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COMPARISON OF FUEL-CELL AND DIESEL INTEGRATED ENERGY SYSTEMS AND A CONVENTIONAL SYSTEM FOR A 500-UNIT APARTMENT

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SUMMARY

Declining supplies of domestic oil and gas and the increased cost of energy have resulted in a renewed emphasis in utilizing our available resources in the most efficient manner possible. This, in turn, has brought about a reassessment of a number of methods for converting fossil fuels to end uses at the highest practical efficiency. One of these is the on-site integrated energy system (OS/IES). This system provides electric power from an on-site powerplant and recovers heat from the powerplant that would normally be rejected to the environment. OS/IES are potentially useful in any application that requires both electricity and heat.

In this report, three energy supply systems (two OS/IES and a conventional system) are analyzed and compared for a common application. One OS/IES is powered by diesel-generators representative of those currently used in commercially available integrated energy systems. A phosphoric acid fuel cell, representative of units presently being developed for commercial use by the early 1980's, powers the other integrated energy system. In the conventional system, electricity is purchased from a utility and heat is generated with an on-site boiler.

The application selected for this study was a 500-unit apartment complex that requires electricity (for lights, appliances, and air-handling motors), space heating and cooling, and domestic hot water. The apartment complex was sited in four locations to evaluate climatic effects.

The energy use for all powerplant and apartment location combinations was computed. For comparison purposes, all energy was computed on the basis of a common starting point defined to be either (1) the coal pile of a central generating station producing electricity for use in the conventional system or (2) the coal pile of a coal-to-synthetic fuel plant producing clean, synthetic fuel for use in the on-site powerplants (as well as for boilers in the conventional system).

The cost of energy to the consumer as a function of fuel price was calculated for the diesel and conventional systems. Using these systems as baselines, the breakeven capital cost of the fuel cell system was found as a function of fuel price. The fuel cell OS/IES is about 10% more energy effective in terms of total coal consumption than either the diesel OS/IES or the conventional system. For the same annual cost to the consumer and for a range of synthetic fuel prices from $2.85 to $4.75 per billion joules ($3.00 to $5.00 per million BTU), the capital cost of the fuel cell system could be from 30 to 55 percent higher, respectively, than the diesel sytem. For the same fuel price range, the conventional system is the most cost effective system if the price of electricity to the consumer is less than about 5 to 6.5 cents per kilowatt-hour respectively.

INTRODUCTION

Today's energy problems originate primarily from the current and projected shortage of clean, domestic petroleum products and natural gas. Production and proven reserves of domestic oil and natural gas peaked in the last decade. Since then, both production and reserves of domestic oil and natural gas have been declining. The result has been an increase in imports of crude oil, petroleum products and natural gas and significantly higher prices for both imported and domestic fuels. This, in turn, has substantially increased the price that consumers must pay for energy. This situation is likely to continue until the cost of converting the nation's abundant supplies of coal and other domestic energy sources into useful forms of clean energy is competitive with the price of imported clean energy.

In the near term, conservation offers the most cost effective method of extending the nation's reserves of oil and natural gas. At the same time, industry and government are re-examining conventional energy conversion equipment such as boilers, furnaces, and rotating equipment, for ways to improve efficiency by improving combustion, installing heat recovery equipment and improving controls.

As part of this effort, the concept of total or integrated energy systems is being reevaluated. These systems provide both electric power and heat to a user by means of an on-site powerplant. The powerplant is designed to supply all or part of the electrical and heating requirements, on demand, with an optimum combination of electric power generation and waste heat recovery. The overall energy utilization for these systems is typically greater than 60% and, depending on the type of powerplant and application, it could exceed 90% (ref. 1). The on-site feature also eliminates the electrical transmission losses that occur with a conventional system where electricity is supplied by a utility-owned, central generating station.

The concept of an on-site integrated energy system (OS/IES) may be appropriate for any application that demands both heat, in the form of steam or hot water, and electricity in proportions that are approximately one-to-one or greater. An OS/IES could be designed to meet the electrical load, on demand, and the useful heat would be recovered in the form of steam or hot water for direct use or stored for later use. Applications with both heat and electric demands can be found in the industrial and the residential/commercial sectors of the economy. Whether an integrated energy system is feasible for any specific application depends on such factors as peak-to-average electric load, the ratio of heat to electric load, temperature of the heat required, the type and availability of fuel, environmental requirements, reliability of operation and economics. On-site systems usually require a clean fuel such as natural gas or light distillates, that can be converted into power and heat in a reliable and trouble-free operation. The conversion equipment must be reliable, efficient and environmentally acceptable. Ultimately, these and other factors translate into a cost of usable energy which must be competitive with the conventional system.

There were approximately 500 total energy systems (ref. 2) in operation in the United States in 1973 ranging in size from 200 kilowatts to 20 megawatts. These are typically powered by diesel engines and, to a lesser extent, gas turbines (ref. 3). Diesels have been utilized primarily in smaller industrial and residential applications such as apartment complexes, shopping centers, schools, hospitals and greenhouses. Gas turbines are more commonly used for the larger industrial applications. Other prime movers that produce both electrical power and useful waste heat are presently being considered for total energy system applications.

Phosphoric acid fuel cell technology has reached the stage where it is expected to be commercially available within the next decade (ref. 4). Fuel cells are nonrotating electrical generators that convert chemical energy in the fuel and oxidant directly to electricity by electrochemical reactions on nonconsumed electrodes, and in the process, produce useable waste heat. Both the electrical and the heat recovery efficiencies are, potentially, greater than those of other integrated energy systems.

