	43.44	12.5	
	Cost, $\$10^6$	1.402	0.58	0.504	2.48
Zone D	Energy, 10^6 kWh	26.28	35.16	37.74[c]	
	Cost, $\$10^6$	1.05	0.47	0.39	1.91
Zones A,D, and E	Energy, 10^6 kWh	87.6	116.7	86.8[d]	
	Cost, $\$10^6$	3.5	1.56	2.18	7.24
Fox Valley Center and Villages	Energy, 10^6 kWh	131.4	155.6	126.6	
	Cost, $\$10^6$	5.26	2.07	3.78	11.11

(a)Cost of electricity 4¢/kWh.

(b)Coefficient of performance for the compressive chillers assumed equal to 3.

(c)Supplied by natural gas with furnace efficiency of 0.75 and a cost of $2.30/$10^6$ Btu.

(d)43.4 x 10^6 kWh supplied by gas and the remaining by electric resistance.

Table 6.16 Differential Capital Costs, Operating and Maintenance Costs, Annual Fuel Cost, and Present Value of All Costs for the Conventional System

Community	Differential Capital Cost ($10^6)	O&M Cost ($10^6)	Annual Fuel Cost ($10^6)	Present Value[a] of all Costs ($10^6)
Fox Valley Center	4.39	0.10	2.48	55.43
Zone D	2.96	0.088	1.91	42.43
Zones A,D, and E	11.37	0.297	7.24	160.44
Fox Valley Center and Villages	16.57	0.43	11.11	244.96

(a)Calculated for a 20-yr life span.

total cost was calculated with the assumptions described in Sect. 6.3.2. Table 6.17 summarizes the results obtained for a Total Energy System serving zone D only, together with the cost of a conventional system as described in Sect. 6.8. Zone D consists mainly of residential space and has demand curves representative of residential customers. The second column of the table gives the capital cost of the installation followed by the NPV of the total cost and the annual fuel consumption for each of the prime-movers and the design options considered.

First we look for the prime-mover that has the minimum fuel consumption. Assuming that the advanced Stirling engine is not yet available, then the Diesel-based system, as well as the current Stirling-based system with design Option B, consume the least amount of fuel. The small difference in the annual fuel consumption between the two systems is considered negligible. (It should be noted that the first- and second-generation Stirling-engine-based systems consume the same amount of heat annually whether it is obtained from coal or oil.) Comparing present values of the total cost of the various systems, the Diesel system with design Option B is the cheapest, if coal is not an acceptable fuel. However, if coal is acceptable, then the second generation, current Stirling-based-system with design Option B is the most economical.

Table 6.17 Summary of Results for Zone D

System Based On:	Capital Cost (k$)	Present Value of Total Cost (k$)	Annual Fuel Consumption
Diesel Engines; Option A	12,748	40,928	2.78 X 10^6 gal of oil
Diesel Engines; Option B	13,203	38,256	2.35 X 10^6 " " "
Gas Turbines; Option A	13,522	49,362	3.59 X 10^6 " " "
Gas Turbines; Option B	13,468	49,447	3.68 X 10^6 " " "
First Generation Current Stirlings; Option A	14,060	42,299	2.66 X 10^6 " " "
First Generation Current Stirlings; Option B	14,315	40,895	2.42 X 10^6 " " "
First Generation Advanced Stirlings; Option A	14,018	38,929	2.24 X 10^6 " " "
First Generation Advanced Stirlings; Option B	14,805	37,195	1.86 X 10^6 " " "
Second Generation Current Stirlings; Option A	15,182	34,961	16,600 tons of coal
Second Generation Current Stirlings; Option B	15,325	34,101	15,100 " " "
Second Generation Advanced Stirlings; Option A	15,736	34,096	14,000 " " "
Second Generation Advanced Stirlings; Option B	15,866	32,495	11,600 " " "
Conventional System	2,960	42,430	--

Repeating the above comparisons and assuming that the advanced Stirling engine is available, then it is found by examining the fuel economy of the various systems that the advanced, Stirling-based system with design Option B consumes the least amount of fuel. As far as the present value of the total cost is concerned, the first-generation, advanced Stirling-based system with design Option B costs the least, if coal is not an acceptable fuel option; the second-generation, advanced-Stirling-based system with design Option B costs the least when coal is an acceptable fuel.

Now, turn to the community consisting of zones A, D, and E. Table 6.18 summarizes the results obtained for this community using the various prime-movers.

If the advanced Stirling engine is not available, then the system that consumes the least amount of fuel is the current Stirling and also the Diesel-based system with design Option B. The difference in fuel value of the total cost is concerned, the Diesel-based system with design Option B is the cheapest when coal is not acceptable, and the second-generation current Stirling-based system with design Option B when coal is an acceptable fuel. When coal is not an acceptable fuel, the advanced Stirling-based system and also the Diesel-based system with Option B presently cost the least; whereas, the second-generation, advanced Stirling-based system with design Option B

Table 6.18 Summary of Results for Zones A, D, and E

System Based On:	Capital Cost (k$)	Present Value of Total Cost (k$)	Annual Fuel Consumption
Diesel Engines; Option A	30,344	128,169	10.36 X 10^6 gal of oil
Diesel Engines; Option B	33,325	115,110	8.09 X 10^6 " " "
Gas Turbines; Option A	30,150	151,118	13.27 X 10^6 " " "
Gas Turbines; Option B	31,137	136,805	11.28 X 10^6 " " "
First Generation Current Stirlings; Option A	33,002	127,662	9.72 X 10^6 " " "
First Generation Current Stirlings; Option B	35,858	118,937	8.03 X 10^6 " " "
First Generation Advanced Stirlings; Option A	35,240	132,434	9.83 X 10^6 " " "
First Generation Advanced Stirlings; Option B	36,746	115,012	7.35 X 10^6 " " "
Second Generation Current Stirlings; Option A	40,049	106,270	60,700 tons of coal
Second Generation Current Stirlings; Option B	38,740	96,317	50,200 " " "
Second Generation Advanced Stirlings; Option A	43,987	113,606	61,400 " " "
Second Generation Advanced Stirlings; Option B	39,441	94,415	45,900 " " "
Conventional System	11,370	160,440	--

presently costs the least when coal is an acceptable fuel option. Similar conclusions are reached for the community consisting of the Fox Valley Center and Villages. These results are presented in Table 6.19.

Finally, we examine the results obtained for the Fox Valley Center (zone A in Fig. 6.1). These results are presented in Table 6.20 for the various prime-movers.

If the advanced Stirling is not available, then the Diesel-based system with design Option B consumes the least amount of fuel. This is easily explained because Fox Valley Center is totally commercial, and the electric demand is the controlling element. Table 6.21 summarizes the assumed efficiencies of the prime-movers and shows that the Diesel engine has the highest electric efficiency compared to the current Stirling and the gas turbine; thus, it out-performs both of them in fuel economy. When the advanced Stirling becomes available with its high electrical efficiency, then any system based on it would consume the least amount of fuel. When the advanced Stirling engine is not available and coal is not an acceptable fuel, then the Diesel-engine-based system with design Option B has the least cost. If coal is an acceptable fuel, then the second-generation, current Stirling-based system (if available) has the least cost, whether coal is considered an acceptable or unacceptable fuel. However, when coal is not acceptable, the

Table 6.19 Summary of Results for the Fox Valley Center and Villages

System Based On:	Capital Cost (k$)	Present Value of Total Cost (k$)	Annual Fuel Consumption
Diesel Engines; Option A	41,494	178,658	14.63 X 10^6 gal of oil
Diesel Engines; Option B	45,604	165,007	12.04 X 10^6 " " "
Gas Turbines; Option A	40,591	210,904	18.86 X 10^6 " " "
Gas Turbines; Option B	42,340	192,298	16.17 X 10^6 " " "
First Generation Current Stirlings; Option A	44,764	183,159	14.51 X 10^6 " " "
First Generation Current Stirlings; Option B	48,701	169,630	11.95 X 10^6 " " "
First Generation Advanced Stirlings; Option A	48,863	188,088	14.22 X 10^6 " " "
First Generation Advanced Stirlings; Option B	50,343	164,275	10.94 X 10^6 " " "
Second Generation Current Stirlings; Option A	55,106	151,178	90,700 tons of coal
Second Generation Current Stirlings; Option B	52,662	135,238	74,700 " " "
Second Generation Advanced Stirlings; Option A	61,630	161,178	89,000 " " "
Second Generation Advanced Stirlings; Option B	54,207	133,350	68,400 " " "
Conventional System	16,570	244,960	--

Table 6.20 Summary of Results for Fox Valley Center

System Based On:	Capital Cost (k$)	Present Value of Total Cost (k$)	Annual Fuel Consumption
Diesel Engines; Option A	11,778	55,129	4.53 X 10^6 gal of oil
Diesel Engines; Option B	12,595	45,246	3.12 X 10^6 " " "
Gas Turbines; Option A	12,200	62,955	5.41 X 10^6 " " "
Gas Turbines; Option B	12,660	63,757	5.41 X 10^6 " " "
First Generation Current Stirlings; Option A	13,043	54,580	4.17 X 10^6 " " "
First Generation Current Stirlings; Option B	14,270	51,089	3.48 X 10^6 " " "
First Generation Advanced Stirlings; Option A	13,244	52,742	3.7 X 10^6 " " "
First Generation Advanced Stirlings; Option B	14,652	44,605	2.59 X 10^6 " " "
Second Generation Current Stirlings; Option A	15,907	45,005	26,000 tons of coal
Second Generation Current Stirlings; Option B	15,596	41,351	21,800 " " "
Second Generation Advanced Stirlings; Option A	16,691	45,088	24,300 " " "
Second Generation Advanced Stirlings; Option B	15,970	37,995	16,200 " " "
Conventional System	4,390	55,430	--

Table 6.21 Assumed Efficiencies of the Prime-Movers as Percent of Fuel Input

Prime-Mover	Electric Efficiency (%)	Recoverable Heat Efficiency (%)	Overall Efficiency (%)
Diesel	34.2	42	76.2
Gas Turbine	22	48	70
Current Stirling	32.3	54	86.3
Advanced Stirling	43.7	41	84.7

Diesel-based system has almost the same present total cost as the advanced Stirling-based system.