This report analyzes and compares a fuel cell OS/IES with a diesel OS/IES and a conventional energy system for a common application. Results include a comparison of energy requirements for four geographic locations representing different climates and an economic comparison for one of these locations. The energy consumption of each system is computed taking into account all energy conversion and transmission losses. For comparison purposes, the common starting point for each system is assumed to be the coal pile of a centrally located plant.

The annual cost of energy to the consumer as a function of fuel price is calculated for each system. Then, by using the diesel and conventional systems as baselines, the breakeven capital cost of the fuel cell system is calculated.

ENERGY DEMANDS

The application chosen for this analysis was a 500-unit apartment complex. The number of units affects the results only in that the energy demands of a large complex permit the use of commercial-size, highly efficient equipment. The large number of users also tends to smooth the various demands. The data base for this application was developed by the Urban Systems Project Office of NASA's Johnson Space Center as part of a design study conducted by NASA (refs. 5 and 6) as a participant in the HUD-MIUS program. The Modular Integrated Utility System (MIUS) program was conducted by the Department of Housing and Urban Development (HUD) to develop and demonstrate the technical, economic and institutional advantages of integrating the systems that provide all or part of the utility services for a community.

The 500-unit apartment complex consists of 20 buildings situated on eleven acres with a population density of 106.5 people per acre. The building types are low-rise garden apartments and high-rise apartments containing both single and family units. The building designs reflect current planning and constructon methods that provide all conveniences and services commensurate with a modern facility. Each apartment is equipped with modern lighting, appliances and laundry facilities and is heated and cooled via individual forced air convectors. The identical apartment complex was sited in four geographic locations for the purpose of evaluating climate effects. Washington, DC was selected to represent an average climate for all seasons of the year. Minneapolis, Minnesota was selected to represent a severe winter and a mild summer while Houston, Texas represents the opposite, i.e., a mild winter and a hot, humid summer. Las Vegas, Nevada is similar to Houston in terms of temperature but has a much dryer climate and was selected to examine the effects of this difference.

Table I gives the seasonal and annual energy demands for each of the four sites. These represent end-use demands that must be supplied by the utility system serving the apartment complex. Electricity is used to operate indoor and outdoor lighting, large and small appliances (including cooking), and motors for air-handling. The energy required for domestic hot water is that needed to heat potable cold water from its reservoir or well temperature to 60°C (140°F). Space heating and cooling demands represent the net heat loss or gain, from or to the apartment units, that is necessary to maintain the apartment temperature at 23°C (74°F) drybulb and 50% relative humidity.

In addition to the seasonal loads which were based on average seasonal days, the MIUS data base developed hourly loads for the design days. These were used to establish the peak heating and cooling loads and thereby the design capacity of the equipment supplying the loads. System design capacity was determined for the Washington DC area only and used as input to the economic calculations. Both the heating and cooling peak loads were based on ambient temperatures that were two standard deviations, below and above the mean winter and summer temperatures, respectively, i.e., based on ambient temperatures that include 95% of the historically observed low and high extremes.

ENERGY SYSTEMS

The energy systems analyzed in this study are assumed to supply, on demand, the energy requirements of the consumer. Space heating and cooling demands are supplied via 2-pipe, hot water and chilled water circulation systems. Hot water supply temperature is 93°C (200°F) with a return temperature of 13°C (55°F). Heat exchangers in each apartment add or remove heat as required to condition the living space. Domestic hot water is supplied to each apartment at a temperature of 60°C (140°F). The system's major performance assumptions are summarized in table II.

Conventional Energy System

The conventional energy system (illustrated in fig. 1), supplies all of the normal electrical demands with electricity purchased from a central utility. The conversion of coal to electricity is assumed to occur at an efficiency of 32.5% which is equivalent to the current national average heat rate of 11.07×10^6 joules/kWh (10,500 BTU/kWh). The electricity is then transmitted at an energy loss of 8% which represents the current national average transmission loss. Space cooling demands are supplied by a compression chiller operated with purchased electricity. Space heating and domestic water heating demands are supplied from an on-site boiler fired with a clean, synthetic fuel derived from a centrally located coal conversion plant operating at a conversion efficiency of 65%. The clean fuel, which is representative of either a synthetic pipeline gas or a synthetic distillate fuel oil, is transported to the on-site boiler at an energy loss of 1.5%, which represents typical pipeline pumping requirements. The boiler, operated at a conversion efficiency of 80%, converts the lower heating value of the clean fuel to low pressure steam at a gauge pressure of approximately 1075 N/m^2 (15 psig) and a temperature of 121°C (250°F).

On-Site/Integrated Energy Systems

The general configuration of the on-site/integrated energy systems is illustrated in figure 2. Both the diesel and fuel cell on-site systems produce electricity and useful heat and are assumed to be completely stand-alone systems, i.e., not connected to the electric utility grid. The on-site powerplant is fueled with a coal-derived synthetic fuel, as described for the conventional on-site boiler.

The on-site powerplant produces electricity on demand, for the normal electrical demands and other auxiliary demands such as heating and cooling when required. In addition to producing electricity, both on-site powerplants also recover two grades of useful heat. High grade heat is recovered in the form of steam at a gauge pressure of 1075 N/m^2 (15 psig) and a temperature of 121°C (250°F) which is condensed and returned to the powerplant as 93°C (200°F) water. This heat is used via a heat exchanger to supply heat for space heating or via an absorption chiller to supply chilled water for space cooling. In the event that the space heating demand is larger than the available by-product heat from electricity generation, this additional heating demand is satisfied by producing electricity for resistance heating while, at the same time, using the associated by-product heat. The primary method of air conditioning is via absorption chillers using high quality heat as input. If additional cooling is required, more electricity is generated to operate compression chillers and the associated high grade heat is used in the absorption chillers. Low grade heat is recovered in the form of hot water at 71°C (160°F) and returned to the powerplant at about 21°C (70°F). This heat is used to supply heat for domestic hot water and to supply a fraction of the heat for space heating.

In order to keep the hot water heating system temperature consistent with accepted practices, no more than one sixth of the heating demand satisfied via by-product heat was assumed to be low quality heat. Use of heat pumps was not considered in this study. For this analysis it was assumed that there is sufficient energy storage capacity in the space heating, cooling and domestic hot water systems to meet the user demands on a daily basis with the high and low grade heat available from the powerplant. This is short term storage designed, for instance, to store excess heat during the day to be used in the evening. Heat that cannot be used within approximately 24 hours is considered lost. This storage requires insulated storage tanks that could store 93°C (200°F) water for space heating, 60°C (140°F) water for domestic hot water and 7°C (45°F) water for space cooling.

The diesel powerplant analyzed in this study is representative of current, commercial engine-generator units with heat recovery equipment designed to recover waste heat from the engine block, exhaust gases and lube oil.

Using the MIUS data base, the diesel powerplant has a total installed capacity of 1834 kW and includes four engine-generator sets, heat exchangers, hot and chilled water storage, fuel storage, electrical distribution equipment and controls.

These multiple units provide sufficient redundancy to insure that the OS/IES reliability is equivalent to the reliability of services provided by the conventional system. The diesel efficiencies (see table II) represent average operating conditions at a load factor of 80%, which is readily achievable with four engines.

The fuel cell operating characteristics, given in table II, are based on phosphoric acid fuel cells currently being developed for testing in a utility application.

The installed capacity of the fuel cell OS/IES, assumed to be the same as for the diesel OS/IES, was 1834 kW. However, since the fuel cell system tends to be highly modularized, it could have a higher reliability than the diesel system for the same installed capacity. Conversely, the fuel cell system may not require as much installed capacity as the diesel system for the same reliability. A determination of the overall reliability of the fuel cell OS/IES was beyond the scope of this study.

FUELS

Petroleum and natural gas emerged after World War II as the dominant fuels consumed in the United States and have maintained this dominance to the present day. Their low price and convenience have resulted in large increases in demand over the last 30 years. This dominance is particularly evident in the case of total energy systems operating today which are fueled, almost exclusively, with natural gas and distillate fuel oil. The clean quality of these fuels makes them ideal for today's equipment and emission requirements.

Natural gas and distillates would continue to be ideal fuels for on-site systems except that declining domestic reserves and production have resulted in concern for their price and availability. This decline has resulted in imports of both fuels increasing significantly in recent years.

Assuming that domestic production of natural gas and petroleum will not increase significantly in the future and that political considerations will limit imports of oil and gas, then any new significant supplies of clean fossil fuel will likely be produced by converting coal to a synthetic liquid or gas. Processes that convert coal to both a synthetic pipeline gas and a clean synthetic crude oil are currently being developed by industry and government. Several coal gasification processes have been commercially demonstrated to the extent that a number of large coal gasification projects have been initiated. Several coal liquefaction processes are in the pilot plant and small demonstration plant stage of development. Cost studies of these new processes have indicated that clean fuel from coal can be produced at an energy conversion efficiency of about 65% and at a product price of about $3.32/billion joules ($3.50/million BTU) based on 1975 dollars.

The quality of clean synthetic fuels from coal is expected to be equivalent to comparable petroleum fuels. Natural gas and pipeline quality synthetic gas are both predominantly methane with a higher heating value of about $29.8X10^3$ joules/m^3 (1000 BTU/SCF) and a lower heating value of about $26.9X10^3$ joules/m^3 (900 BTU/SCF). Distillate fuel oil from synthetic coal liquids is comparable to No. 2 fuel oil which has a higher heating value of about $3.9X10^7$ joules/liter (140,000 BTU/gallon) and a lower heating value of about $3.6X10^9$ joules/liter (130,000 BTU/gallon). The fuel oil must have a sulfur content less than about 0.8% by weight in order to meet the federal emission standards of 344 grams of SO_2 per billion joules of heat input (0.8 lb per million BTU).

The primary fuel for this study was assumed to be coal as illustrated in figures 1 and 2. For the conventional system, coal was used directly in a coal/steam central station powerplant. For on-site use in all systems, the coal is assumed to have been previously converted into a clean, synthetic gas or distillate fuel oil and

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delivered to the site. Fuel costs were a variable in this analysis with delivered fuel prices assumed to be in the range of $2.85 to $4.75 per billion joules ($3.00 to $5.00 per million BTU).

ANALYSIS

This analysis was divided into two parts. In the first, an energy analysis was performed for an apartment complex sited in four locations and powered by a conventional system and two OS/IES. The energy demands and energy systems are described in detail in previous sections. Secondly, a comparative economic analysis of the three energy systems was performed, assuming the Washington, DC location.