The results obtained in the above comparisons are summarized in Table 6.22. The four groupings of zones or communities are arranged in order of increasing commercial and office component. Zone D with 11% commercial is followed by zones A, D, and E with 40% commercial. Next is the Fox Valley Center and Villages with 52% commercial, and finally the Fox Valley Center which is 100% commercial. For all the grouping of zones and all the criteria for choosing the best prime-mover the design Option B gave the best results; therefore, this design option is implied in all systems listed in Table 6.19. The criteria for selecting the prime-mover are the fuel economy and the present value of the total cost; these are applied under four different situations. For selecting the prime-mover with the best fuel economy, we considered two cases. In the first case, we assumed that Stirling engines of current technology are available; whereas, in the second case, we assumed that current-as well as advanced-technology-Stirling engines were available. In the first case, the Diesel engine gave the best fuel economy for all four communities. The fuel economy of the current-technology Stirling was almost the same as that of the Diesel, except for the Fox Valley Center for the reason given earlier. For the second case, we see that the advanced Stirling engine outperforms all other prime-movers as far as fuel economy is concerned.

Turning now to the present value of the total cost, consider, in addition to the two cases described above, two different scenarios. In the "no coal" scenario, use of coal as a fuel is not allowed because the required technology is not yet available. In the "coal" scenario, the capability of using coal as a fuel exists. Table 6.22 shows that in all four communities

Table 6.22 Best Choice of Prime-Mover for the Four Communities

Criterion/Community	Zone D (89% Residential)	Zones A, D, and E (60% Residential)	Fox Valley Center and Villages (48% Residential)	Fox Valley Center (100% Commercial)
Fuel Economy				
Current Technology	Diesel, Stirling	Diesel, Stirling	Diesel, Stirling	Diesel
Advanced Technology	←	Advanced Stlirling	→	→
Present Value of Total Cost (no coal)				
Current Technology	←	Diesel	→	→
Advanced Technology	Advanced Stirling	Advanced Stirling, Diesel	Advanced Stirling, Diesel	Advanced Stirling, Diesel
Present Value of Total Cost (coal allowed)				
Current Technology	←	2nd Generation Current Stirling	→	→
Advanced Technology	←	2nd Generation Advanced Stirling	→	→

the Diesel-based system costs the least for all four communities; whereas, the Diesel-based system has a comparable cost with the advanced Stirling for three out of the four communities. For the "coal" scenario, the conclusions are the same for all the four communities, i.e., second-generation, current Stirling for the current technology, and second-generation, advanced Stirling for the advanced technology.

The conclusions to be drawn from these results are that, in the "no coal" scenario, only the advanced Stirling can compete with the Diesel. However, in the "coal" scenario, both the current and the advanced-technology, Stirling-based systems outperform the Diesel-based systems. When coal is considered as an alternative fuel, then the second-generation (i.e., coal-burning) Stirling gives the best results. The reason is very simple: if, using the assumptions described in Sect. 6.3.2, we calculate the cost of fuel/10^6 Btu; the cost of oil turns out to be \$2.93/10^6 Btu; whereas, for coal, it is \$1.67/10^6 Btu. This lower price for coal makes this alternative attractive.

7. DEVELOPMENT GOALS

7.1 GENERAL

The Stirling engine clearly offers unique capabilities, such as high efficiency and fuel flexibility, that make it a prime candidate for development. Its use in Total or Integrated Energy Systems would be advantageous in terms of fuel conservation, non-scarce fuel utilization, and lifecycle costs if certain development targets are met. However, three points that should be emphasized to make the Stirling truely competitive with Diesel engines are:

(1) capital costs,

(2) operating and maintenance costs, and

(3) fuel flexibility.

Furthermore, for such an engine, development is significantly different from that for automotive use, so that a different strategy and set of goals are required.

Upwards of $250 million is expected to be spent over the next 8-10 years in developing Stirling engines for automotive applications. Certainly a large portion of this effort would be applicable to the development of Stirling engines for stationary applications; thus, it may not be obvious why a substantial development effort should be initiated for stationary Stirling engines for use in Total Integrated Energy Systems. However, the development of stationary Stirling engines may proceed along considerably different paths than that of automotive systems to maximize the Stirling engines advantages of fuel flexibility and high thermal efficiency. Moreover, the reliability and operating life requirements of stationary Stirling engines are far more demanding than those for automotive engines.

The primary requirements for automotive engines are considerably different from those for stationary applications which place a unique set of criteria on these engines. These requirements include:

- size and weight,
- combustion/heat exchanger arrangement,
- "isothermalized" Stirling engines,
- "partial" Stirling engines, and
- coot.

7.2 AUTOMOTIVE VS STATIONARY STIRLING DEVELOPMENT

To fit under the hood of an automobile, the automotive Stirling engine must have a very high power density (0.23 hp/lb). This stringent size requirement, in turn, has greatly influenced system design and operating parameters by:

- stressing the use of hydrogen as the working gas with its attendant safety problems, i.e., tendency to permeate materials of construction, and adversely affect the strength of high-temperature materials (hydrogen embrittlement),
- forcing the system to use a high-pressure gas which causes high stresses in the hot end and limits operating temperature levels,
- requiring a very high heat flux in the hot end which leads to significant temperature drops between the hot end tubes and the working gas; and
- limiting the choice of sealing arrangement, drive mechanism, and cylinder arrangements to result in highly compact configurations.

The automotive Stirling engines are being designed to burn conventional liquid (gasoline) or gaseous fuels in high heat flux arrangements with good transient response. Therefore, the requirements for stationary power systems would be considerably different and, in particular, would probably stress combustor/heat transfer systems capable of burning solid fuels as well as liquids and gases.

To be competitive with automotive Otto, gas turbine, and Diesel engines, the automotive Stirling engine must cost between $5 and $10/hp. This cost restriction is about an order of magnitude lower than that acceptable for a Community System application. This very stringent cost goal severely restricts the choice of materials and fabrication techniques that can be used in an automotive Stirling engine.

7.3 SPECIFIC TECHNICAL DEVELOPMENT AREAS

The above restrictions placed on the automotive Stirling engine can be relaxed for stationary applications so that engines optimized for use in Community Energy Systems can be developed. Several areas that might be subject to such a development program include:

- Working Gas. Helium may be a better working gas in stationary Stirling engines because it does not permeate through containment materials as readily as hydrogen, and there are fewer safety problems associated with its use.

- Seal Design. Lower working pressure levels, lower operating speeds, less stringent cost goals, and the use of helium, may make it possible to develop sealing arrangements that are more reliable than the rollsock seals now used.

- Engine Configuration. Present automotive activities stress double acting/swash drive designs to maximize power density and reduce costs. Alternative configurations, such as those using crankshaft drives, may be more appropriate for stationary applications that stress efficiency, maintainability, and reliability.

- Heater/Combustion System. The tubular heater arrangements can be directly fired only with very clean fuels without undergoing unacceptable fouling. For stationary applications, it will probably be necessary to emphasize heaters using heat pipes to transfer heat from the hot combustion gases to the heater tubes. The use of high temperature (preferably 1600°F and higher) materials also should be stressed to increase efficiency levels. Moreover, appropriate combustion systems, that clearly can burn a variety of fuel forms using highly preheated air, will have to be developed for those systems.

- Air Preheater. The overall thermal efficiency of a fuel-fired Stirling engine is highly influenced by the effectiveness of the air preheater. Requirements on the preheater become more severe as heater input temperature levels increase to maximize engine efficiency. For stationary applications, therefore, ceramic preheaters (either stationary or rotary regenerative) may have to be developed (possibly based on gas turbine technology) if the high efficiency potential of the Stirling engine is to be realized.

• Regenerator. Thermal effectiveness and pressure drops across the regenerator are critical in determining engine efficiency. Present designs (usually stacked, perforated stainless-steel disks) stress low cost at reasonably high effectiveness (about 0.9). Alternative designs that emphasize efficiency should be pursued. Also, as operating temperature levels increase, high temperature alloys and/or ceramics may have to be incorporated into the regenerator design. The higher allowable costs of stationary applications (as compared with automotive) provide a high degree of configuration and material selection flexibility in the design of the regenerator.

• Radical Departures. Implicit in the foregoing discussion is the assumption that the basic Stirling engine configuration, typified by the developments of Philips and United Stirling, will be the basis of an engine optimized for a stationary power application. A review of the literature and the goals of the automotive Stirling engine program indicates that almost all present-day Stirling engine developments are outgrowths of the work at Philips and its licensees (such as United Stirling, MAN, and various U.S. automotive companies). This incestuous situation could tend to stifle the influx of new ideas which result in engine approaches now under development.