Energy Analysis

The results of the energy analysis are summarized in figure 3. For each of the four cities, the annual energy demands of the 500-unit apartment complex are shown in units of trillion joules and identified as electricity, domestic water heating, space heating and space cooling (air conditioning). Only the space heating and cooling demands vary appreciably with geographic location. Houston, because of its large air conditioning load, has the highest annual energy demand at 51.6 trillion joules while Washington, with a more moderate climate has the lowest annual demand at 44.3 trillion joules. For this application, the effect of different climates on energy demand is less than 10% of the average demand of the four cities.

The energy required to supply the demands at each of the four cities is also shown in figure 3 for the three energy supply systems analyzed. The size of the supply and demand bars cannot be directly compared since the energy analysis takes into account the various efficiencies and coefficients of performance of the energy system equipment. For example, in the conventional system the electrical and space cooling (compression air conditioning) demands can't be summed to obtain the electricity supplied since the compression air conditioner doesn't operate at a COP of 1.0 but at 4.5. The analysis for the on-site systems is more complex. A sample calculation is shown in the appendix. For the fuel cell and diesel OS/IES, the useful portion of the energy is represented by electricity, low grade heat and high grade heat while the conventional system supplied the demands with electricity and high grade heat from the boiler. The losses shown for each system represent all of the conversion losses at the synthetic fuel plant and steam/electric powerplant, fuel and electric transmission losses, and on-site powerplant and boiler losses. The total bar graph therefore represents the total annual coal consumption required to meet the consumer demands.

In all cases, the fuel cell OS/IES utilized the least amount of primary fuel, i.e., coal, while supplying all consumer demands. The diesel OS/IES was slightly more efficient than the conventional system in most cases. In Houston, the conventional system used less coal than the diesel system. In this one case, which had a very large air conditioning demand, the high COP offered by the compression chiller in the conventional system out-weighed the advantages of an on-site system. In general, the fuel cell system consumed about 10% less coal than the other systems. In terms of average overall energy utilization of the primary fuel, coal, the fuel cell system supplied the consumer energy demands with about 49% of the coal's higher heating value while the diesel and conventional systems utilized about 45% of the coal's heating value.

The OS/IES worked well for this application. As shown in table III, nearly all space heating demands were met with by-product heat. The diesel system satisfied nearly half the cooling demand with absorption chillers and the fuel cell system satisfied over 40%. All domestic hot water could be heated with by-product heat. In both systems, a very small fraction of the recoverable heat had to be rejected. Most of this heat could have been used if the hydronic heating system temperature or the absorption chiller source temperature had been reduced.

Economic Analysis

Most studies of integrated energy systems show an energy savings when compared to conventional systems. However, the acceptance of an integrated energy system for any application must ultimately be based on its cost effectiveness when compared to a conventional system. An economic comparison of the three systems considered in this study required specifying certain economic criteria that were then applied uniformly to each. In all cases, costs are quoted in 1977 dollars.

Economic comparisons are made on the basis of supplying the energy demands of the Washington, DC apartment complex. The Washington location was chosen for the economic comparison since it represents a moderate climate and because load data were generated for this location.

The three energy systems are compared on the basis of levelized annual cost per apartment (dollars/year). All comparisons are made on a constant 1977 dollar basis, i.e., no inflation was assumed. an annual fixed charge rate of 13% was assumed for levelizing the initial capital investment. The total levelized annual cost of energy is the sum of the levelized capital investment, the annual operating and maintenance cost and the annual fuel cost.

For the same annual cost of energy for each baseline system (the diesel and conventional systems), the breakeven capital cost ($/kW) of the fuel cell system was then determined.

Based on the MIUS data (ref. 7), the diesel OS/IES was estimated to have a total installed capital cost of $275/kW in 1977 dollars. For the purpose of illustrating the sensitivity of the results to this estimate, calculations were also performed for an assumed diesel system cost of $375/kW.

For the assumed fixed charge rate on capital of 13% per year, the levelized annual capital cost of the diesel system at $275/kW was $65,000 per year. The annual labor cost for operating the diesel powerplants was estimated to be $55,000 and the annual maintenance cost was estimated at $29,000 for a total annual operating and maintenance cost of $84,000 per year (ref. 7). The annual operating and maintenance cost of the fuel cell OS/IES was assumed to be the same as for the diesel OS/IES.

Cost comparisons are illustrated in figures 4, 5, and 6. Figure 4 compares the diesel and fuel cell systems, figure 5 compares the conventional and fuel cell systems, and figure 6 is a composite that shows the most economic system given a price of fuel and electricity.

In figure 4(a), the annual cost of energy for each apartment is shown as a function of capital cost and the price of synthetic fuel for the diesel on-site integrated energy system. The annual cost includes the capital charges, O&M costs and fuel cost. It shows that the annual cost of energy varies from about $675 to $980 over the fuel price range of $2.85 to $4.75 per billion joules ($3.00 to $5.00 per million BTU) and a range of capital cost from $275/kW to $375/kW. Figure 4(b) shows that in order for the fuel cell OS/IES to achieve the same annual cost of energy as the diesel OS/IES, the installed capital cost of the fuel cell system cannot exceed $360/kW to $535/kW over the same range of fuel and capital costs. Current estimates of fuel cell powerplant costs, including fuel processor, power conditioner and heat recovery equipment fall within this range (refs. 8 and 9).

Figure 5(a) shows that the conventional system could achieve the same annual cost per apartment for energy as the diesel system if the purchase price of electricity does not exceed $0.05 to $0.07 per kilowatt-hour for the same range of fuel prices.

Figure 5(b) shows the installed costs that a fuel cell OS/IES would have to meet in order to be competitive with the conventional system. This is a wider range of breakeven costs than in the diesel comparison since both the fuel and electricity costs are varying.

Figure 6 superimposes figures 4(b) and 5(b) to show which system is more economic under a given set of price assumptions. For example, if fuel were to cost $\$4/10^9$joules and electricity were to cost $0.06/kWh, a diesel OS/IES at $375/kW would not be economically attractive while a $275/kW diesel system would be attractive. At the same fuel and electricity costs, the fuel cell OS/IES capital costs would have to be less than $480/kW to be economically attractive. Figure 6 also points out the fact that fuel cells are economically more attractive than diesels at higher fuel prices, due to the higher overall efficiency of the fuel cell. The opposite is true when comparing the fuel cell system to a conventional system, because the fuel cell system uses a premium fuel to satisfy all user demands while the conventional system only heats with the premium fuel.

CONCLUDING REMARKS

This analysis has shown that for a 500-unit apartment complex, a phosphoric-acid fuel-cell on-site integrated energy system would be about 10% more energy conservative in terms of total coal consumption than either a diesel on-site integrated energy system or a conventional system. This conclusion is relatively independent of location, i.e., climatic conditions. This conclusion is also based on a synthetic fuel scenario wherein the clean fuel (gas or distillate oil) supplied to the apartment complex is derived from coal at a central coal conversion facility. For a non-synthetic fuel scenario (today's situation) the energy savings of the on-site integrated energy systems over the conventional system is estimated to be about 40%.

For a range of synthetic fuel prices from $2.85 to $4.75 per billion joules ($3.00 to $5.00 per million BTU), the fuel cell OS/IES would breakeven with a diesel OS/IES (diesel capital cost of $275/kW) at a capital cost of $360 to $435/kW respectively or about 30 to 55 percent greater capital cost than the diesel system. If these capital costs can be achieved for the fuel cell OS/IES, then its other attributes such as low emissions, low noise levels and rapid response to load changes, should make the fuel cell system particularly attractive for residential OS/IES. However, it should be noted that for the same range of synthetic fuel costs, if the purchase price of conventional electricity is less than about $0.05/kWh to $0.065/kWh respectively, then the conventional system would be the most attractive choice.

APPENDIX

SAMPLE CALCULATIONS

The seasonal energy demands specified in table I formed the basis for the energy analysis. For each seasonal demand, the analytical procedure for both the fuel cell and the diesel OS/IES was to first generate sufficient electricity to satisfy all of the normal power demands and then determine the heating and/or cooling demands that could be supplied by the high and low grade heat produced by the powerplant. When the heating and cooling demands were not satisfied, additional electricity was generated to operate either resistance heaters or compression chillers, but only to the extent that all additional high and low grade heat was utilized as much as possible and all demands were satisified.

For each system, the seasonal energy requirements were accumulated to determine the total annual energy supply required to meet all of the consumer demands. All conversion efficiencies were considered so that the total energy supply represents the annual consumption of coal, which is the primary fuel.

To determine the seasonal fuel requirement for each on-site system an iterative approach was used. The energy demands for this example (Spring season in Washington, DC) are:

Electricity	4.743×10^{12} joules
Domestic Hot Water	3.052×10^{12} joules
Space Heating	0.269×10^{12} joules
Space Cooling	1.874×10^{12} joules

Hot water for space heating is supplied by a combination of high quality and low quality by-product heat in the limit ratio of 5:1 as discussed in the Energy Systems Section. For this application, the ratio gives 0.224×10^{12} joules of high quality heat and 0.045×10^{12} joules of low quality heat to satisfy the space heating demand. Domestic hot water is supplied entirely by low quality heat.

The energy demands in terms of the powerplant products are:

Electricity	4.743×10^{12} joules
Low Quality Heat	3.097×10^{12} joules max.
High Quality Heat	0.224X1012 joules
Space Cooling	1.874×10^{12} joules

The only calculation differences between a fuel cell on-site system and a diesel on-site system arise from differences in the powerplants' performance assumptions. A fuel cell will be used in this example to illustrate the calculations for the on-site system. A sample calculation for the conventional system is also included.

Fuel Cell On-Site System Energy Consumption

The performance assumptions for the on-site system are:

Breakdown of Usable Fuel Cell Output:	
Electricity	38%
High Quality Heat	20%
Low Quality Heat	24%
Absorption Chiller COP	0.65
Compression Chiller COP	4.5
Coal-to-Synthetic Fuel Conversion Efficiency (HHV)*	65%
Synthetic Fuel Transmission Efficiency*	98.5%

The calculation begins by assuming a total fuel usage and then determining if the demands are satisfied. Assume that the total fuel usage is 12.656×10^{12} joules. At 38% electrical production efficiency the electricity produced is

$(12.656 \times 10^{12}$ joules$)$ $(0.38) = 4.809 \times 10^{12}$ joules of electricity which is in excess of the electrical demand by

$(4.809 \times 10^{12}$ joules$) - (4.743 \times 10^{12}$ joules$) = 0.066 \times 10^{12}$ joules This electricity is used by a compression chiller at a COP of 4.5 to yield.

$(0.066 \times 10^{12}$ joules$)$ $(4.5) = 0.297 \times 10^{12}$ joules of cooling.

(If this were the winter season the excess electricity would be used for resistance heating.)

The remaining cooling demand is

$(1.874 \times 10^{12}$ joules$) - (0.297 \times 10^{12}$ joules$) = 1.577 \times 10^{12}$ joules which must be satisfied by absorption chillers using high quality heat at COP of 0.65; i.e.,

$(1.577 \times 10^{12}$ joules$)/(0.65) = 2.426 \times 10^{12}$ joules of high quality heat required.