7.4 OVERALL GOALS OF ENGINE DEVELOPMENT

The above specific technical research and development goals should be aimed at developing a Stirling engine that can meet reliability and maintainability standards already achieved with the larger stationary Diesel engines. The specific overall goals should be to:

(1) develop stationary Stirling engine with a thermal efficiency at least as good as current, low-to-medium speed Diesel engines, i.e., 38-40%;

(2) develop engines that can use fuels other than distillates, including coal, wood chips, municipal waste, etc; and

(3) achieve a cost for a non-scarce-fueled, Stirling engine that is not more than twice the cost of current low-to-medium speed Diesel engines.

8. SUGGESTED DEVELOPMENTAL PROGRAM

8.1 GENERAL

The development of a large Stirling engine suitable for stationary power applications admittedly is a large undertaking with numerous technological risks. However, many of the technical problems that must be resolved already are being addressed in the automotive Stirling engine development programs, so that most of the effort can be devoted specifically to large Stirling engine technological issues as outlined in Chapter 7. With this in mind, a general outline is given in the following of an overall program that should result in a demonstrated large Stirling engine in about 6-7 years. However, detailed program plans and budget allocations can change the overall program progress. After the successful completion of this program, the engine technology is expected to be commercialized.

8.1 DEVELOPMENT PROGRAM

A generalized milestone chart for the overall large Stirling engine developmental program is given in Fig. 8.1 which shows the program is broken

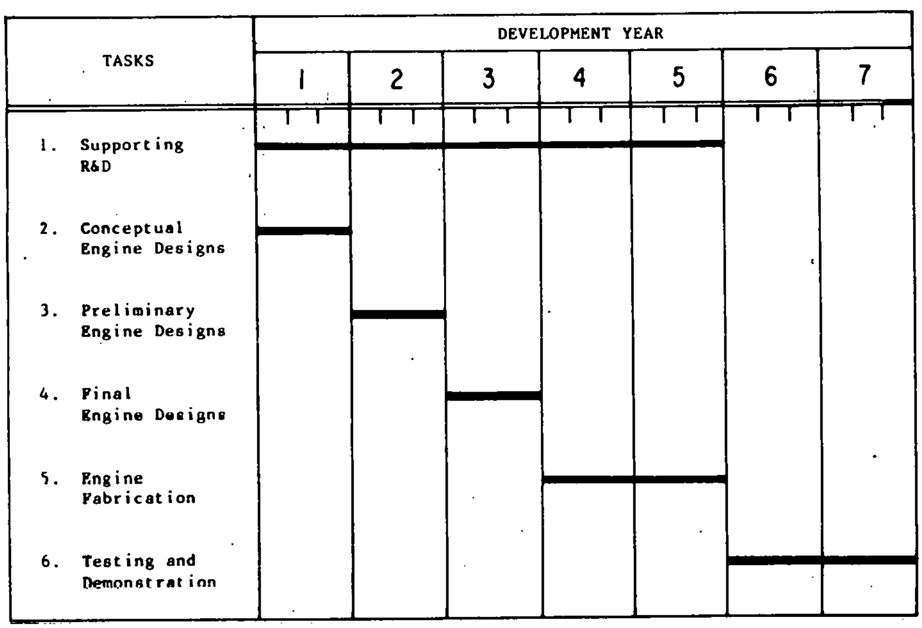

Fig. 8.1 Overall Large Stirling Engine Development Program

down into six main tasks including:

1. supporting R&D;
2. conceptual engine designs;
3. preliminary engine design;
4. final engine designs;
5. engine fabrication, and
6. testing and demonstrations.

Each of the initial tasks is expected to involve a number of contracts for the development of several engines with, perhaps, unique technical approaches. The ultimate goal of the program is to demonstrate for commercialization a reliable, high-efficiency, economically competitive engine that can burn non-scarce fuels such as coal, coal-derived fuels, and industrial and municipal wastes.

8.1.1 <u>Supporting Research and Development</u>

This portion of the program would be devoted to the development of solutions to the various technical areas addressed in Chapter 7 and would support the engine development and fabrication in the subsequent, on-going tasks. Supporting R&D would include work in solid-fuel combustion systems, engine working fluids, seal designs, heat transport system, preheater design, and recuperator designs. These particular areas can be addressed separately from the overall engine design and will help in the design of novel engine configurations. Work in this area would be performed either by the prime engine contractors of Phases I-V or by independent researchers.

8.2 ENGINE DESIGN AND DEMONSTRATIONS

The overall engine design and demonstration will be divided into four phases as follows:

(1) conceptual engine designs
(2) preliminary engine designs
(3) final engine designs and engine fabrication, and
(4) testing and demonstration.

A brief description of each phase follows.

8.2.1 Conceptual Engine Designs

The first phase of engine design and demonstration will develop several engine conceptual designs that emphasize:

(a) fuels flexibility,
(b) high efficiency,
(c) reliability,
(d) serviceability, and
(e) potentially economic, competitive production costs.

This phase will include state-of-the-art conceptual design with a high potential for demonstration by 1985, as well as advanced designs that may require significant R&D before demonstration and subsequent commercialization. These designs include a potentially workable heat transport system and combustion systems that could handle a variety of fuels. These engine designs are to be directed toward engines in the 500-3000 hp range.

8.2.2 Preliminary Engine Designs

Based on the conceptual designs developed in the first phase of the development program, a more detailed preliminary design phase will be undertaken. This effort is intended to develop the most promising designs of Phase I to a stage where a definitive evaluation can be made. Next, a detailed, working drawing phase would be begun toward the fabrication of one or more demonstration engines.

8.2.3 Final Engine Designs and Engine Fabrication

After evaluating the preliminary designs, the most promising will go into final design and fabrication of one or more engines. These phases are expected to cover a one-year period and will be strongly coordinated with ongoing, supportive research and development work to help resolve technical problems as they arise.

8.2.4 Testing and Demonstration

When the engines have been built they will undergo extensive laboratory and field tests to demonstrate their technical attributes. These tests will cover at least a two-year period to allow enough documentation of performance and cost to determine a commercialization strategy. It should be expected that further developmental work would be needed for various engine components subsequent to this phase.

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APPENDIX A

LIST OF FIGURES
(For Appendix A)

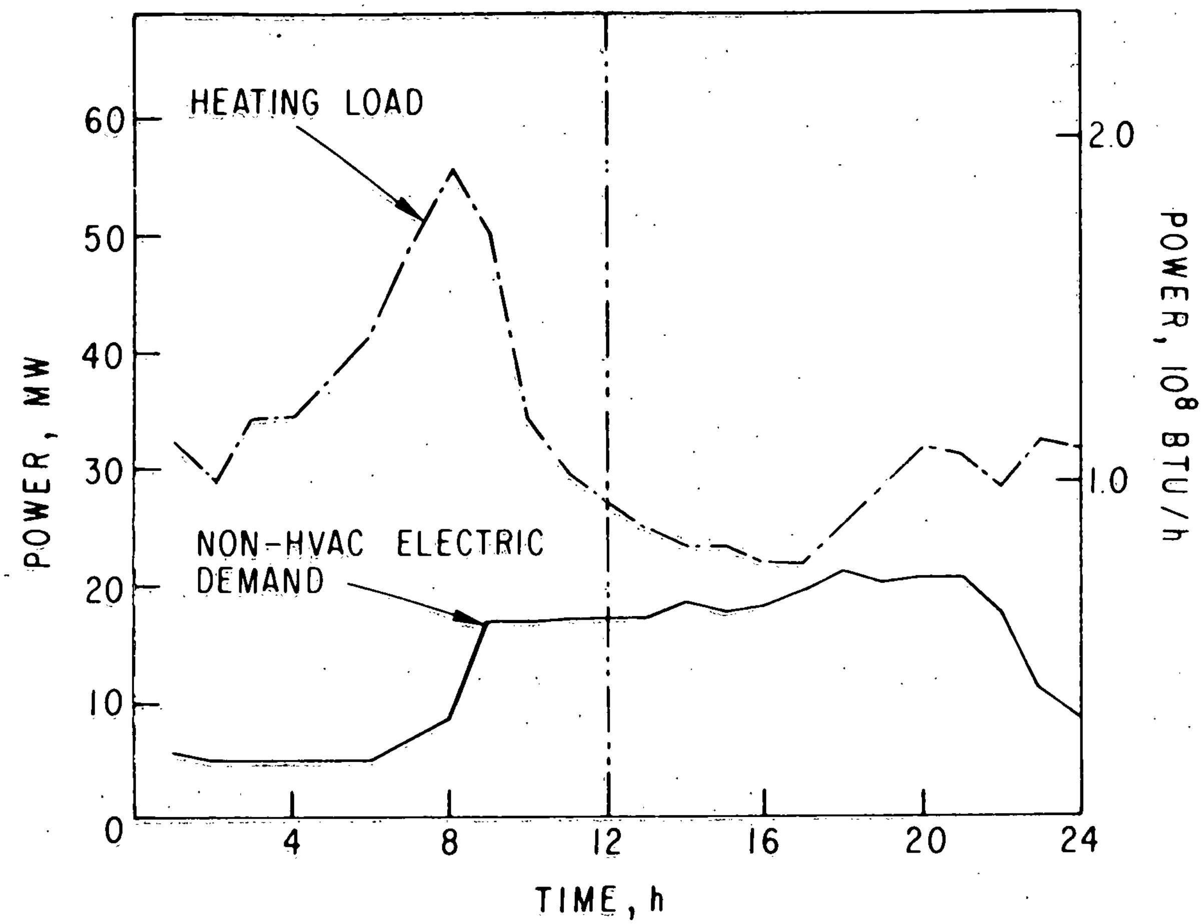

Fig. A.1 Non-HVAC Electric and Heating Demand Profile of Zone D for the Winter Design Day