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* Applies to Conventional System also.

The total high quality heat demand is the sum of the high quality heat required for absorption air conditioning, and the high quality heat required for space heating, i.e.,

$$(2.426\text{X}10^{12}\text{ joules}) + (0.224\text{X}10^{12}\text{ joules}) = 2.650\text{X}10^{12}\text{ joules.}$$

The high quality heat available is

$$(12.656\text{X}10^{12}\text{ joules})\ (0.20) = 2.531\text{X}10^{12}\text{ joules.}$$

This does not satisfy the high quality heat demand. The low quality heat available is

$$(12.656\text{X}10^{12}\text{ joules})\ (0.24) = 3.037\text{X}10^{12}\text{ joules}$$

which also does not satisfy the low quality heat demand of $3.097\text{X}10^{12}$ joules. Thus a slightly larger total fuel usage must be assumed. It may be shown that $12.733\text{X}10^{12}$ joules (LHV) of synthetic fuel satisfies all requirements. Taking into account coal-to-synthetic fuel losses, fuel transmission losses and low to high heating value ratios, the coal needed to supply this energy is

$$(12.733\text{X}10^{12}\text{ joules})/0.65/0.985/0.94 = 21.157\text{X}10^{12}\text{ joules of coal (HHV).}$$

Conventional System Energy Consumption

The pertinent conversion efficiencies for the conventional system are:

Coal-to-Synthetic Fuel Conversion Efficiency (HHV)	65%
Coal-to-Electric Conversion Efficiency (HHV)	32.5%
Electricity Transmission Efficiency	92%
Synthetic Fuel Transmission Efficiency	98.5%
Package Boiler Efficiency (LHV)	80%
LHV to HHV ratio for Synthetic Liquid	0.94

The base electric and air conditioning demands (at a COP of 4.5) are satisfied by purchased electricity;

$$(4.743\text{X}10^{12}\text{ joules} + \frac{1.874\text{X}10^{12}}{4.5}\text{ joules})/0.325/0.92 =$$

$$17.255\text{X}10^{12}\text{ joules of coal (HHV).}$$

Domestic hot water and space heating demands are satisified by a package boiler, i.e.,

(3.052X10^{12} joules+ 0.269X10^{12} joules)/0.80/0.985/0.65/0.94 = 6.898X10^{12} joules of coal (HHV).

The total coal requirement is 24.153X10^{12} joules (HHV). To obtain the total annual fuel usage the four seasonal fuel usage values are simply summed.

Economic Analysis

The annual fuel usage for the fuel cell on-site system in the Washington, DC area is 52.857X10^{12} joules in terms of the synthetic fuel's lower heating value. Fuel costs however are computed using the higher heating value. The ratio of lower heating value to higher heating value is 0.94 for a synthetic liquid. The fuel requirement in terms of higher heating value is 56.231X10^{12} joules. Assuming synthetic fuel costs \$4.75/billion joules (\$5.00/million BTU) an annual fuel cost per apartment may be calculated, i.e.,

(\$4.75/10^{9} joules) (56.231X10^{12} joules)/500 apt = \$534/yr/apt.

O&M costs for the fuel cell system are assumed to be the same as for the diesel system. The yearly O&M charge per apartment is

(\$84,000/yr)/500 apt. = \$168/yr/apt.

The annual breakeven capital charge per apartment is found by subtracting the fuel cell fuel and O&M charges from the total diesel system cost of \$932/yr/apt (fig. 4(a)). This gives a breakeven capital charge for the fuel cell system of \$230/yr/apt. For a fixed charge rate on capital of 13% per year the total breakeven installed capital cost of the fuel cell system is

(500 apt) (\$230/yr/apt)/0.13 = \$884,615

The installed capacity is 1834 kW. The resulting breakeven unit price of the fuel cell system is \$482/kW.

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TABLE I. - END USE DEMANDS

10^{12} Joules

	Winter	Spring	Summer	Fall	Annual
Washington D. C.					
Electricity	4.638	4.743	4.743	4.689	18.818
Domestic Hot Water	2.986	3.052	3.052	3.020	12.111
Space Heating	2.258	0.269	-	0.178	2.705
Space Cooling	0.051	1.874	6.543	2.190	10.658
Minneapolis, Minnesota					
Electricity	5.064	4.723	4.742	4.688	19.238
Domestic Hot Water	2.987	3.054	3.051	3.018	12.111
Space Heating	5.362	0.688	-	0.352	6.402
Space Cooling	-	0.768	5.290	1.266	7.324
Houston, Texas					
Electricity	4.638	4.743	4.743	4.689	18.813
Domestic Hot Water	2.986	3.054	3.052	3.020	12.112
Space Heating	0.334	-	-	-	0.334
Space Cooling	1.607	4.303	9.998	4.442	20.351
Las Vegas, Nevada					
Electricity	4.638	4.743	4.743	4.689	18.813
Domestic Hot Water	2.986	3.052	3.052	3.020	12.110
Space Heating	1.124	0.054	-	0.037	1.215
Space Cooling	0.671	3.809	7.416	4.088	15.985

Source: Fulbright, Ben E.: MIUS Community Conceptual Design Study. NASA TMX-58176, 1976.

TABLE II - PERFORMANCE ASSUMPTIONS

Coal-to-Electric Conversion Efficiency	32.5% (HHV)
Coal-to-Synthetic Fuel Conversion Efficiency	65% (HHV)
Fuel Cell Usable Output	38% Electricity (LHV) 24% 71°C (160°F) Water 20% 121°C (250°F) Steam
Diesel Usable Output	33% Electricity (LHV) 17% 71°C (160°F) Water 22% 121°C (250°F) Steam
Package Boiler Efficiency	80% 121°C (250°F) Steam (LHV)
Compression Chiller COP	4.5
Absorption Chiller COP	0.65
Ratio of LHV to HHV - Synthetic Liquid	0.94
- Synthetic Gas	0.90
Synthetic Fuel Transmission Efficiency	98.5%
Electricity Transmission Efficiency	92%

(HHV) Based on the higher heating value

(LHV) Based on the lower heating value

COP = Coefficient of performance

TABLE III - By-Product Heat Use

City	Season	Air Conditioning Demand, 10^{12} Joules	% Satisfied by Absorption A/C		Space Heating Demand, 10^{12} Joules	% Satisfied with by-product heat	
			Fuel Cell	Diesel		Fuel Cell	Diesel
Washington	Winter	0.051	100	100	2.258	100	100
	Spring	1.874	80	82	0.269	100	100
	Summer	6.543	30	36	-----	---	---
	Fall	2.190	70	78	0.178	100	100
	Total	10.658	47	53	2.705	100	100
Houston	Winter	1.607	85	90	0.334	100	100
	Spring	4.303	42	48	-----	---	---
	Summer	9.998	22	27	-----	---	---
	Fall	4.442	41	46	-----	---	---
	Total	20.351	35	41	0.334	100	100
Las Vegas	Winter	0.671	100	100	1.124	100	100
	Spring	3.809	46	51	0.054	100	100
	Summer	7.416	27	34	-----	---	---
	Fall	4.088	43	50	0.037	100	100
	Total	15.985	39	44	1.215	100	100
Minneapolis	Winter	------	---	---	5.362	75	79
	Spring	0.768	100	100	0.688	100	100
	Summer	5.290	35	42	-----	---	---
	Fall	1.266	100	100	0.352	100	100
	Total	7.324	53	57	6.402	79	82

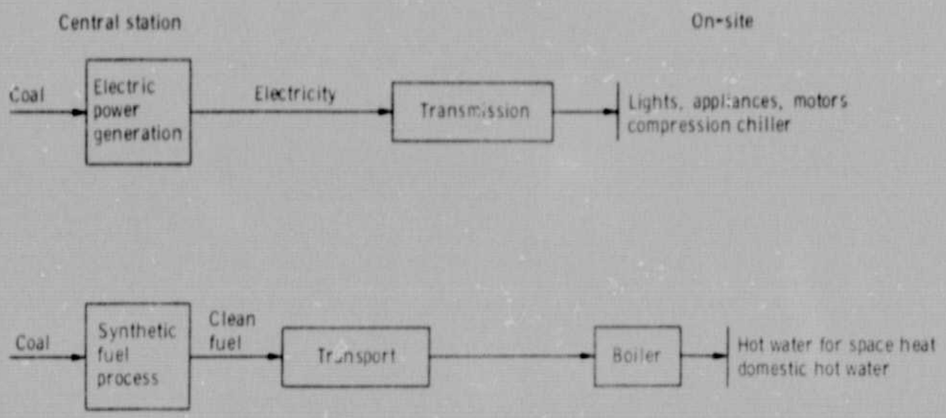


Figure 1. - Conventional system.

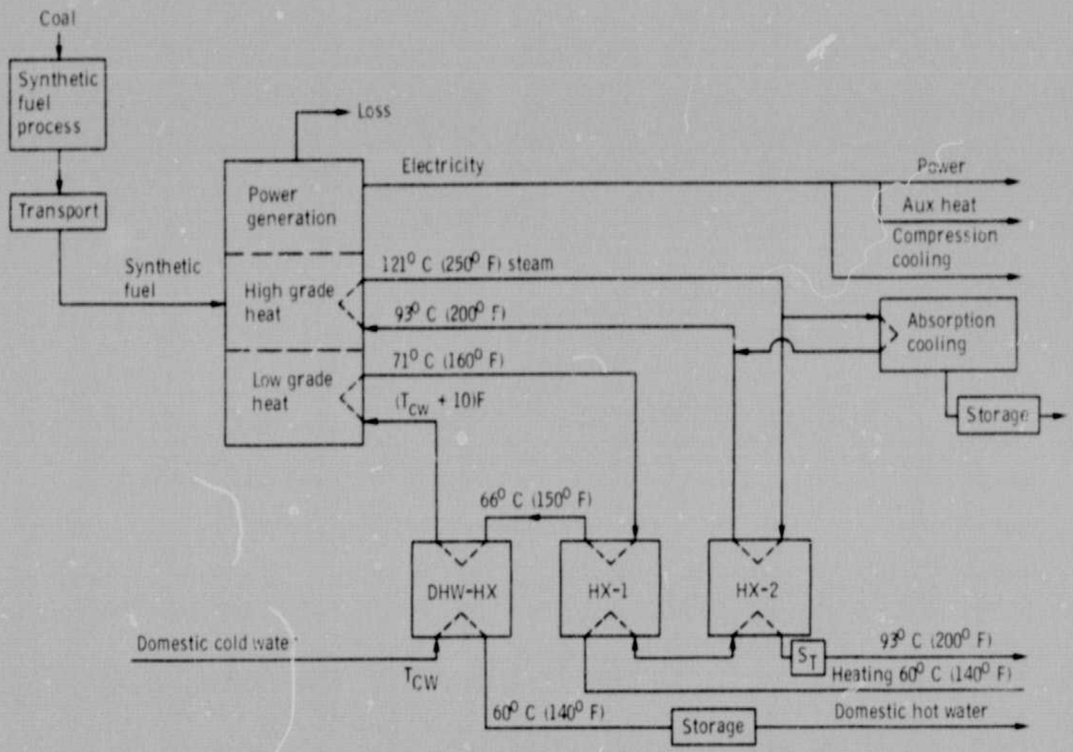


Figure 2. - On-site integrated energy system.