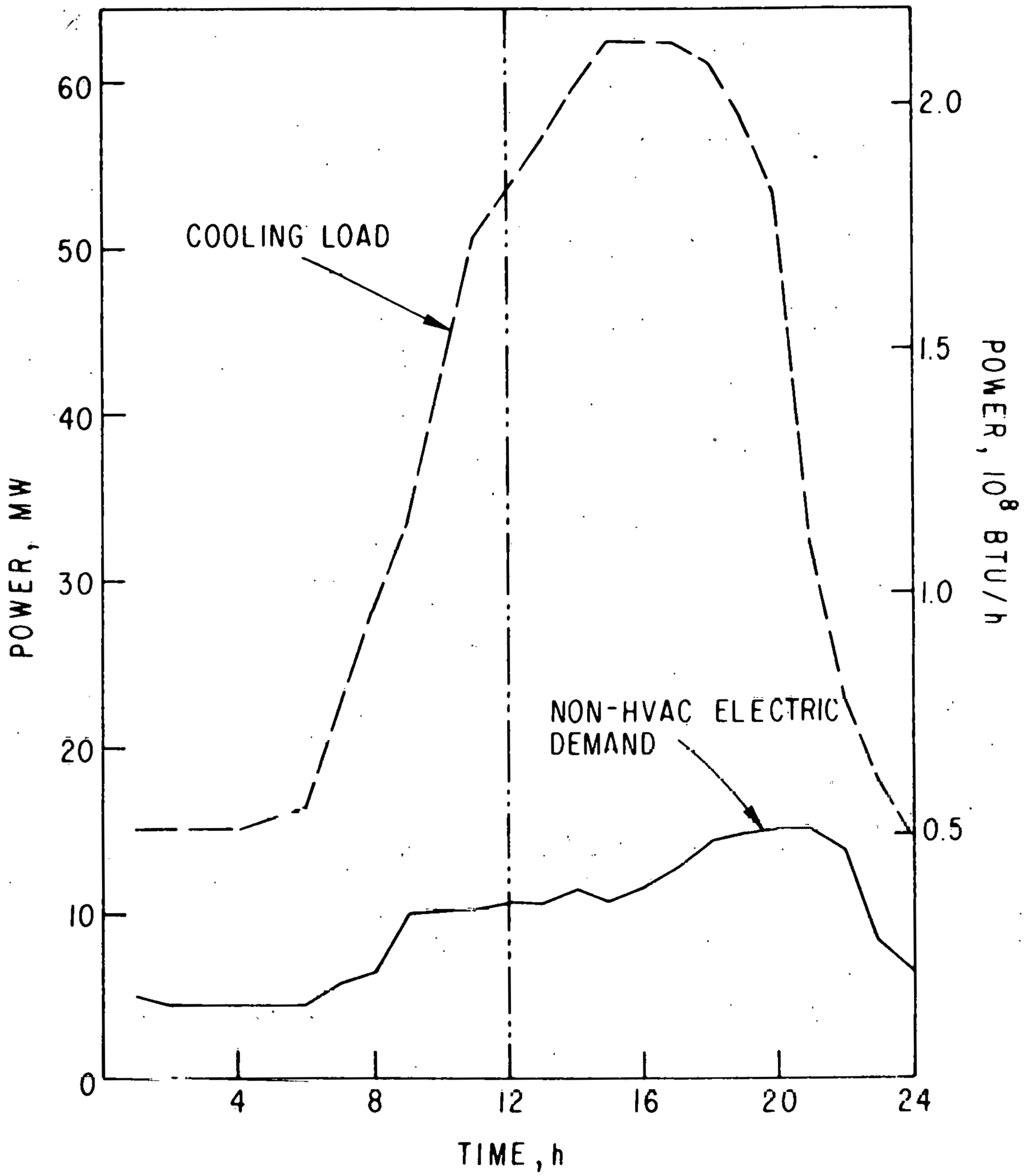

Fig. A.2 Non-HVAC Electric and Cooling Demand Profile of Zone D for the Summer Design Day

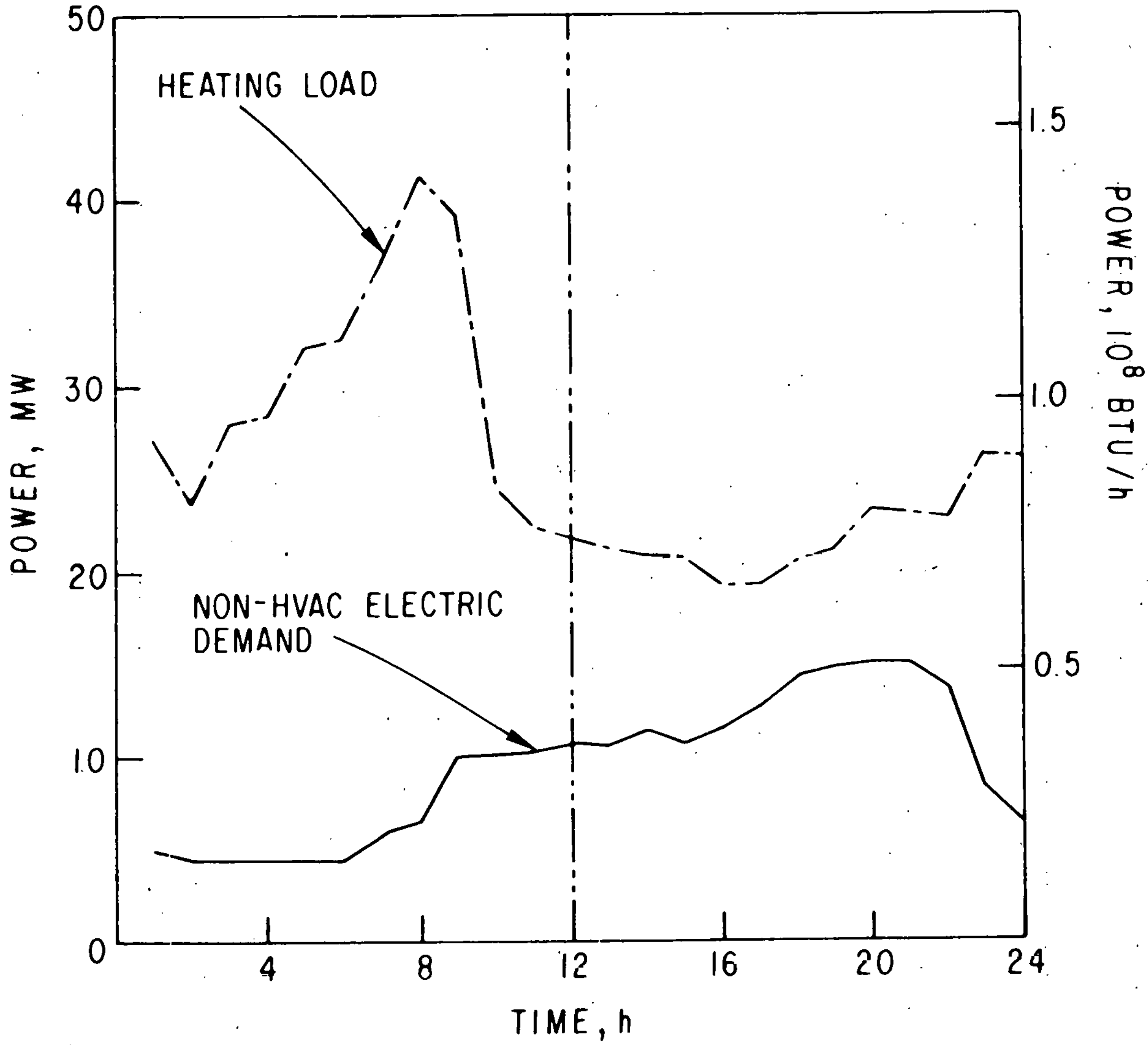

Fig. A.3 Non-HVAC Electric and Cooling Demand Profile of Zones A, D, and E for the Winter Design Day