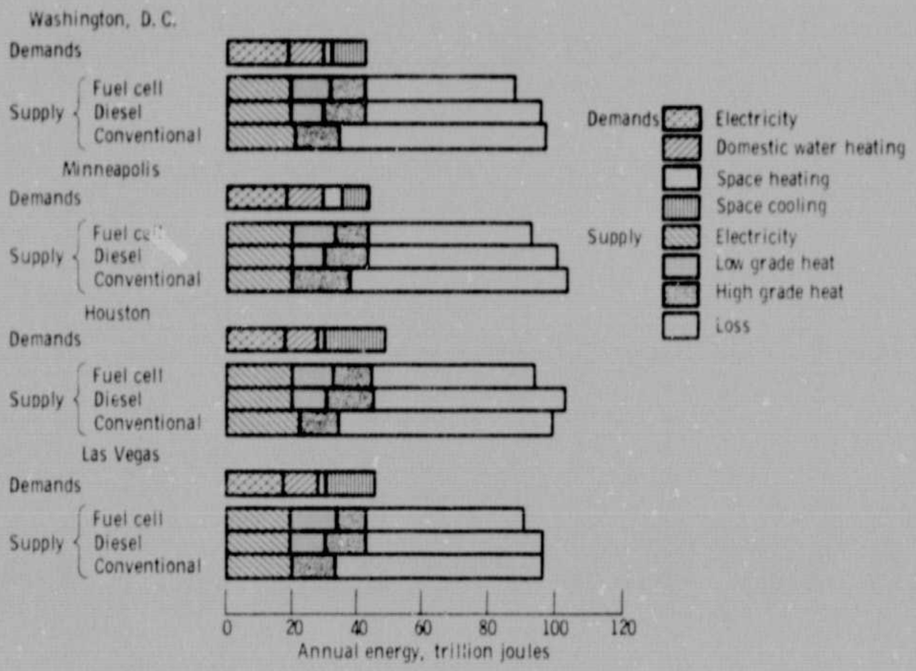
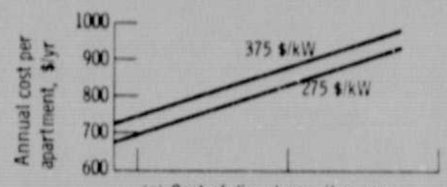
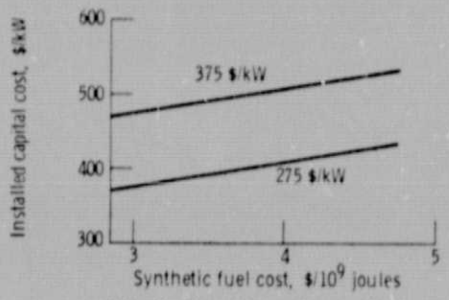


Figure 3. - Energy comparison.

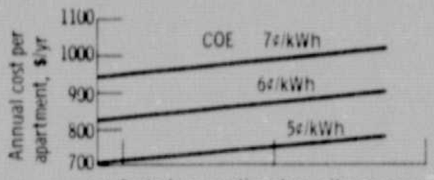


(a) Cost of diesel on-site energy.

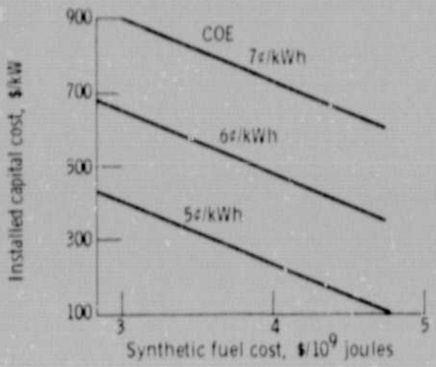


(b) Fuel cell cost to breakeven with diesel.

Figure 4. - Cost comparison with diesel.



(a) Cost of conventional on-site energy.



(b) Fuel cell cost to breakeven with conventional.

Figure 5. - Cost comparison with conventional.

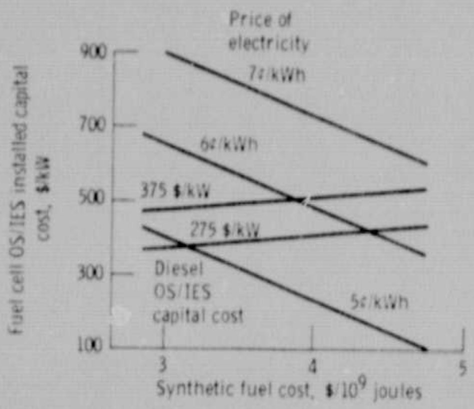

Price of electricity
7¢/kWh
6¢/kWh
5¢/kWh
375 $/kW
275 $/kW
Diesel OS/IES capital cost
Fuel cell OS/IES installed capital cost, $/kW
900
700
500
300
100
3
4
5
Synthetic fuel cost, $/10^9 joules

Figure 6.