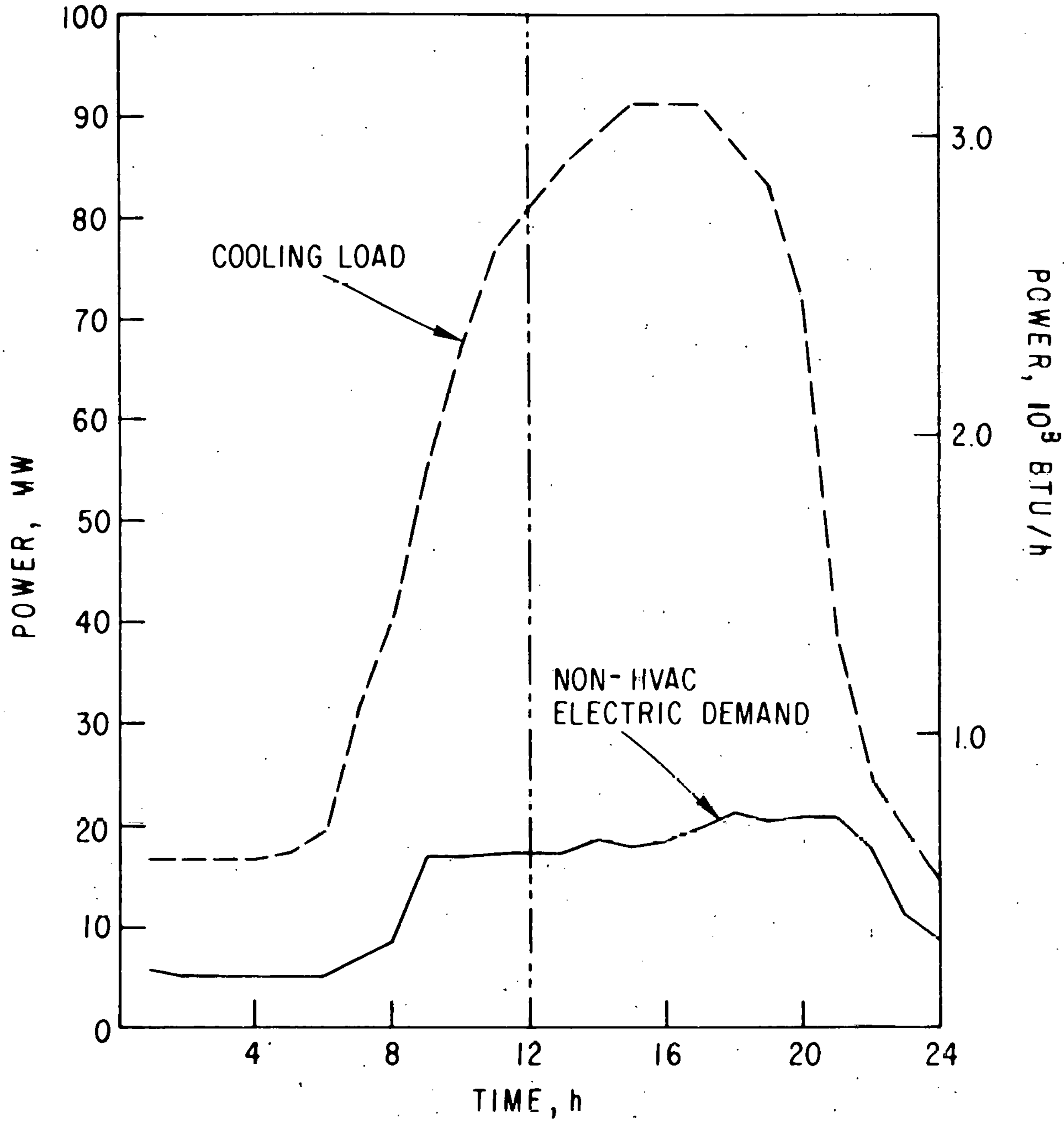

Fig. A.4 Non-HVAC Electric and Cooling Demand Profile of Zones A, D, and E for the Summer Design Day

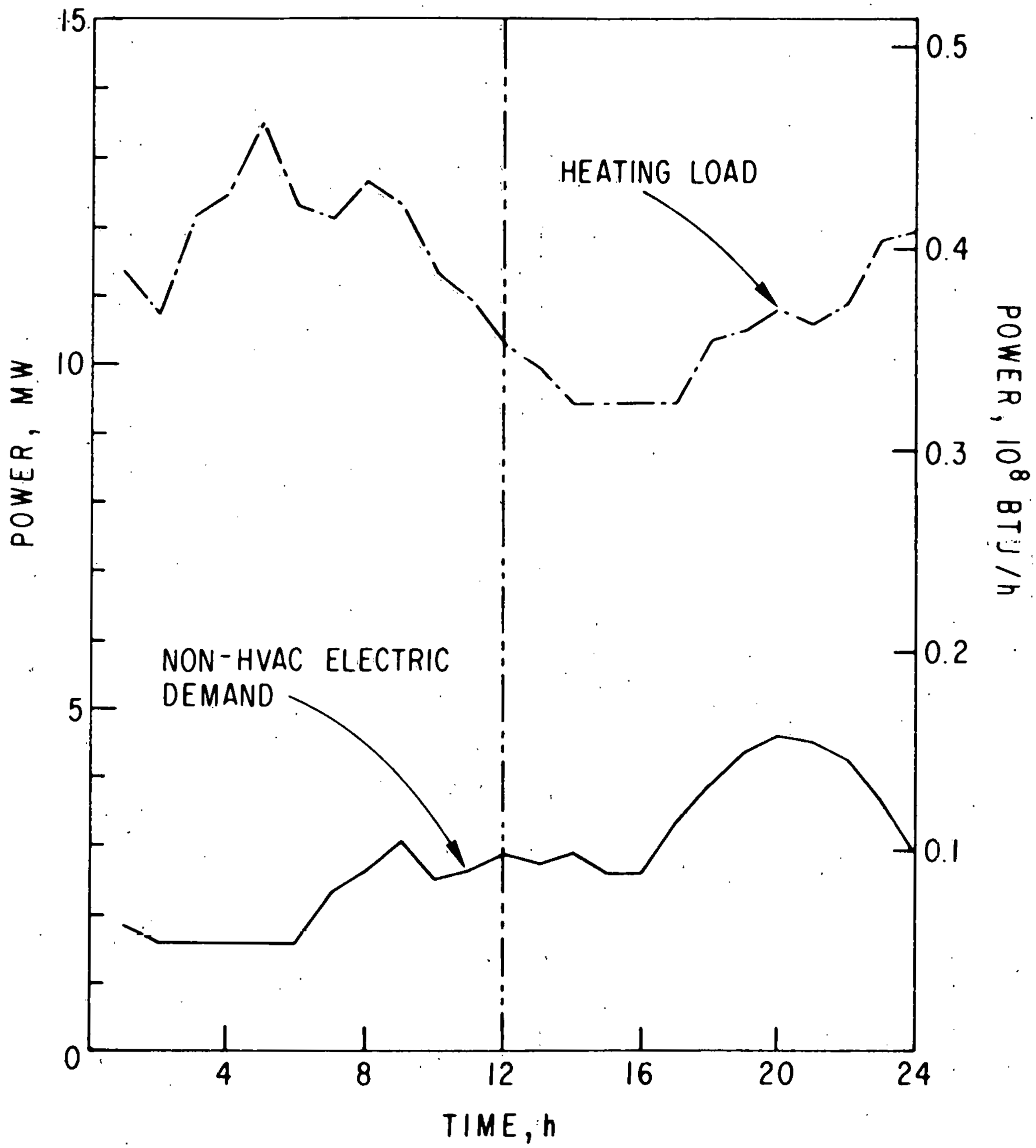

Fig. A.5 Non-HVAC Electric and Cooling Demand Profile of the Fox Valley Center and Villages for the Winter Design Day

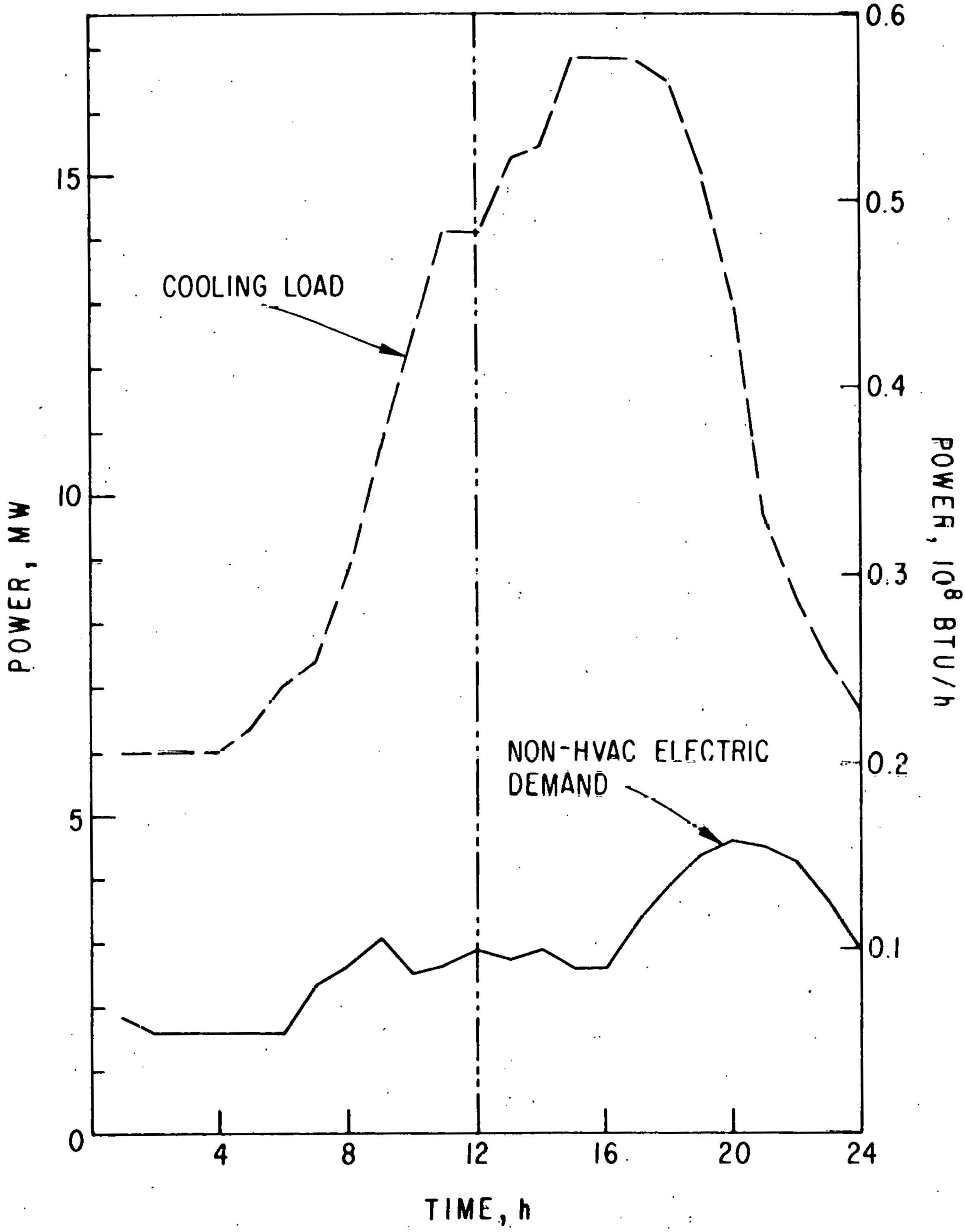

Fig. A.6 Non-HVAC Electric and Cooling Demand Profile of the Fox Valley Center and Villages for the Summer Design Day

LIST OF TABLES
(for Appendix A)

LIST OF TABLES (Cont'd)
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Table A.1 Costs of Diesel Based Total Energy System, Option A, for Zone D

Description	Cost ($ 1000)	
Diesel Engines 3 X 3.7 MW ($330/kW)	3,663	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW	180	
Hot Water Boilers 3 X 5.57 MW	383	
Absorption Chillers 4 X 1500 tons	793	
Cooling Towers 4 X 1500 tons	472	
Chemical Treatment	84	(CD 5,845)
Oil Preparation $(3.79 + 0.77)10^5$ gal 0.97 $/gal	442	(CE 6,287)
Building and Lot 10% CD	584	
Instrumentation and Controls 15% CE	943	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	12,748	

O&M 6% CE 377.

fuel 2.78×10^6 gal/yr oil

Table A.2 Costs of Diesel Based Total Energy System, Option B, for Zone D

Description	Cost ($ 1000)	
Diesel Engines 3 X 4.4 MW ($324/kW)	4,277	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW	180	
Absorption Chillers 3 X 1580 tons	615	
Cooling Towers 3 X 1580 tons	372	
Compression Chillers 2 X 1340	257	
Cooling Towers 2 X 1340	213	
Chemical Treatment	84	(CD 6,268)
Oil Preparation 3.85 X 10^5 gal X 0.98 $/gal	377	(CE 6,645)
Building and Lot 10% CD	627	
Instrumentation and Controls 15% CE	997	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	13,203	

O&M 6% CE 399.

fuel 2.35 X 10^6 gal/yr oil

Table A.3 Costs of Gas Turbine Based Total Energy System, Option A, for Zone D

Description	Cost ($ 1000)	
Gas Turbines 2 X 7.4 MW ($297/kW)	4,396	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 2.4 MW	96	
Hot Water Boilers 2 X 4.56 MW	242	
Absorption Chillers 4 X 1500 tons	793	
Cooling Towers 4 X 1500 tons	472	
Chemical Treatment	84	(CD 6,353)
Oil Preparation 5.99 X 10^5 gal X 0.94 $/gal	563	(CE 6,916)
Building and Lot 10% CD	635	
Instrumentation and Controls 15% CE	1,037	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	13,522	

O&M 6% CE 415.

fuel 3.65 X 10^6 gal/yr oil

Table A.4 Costs of Gas Turbine Based Total Energy System, Option B, for Zone D

Description	Cost ($ 1000)	
Gas Turbines 2 X 7.7 MW ($294/kW)	4,528	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 2.4 MW	96	
Absorption Chillers 4 X 1427 tons	768	
Cooling Towers 4 X 1427 tons	452	
Compression Chillers 2 X 220 tons	64	
Cooling Towers 2 X 220 tons	43	
Chemical Treatment	84	(CD 6,305)
Oil Preparation 6.04 X 10^5 X 0.94 $/gal	568	(CE 6,873)
Building and Lot 10% CD	630	
Instrumentation and Controls 15% CE	1,031	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	13,468	

O&M 6% CE 412.

fuel 3.68 X 10^6 gal/yr oil

Table A.5 Costs of First Generation, Current Stirling Engine Based System, Option A, for Zone D

Description	Cost ($ 1000)	
First Generation Current		
Stirling Engines 3 X 3.7 MW ($420/kW)	4,662	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW	180	
Hot Water Boilers 3 X 2.88 MW	331	
Absorption Chillers 4 X 1500 tons	793	
Cooling Towers 4 X 1500 tons	472	
Chemical Treatment	84	(CD 6,792)
Oil Preparation $(4.1 + 1.78)10^5$ gal X 0.94 $/gal	553	(CE 7,345)
Building and Lot 10% CD	679	
Instrumentation and Controls 15% CE	1,102	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	14,060	

O&M 6% CE 441.

fuel 2.66 X 10^6 gal/yr oil

Table A.6 Costs of Second Generation, Current Stirling Engine Based System, Option A, for Zone D

Description	Cost ($ 1000)	
Second Generation Current		
Stirling Engines 3 X 3.7 MW ($473/kW)	5,250	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW (20/kW)	180	
Hot Water Boilers 3 X 2.87 MW	540	
Absorption Chillers 4 X 1500 tons	793	
Cooling Towers 4 X 1500 tons	472	
Chemical Treatment	84	(CD 7,589)
Coal Preparation 4.35 ton/h	662	(CE 8,251)
Building and Lot 10% CD	759	
Instrumentation and Controls 15% CE	1,238	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	15,182	

O&M 6% CE 495.

fuel 16.600 ton/yr coal

Table A.7 Costs of First Generation, Current Stirling Engine Based System, Option B, for Zone D

Description	Cost ($ 1000)	
First Generation Current		
Stirling Engines 3 X 4.2 MW ($414/kW)	5,216	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW	180	
Absorption Chillers 4 X 1266 tons	709	
Cooling Towers 4 X 1266 tons	404	
Compression Chillers 2 X 700 tons	164	
Cooling Towers 2 X 700 tons	120	
Chemical Treatment	84	(CD 7,147)
Oil Preparation 3.97 X 10^5 gal X 0.98 $/gal	389	(CE 7,536)
Building and Lot 10% CD	715	
Instrumentation and Controls 15% CE	1,130	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	14,315	

O&M 6% CE 452.

fuel 2.42 X 10^6 gal/yr oil

Table A.8 Costs of Second Generation, Current Stirling Engine Based System, Option B, for Zone D

Description	Cost ($ 1000)	
Second Generation Current		
Stirling Engines 3 X 4.2 MW ($466/kW)	5,872	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	64	
Electric Heaters 2 X 4.5 MW	180	
Absorption Chillers 4 X 1266 tons	709	
Cooling Towers 4 X 1266 tons	404	
Compression Chillers 2 X 700 tons	164	
Cooling Towers 2 X 700 tons	120	
Chemical Treatment	84	(CD 7,803)
Coal Preparation 3.57 ton/h	554	(CE 8,357)
Building and Lot 10% CD	780	
Instrumentation and Controls 15% CE	1,254	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	15,325	

O&M 6% CE 501.

fuel 15,100 ton/yr coal

Table A.9 Costs of First Generation, Advanced Stirling Engine Based System, Option A, for Zone D

Description	Cost ($ 1000)	
First Generation Advanced Stirling Engines 3 X 3.7 MW	4,662	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.5 MW ($20/kW)	270	
Hot water boilers 3 X 4.75 MW	366	
Absorption Chillers 4 X 1470 tons	784	
Cooling Towers 4 X 1470 tons	468	
Chemical Treatment	84	(CD 6,936)
Oil Preparation 3.68 X 10^5 gal X .98 $/gal	360	(CE 7,297)
Building and Lot 10% CD	694	
Instrumentation and Controls 15% CE	1,094	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	14,018	

O&M 6% CE 438.

fuel 2.24 X 10^6 gal/yr oil

Table A.10 Costs of Second Generation, Advanced Stirling Engine Based System, Option A, for Zone D

Description	Cost ($ 1000)	
Second Generation Advanced		
Stirling Engines 3 X 3.7 MW ($473/kW)	5,250	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.5 MW	270	
Hot water boilers 3 X 4.75 MW (coal)	894	
Absorption Chillers 4 X 1470 tons	784	
Cooling Towers 4 X 1470 tons	468	
Chemical Treatment	84	(CD 8,052)
Coal Preparation 4.2 ton/h	641	(CE 8,693)
Building and Lot 10% CD	805	
Instrumentation and Controls 15% CE	1,304	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	15,736	

O&M 6% CE 522.

fuel 14,000 ton/yr coal

Table A.11 Costs of First Generation, Advanced Stirling Engine Based System, Option B, for Zone D

Description	Cost ($ 1000)	
First Generation Advanced		
Stirling Engines 3 X 4.5 MW ($410/kW)	5,535	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.5 MW	270	
Absorption Chillers 3 X 1575 tons	615	
Cooling Towers 3 X 1575 tons	369	
Compression Chillers 2 X 1250 tons	244	
Cooling Towers 2 X 1250	200	
Chemical Treatment	84	(CD 7,619)
Oil Preparation 3.05 X 10^5 gal X 0.99 $/gal	302	(CE 7,921)
Building and Lot 10% CD	762	
Instrumentation and Controls 15% CE	1,188	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	14,805	

O&M 6% CE 475.

fuel 1.86 10^6 gal/yr oil

Table A.12 Costs of Second Generation, Advanced Stirling Engine Based System, Option B, for Zone D

Description	Cost ($ 1000)	
Second Generation Advanced Stirling Engines 3 X 4.5 MW ($463/kW)	6,250	
In Plant Hot and Chilled Water Systems	206	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 4.5 MW	615	
Absorption Chillers 3 X 1575 tons	369	
Cooling Towers 3 X 1575 tons	244	
Compression Chillers 2 X 1250 tons	200	
Cooling Towers 2 X 1250	238	
Chemical Treatment	84	(CD 8,334)
Coal Preparation 2.82 ton/h	448	(CE 8,782)
Building and Lot 10% CD	833	
Instrumentation and Controls 15% CE	1,317	
Distribution: Heating and Cooling	4,550	
Electric	384	
TOTAL COST	15,866	

O&M 6% CE 527.

fuel 11,600 ton/yr coal

Table A.13 Costs of Diesel Based Total Energy System, Option A, for Zones A, D, and E

Description	Cost ($ 1000)	
Diesel Engines 5 X 5.5 MW ($318/kW)	8,745	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 13.4 MW	462	
Hot Water Boilers 5 X 17.3 MW	1,002	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 14,479)
Oil Preparation 16.99 X 10^5 gal X 0.74 $/gal	1,257	(CE 15,736)
Building and Lot 10% CD	1,448	
Instrumentation and Controls 15% CE	2,360	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	30.344	

O&M 6% CE 944.

fuel 10.36 X 10^6 gal/yr oil

Table A.14 Costs of Diesel Engine Based Total Energy System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
Diesel Engines 5 X 7.6 MW ($309/kW)	11,742	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	128	
Electric Heaters 5 X 13.4 MW	770	
Absorption Chillers 7 X 1580 tons	1,436	
Cooling Towers 7 X 1580 tons	862	
Compression Chillers 6 X 1580 tons	864	
Cooling Towers 6 X 1580 tons	739	
Chemical Treatment	230	(CD 17,031)
Oil Preparation 13.27 X 10^5 gal X 0.81 $/gal	1,075	(CE 18,106)
Building and Lot 10% CD	1,703	
Instrumentation and Controls 15% CE	2,716	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	33,325	

O&M 6% CE 1,086

fuel 8.09 X 10^6 gal/yr oil

Table A.15 Costs of Gas Turbine Based Total Energy System, Option A, for Zones A, D, and E

Description	Cost ($ 1000)	
Gas Turbines 4 X 7.4 MW (297/kW)	8,791	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 7 MW	330	
Hot Water Boilers 4 X 15.64 MW	768	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 14,159)
Oil Preparation 21.76 X 10^5 gal X $/0.66	1,436	(CE 15,595)
Building and Lot 10% CD	1,416	
Instrumentation and Controls 15% CE	2,339	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	30,150	

O&M 6% CE 936.

fuel 13.27 X 10^6 gal/yr oil

Table A.16 Costs of Gas Turbine Based Total Energy System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
Gas Turbines 4 X 8.8 MW ($286/kW)	10,067	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 7 MW	330	
Absorption Chillers 10 X 1440 tons	1,930	
Cooling Towers 10 X 1440 tons	1,140	
Compression Chillers 4 X 1467 tons	548	
Cooling Towers 4 X 1467 tons	460	
Chemical Treatment	230	(CD 15,061)
Oil Preparation 18.5 X 10^5 gal X $0.71/gal	1,314	(CE 16,375)
Building and Lot 10% CD	1,506	
Instrumentation and Controls 15% CE	2,456	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	31,137	

O&M 6% CE 982.

fuel 11.28 X 10^6 gal/yr oil

Table A.17 Costs of First Generation, Current Stirling Engine Based System, Option A, for Zones A, D, and E

Descrption	Cost ($ 1000)	
First Generation Current		
Stirling Engine 5 X 5.5 MW ($402/kW)	11,055	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 13.4 MW	462	
Hot Water Boilers 5 X 12.5 MW	860	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 16,647)
Oil Preparation 15.94 X 10^5 gal X $0.76/gal	1,211	(CE 17,858)
Building and Lot 10% CD	1,665	
Instrumentation and Controls 15% CE	2,679	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	33,002	

O&M 6% CE 1,072

fuel 9.72 X 10^6 gal/yr oil

Table A.18 Costs of Second Generation, Current Stirling Engine Based System, Option A, for Zones A, D, and E

Description	Cost ($ 1000)	
Second Generation Current		
Stirling Engine 5 X 5.5 MW ($452/kW)	12,430	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 13.4 MW	462	
Hot Water Boilers 5 X 12.5 MW	3,925	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 21,087)
Coal Preparation 19.16 ton/h	2,513	(CE 23,600)
Building and Lot 10% CD	2,109	
Instrumentation and Controls 15% CE	3,540	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	40,049	

O&M 6% CE 1,416.

fuel 60,700 ton/yr coal

Table A.19 Costs of First Generation, Current Stirling Engine Based System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
First Generation Current		
Stirling Engine 5 X 7.2 MW ($390/kW)	14,040	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 13.4 MW	462	
Absorption Chillers 8 X 1610 tons	1,664	
Cooling Towers 8 X 1610 tons	1,002	
Compression Chillers 6 X 1220 tons	723	
Cooling Towers 6 X 1220 tons	588	
Chemical Treatment	230	(CD 19,065)
Oil Preparation 13.17 X 10^5 gal ($0.81/gal)	1,067	(CE 20,132)
Building and Lot 10% CD	1,906	
Instrumentation and Controls 15% CE	3,020	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	35,858	

O&M 6% CE 1,208.

fuel 8.03 X 10^6 gal/yr oil

Table A.20 Costs of Second Generation, Current Stirling Engine Based System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
Second Generation Current		
Stirling Engine 5 X 7.2 MW ($438/kW)	15,768	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 13.4 MW	462	
Absorption Chillers 8 X 1610 tons	1,664	
Cooling Towers 8 X 1610 tons	1,002	
Compression Chillers 6 X 1220 tons	723	
Cooling Towers 6 X 1220 tons	588	
Chemical Treatment	230	(CD 20,793)
Coal Preparation 12.37 ton/h	1,695	(CE 22,488)
Building and Lot 10% CD	2,079	
Instrumentation and Controls 15% CE	3,373	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	38,740	

O&M 6% CE 1,349.

fuel 50,200 ton/yr coal

Table A.21 Costs of First Generation, Advanced Stirling Engine Based System, Option A, for Zones A, D, and E

Description	Cost ($ 1000)	
First Generation Advanced		
Stirling Engine 5 X 6.35 MW ($396/kW)	12,573	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 21.4 MW	591	
Hot Water Boilers 5 X 16.53 MW	988	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 18,422)
Oil Preparation 16.12 X 10^5 gal X $0.76/gal	1,228	(CE 19,650)
Building and Lot 10% CD	1,842	
Instrumentation and Controls 15% CE	2,948	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	35,240	

O&M 6% CE 1,179.

fuel 9.83 X 10^6 gal/yr oil

Table A.22 Costs of Second Generation, Advanced Stirling Engine Based System, Option A, for Zones A, D, and E

Description	Cost ($ 1000)	
Second Generation Advanced		
Stirling Engine 5 X 6.35 MW ($445/kW)	14,129	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 21.4 MW	591	
Hot Water Boilers 5 X 16.53 MW	5,190	
Absorption Chillers 12 X 1440 tons	2,316	
Cooling Towers 12 X 1440 tons	1,368	
Chemical Treatment	230	(CD 24,180)
Coal Preparation 19.7 ton/h	2,576	(CE 26,756)
Building and Lot 10% CD	2,418	
Instrumentation and Controls 15% CE	4,013	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	43,987	

O&M 6% CE 1,605.

fuel 61,400 ton/yr coal

Table A.23 Costs of First Generation, Advanced Stirling Engine Based System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
First Generation Advanced		
Stirling Engine 5 X 7.6 MW ($388/kW)	14,744	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 21.4 MW	591	
Absorption Chillers 7 X 1645 tons	1,477	
Cooling Towers 7 X 14645tons	896	
Compression Chillers 7 X 1250 tons	854	
Cooling Towers 7 X 1250 tons	700	
Chemical Treatment	230	(CD 19,848)
Oil Preparation 12.05 X 10^5 gal X $0.82	988	(CE 20,836)
Building and Lot 10% CD	1,985	
Instrumentation and Controls 15% CE	3,125	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	36,746	

O&M 6% CE 1,250.

fuel 7.35 X 10^6 gal/yr oil

Table A.24 Costs of Second Generation, Advanced Stirling Engine Based System, Option B, for Zones A, D, and E

Description	Cost ($ 1000)	
Second Generation Advanced		
Stirling Engine 5 X 7.6 MW ($436/kW)	16,568	
In Plant Hot and Chilled Water Systems	260	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 21.4 MW	591	
Absorption Chillers 7 X 1645 tons	1,477	
Cooling Towers 7 X 1645 tons	896	
Compression Chillers 7 X 1250 tons	854	
Cooling Towers 7 X 1250 tons	700	
Chemical Treatment	230	(CD 21,672)
Coal Preparation 9.6 ton/h	1,349	(CE 23,021)
Building and Lot 10% CD	2,167	
Instrumentation and Controls 15% CE	3,453	
Distribution: Heating and Cooling	9,600	
Electric	1,200	
TOTAL COST	39,441	

O&M 6% CE 1,381.

fuel 45,900 ton/yr coal

Table A.25 Costs of Diesel Based Total Energy System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Diesel Engines 6 X 6.1 MW ($315/kW)	11,529	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	112	
Electric Heaters 4 X 20.5 MW	772	
Hot Water Boilers 6 X 19.8 MW	1,310	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 19,656)
Oil Preparation 24. X 10^5 gal X $0.61/gal	1,464	(CE 21,120)
Building and Lot 10% CD	1,966	
Instrumentation and Controls 15% CE	3,168	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	41,494	

O&M 6% CE 1,268.

fuel 14.63 X 10^6 gal/yr oil

Table A.26 Costs of Diesel Based Total Energy System, Option B, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Diesel Engines 6 X 8.6 MW ($305/kW)	15,738	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	128	
Electric Heaters 6 X 20.5 MW	1,158	
Absorption Chillers 10 X 1494 tons	1,980	
Cooling Towers 10 X 1494 tons	1,170	
Compression Chillers 9 X 1480 tons	1,242	
Cooling Towers 9 X 1480 tons	1,044	
Chemical Treatment	300	(CD 23,038)
Oil Preparation 19.75 X 10^5 gal X 0.69 $/gal	1,362	(CE 24,400)
Building and Lot 10% CD	2,304	
Instrumentation and Controls 15% CE	3,660	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	45,604	

O&M 6% CE 1,464.

fuel 12.04 X 10^6 gal/yr oil

Table A.27 Costs of Gas Turbine Based Total Energy System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Gas Turbines 4 X 10.2 MW ($277/kW)	11,302	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 25.5 MW	648	
Hot Water Boilers 4 X 20 MW	876	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 18,855)
Oil Preparation 31 X 10^5 gal X $0.5/gal	1,550	(CE 20,405)
Building and Lot 10% CD	1,885	
Instrumentation and Controls 15% CE	3,061	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	40,591	

O&M 6% CE 1,224.

fuel 18.86 X 10^6 gal/yr oil

Table A.28 Costs of Gas Turbine Based Total Energy System, Option B, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Gas Turbines 4 X 12.5 MW ($265.6/kW)	13,280	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 25.5 MW	648	
Absorption Chillers 14 X 1440 tons	2,702	
Cooling Towers 14 X 1440 tons	1,582	
Compression Chillers 6 X 1360 tons	780	
Cooling Towers 6 X 1360 tons	648	
Chemical Treatment	300	(CD 20,314)
Oil Preparation 26.52 X 10^5 galX $0.56/gal	1,485	(CE 21,799)
Building and Lot 10% CD	2,031	
Instrumentation and Controls 15% CE	3,270	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	42,340	

O&M 6% CE 1,308.

fuel 16.17 X 10^6 gal/yr oil

Table A.29 Costs of First Generation, Current Stirling Engine Based System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
First Generation Current		
Stirling Engine 6 X 6.1 MW ($397/kW)	14,530	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 20.5 MW	579	
Hot Water Boilers 6 X 15.12 MW	1,131	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 22,269)
Oil Preparation 23.8 X 10^5 gal X 0.61$/gal	1,452	(CE 23,721)
Building and Lot 10% CD	2,227	
Instrumentation and Controls 15% CE	3,558	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	44,746	

O&M 6% CE 1,423.

fuel 14.51 X 10^6 gal/yr oil

Table A.30 Costs of Second Generation, Current Stirling Engine Based System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Second Generation Current Stirling Engines 6 X 6.1 MW ($447/kW)	16,360	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 20.5 MW	579	
Hot Water Boilers 6 X 15.12 MW	6,697	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 28,665)
Coal Preparation 27.76 ton/h	2,508	(CE 32,173)
Building and Lot 10% CD	2,867	
Instrumentation and Controls 15% CE	4,826	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	55,106	

O&M 6% CE 1,930.

fuel 90.700 ton/yr coal

Table A.31 Costs of First Generation, Current Stirling Engine Based System, Option B, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
First Generation Current		
Stirling Engines 6 X 8.1 MW ($386/kW)	18,760	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 20.5 MW	579	
Absorption Chillers 11 X 1624 tons	2,299	
Cooling Towers 11 X 1624 tons	1,386	
Compression Chillers 7 X 1533 tons	987	
Cooling Towers 7 X 1533	840	
Chemical Treatment	300	(CD 25,525)
Oil Preparation 19.6 X 10^5 gal X 0.69$/gal	1,352	(CE 26,877)
Building and Lot 10% CD	2,552	
Instrumentation and Controls 15% CE	4,032	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	48,701	

O&M 6% CE 1,613.

fuel 11.93 X 10^6 gal/yr oil

Table A.32 Costs of Second Generation, Current Stirling Engine Based System, Option B, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Second Generation Current		
Stirling Engines 6 X 8.1 MW ($433/kW)	21,044	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 20.5 MW	579	
Absorption Chillers 11 X 1624 tons	2,299	
Cooling Towers 11 X 1624 tons	1,386	
Compression Chillers 7 X 1533 tons	987	
Cooling Towers 7 X 1533	840	
Chemical Treatment	300	(CD 27,809)
Coal Preparation 17.48 ton/h	2,314	(CE 30,123)
Building and Lot 10% CD	2,781	
Instrumentation and Controls 15% CE	4,518	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	52,662	

O&M 6% CE 1,807.

fuel 74,700 ton/yr coal

Table A.33 Costs of First Generation, Advanced Stirling Engine Based System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
First Generation Advanced		
Stirling Engines 6 X 7.5 MW ($389/kW)	17,505	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 32.5 MW	732	
Hot Water Boilers 6 X 19.59 MW	1,302	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 25,568)
Oil Preparation 23.32 X 10^5 gal ($0.62/gal)	1,446	(CE 27,014)
Building and Lot 10% CD	2,557	
Instrumentation and Controls 15% CE	4,052	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	48,863	

O&M 6% CE 1,621.

fuel 14.22 X 10^6 gal/yr oil

Table A.34 Costs of Second Generation, Advanced Stirling Engine Based System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Second Generation Advanced		
Stirling Engines 6 X 7.5 MW ($437/kW)	19,665	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 32.5 MW	732	
Hot Water Boilers 6 X 19.59 MW	7,381	
Absorption Chillers 17 X 1495 tons	3,366	
Cooling Towers 17 X 1495 tons	1,989	
Chemical Treatment	300	(CD 33,807)
Coal Preparation 28.5 ton/h	3,592	(CE 37,399)
Building and Lot 10% CD	3,381	
Instrumentation and Controls 15% CE	5,610	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	61,630	

O&M 6% CE 2,244.

fuel 89,000 ton/yr coal

Table A.35 Costs of First Generation, Advanced Stirling Engine Based System, Option B, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
First Generation Advanced Stirling Engines 6 X 8.9 MW ($382/kW)	20,399	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 32.5 MW	732	
Absorption Chillers 8 X 1555 tons	1,624	
Cooling Towers 8 X 1555 tons	968	
Compression Chillers 11 X 1300 tons	1,386	
Cooling Towers 11 X 1300 tons	1,144	
Chemical Treatment	300	(CD 26,927)
Oil Preparation 17.94 X 10^5 gal ($0.7/gal)	1,256	(CE 28,183)
Building and Lot 10% CD	2,693	
Instrumentation and Controls 15% CE	4,227	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	50,343	

O&M 6% CE 1,691.

fuel 10.94 X 10^6 gal/yr oil

Table A.36 Costs of Second Generation, Advanced Stirling Engine Based System, Option A, for Fox Valley Center and Villages

Description	Cost ($ 1000)	
Second Generation Advanced Stirling Engines 6 X 8.9 MW ($428/kW)	22,885	
In Plant Hot and Chilled Water Systems	278	
Hot and Chilled Water Storage	96	
Electric Heaters 3 X 32.5 MW	732	
Absorption Chillers 8 X 1555 tons	1,624	
Cooling Towers 8 X 1555 tons	968	
Compression Chillers 11 X 1300 tons	1,386	
Cooling Towers 11 X 1300 tons	1,144	
Chemical Treatment	300	(CD 29,413)
Coal Preparation 14.16 ton/h	2,914	(CE 31,327)
Building and Lot 10% CD	2,941	
Instrumentation and Controls 15% CE	4,699	
Distribution: Heating and Cooling	13,400	
Electric	1,840	
TOTAL COST	54,207	

O&M 6% CE 1,880.

fuel 68,400 ton/yr coal

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