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Stephen N. Simons
Lewis Research Center
Cleveland, Ohio

and

William L. Maag
Solar Energy Products Company
Avon Lake, Ohio

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Stephen N. Simons*
NASA, Lewis Research Center
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Abstract

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 power plant and recovers heat from the power plant that would normally be rejected to the environment. An OS/IES is potentially useful in any application that requires both electricity and heat.

This paper analyzes several OS/IES for a residential complex. The paper is divided into two sections; the first compares three energy supply systems, the second compares various designs for fuel cell OS/IES.

Summary

In the first section of the paper, three energy supply systems (two OS/IES and a conventional system) are analyzed and compared for a 500-unit apartment complex representative of those currently used in commercially available integrated energy systems. A phosphoric acid fuel cell 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 energy use for all power plant and four apartment location combinations was computed. For comparison purposes, all energy was computed on the basis of a common starting point.

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 to $5 per million BTU), the capital cost of the fuel cell system could be from 30 to 50 percent higher, respectively, than the diesel system. For the same fuel price range, the conventional system is the most cost effective one if the price of electricity to the consumer is less than about 5 to 6.5¢ per kilowatt-hour, respectively.

In the second section, several parametric combinations of fuel cell power plant and state-of-the-art energy recovery systems were analyzed and an annual fuel requirement was calculated for the same four locations. The range of phosphoric acid fuel cell operating characteristics used is representative of nits being developed for commercialization in the mid-1980s. The OS/IES contains energy conversion equipment including combinations of compression and absorption chillers, heat pumps, electric resistance heaters and thermal storage.

In addition to calculating the annual fuel requirement, the fuel cell breakeven cost was calculated for one specific system.

The energy analysis shows that even in integrated energy systems that use by-product heat rather than reject it to the environment, electrical efficiency cannot be traded off against thermal efficiency without paying a penalty in system efficiency. This is because electrically driven devices such as heat pumps and compression chillers have a mechanical advantage (COP > 1) that allows them to provide a thermal output greater than the electrical input to the device. Thermally driven devices always have a thermal output less than their thermal input.

The energy analysis also shows that OS/IES component choices have a major influence on annual fuel consumption.

For one case, the economic analysis shows that a $50/kW capital cost premium can be absorbed for a high-efficiency fuel cell. This is about 10 percent of the power plant cost.

Introduction

In light of today's energy-related problems there are two major goals in the energy technology field. The long-term goal is to develop technologies that are not dependent on the shrinking world supplies of petroleum. The more near-term goal is to develop technologies that make more efficient use of the resources presently available and that smooth the transition to coal and renewable resources that will be in widespread use in the future. The phosphoric acid fuel cell can help meet both of these objectives by efficiently converting natural gas to electricity and heat and by efficiently using coal-derived synthetic gases or liquids when these become available.

The heart of the fuel cell power plant is the stack (sometimes called power section) which derives its name from the fact that in each power plant many individual cells are stacked to provide the total power level required.

The single cell, illustrated in Figure 1, consists of an anodic current collector, anode, matrix, cathode, and cathodic current collector. Both current collectors perform the dual function of conducting electricity and of providing reactant flow channels in their surfaces. Both electrodes use a noble metal supported on carbon particles as a

*Technical Manager, Fuel Cell Project Office

catalyst. These catalyst particles are bonded to a porous graphite paper to form an electrode. The matrix is a porous separator, filled with the phosphoric acid electrolyte, that acts as an electron insulator and ionic conductor between the anode and cathode.

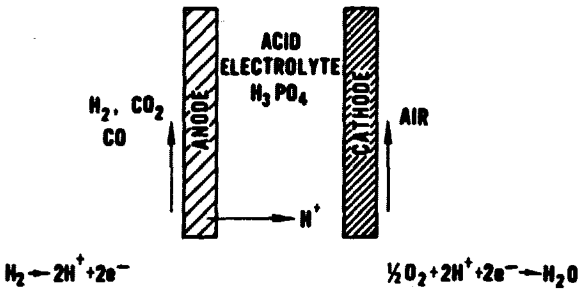

Fig. 1 The Elemental Fuel Cell Model.

The cell reactions are also illustrated in Figure 1. Hydrogen is oxidized at the anode. Oxygen is reduced at the cathode. At the anode H_2 gives up electrons to form H^+ ions. Current flows through an external circuit and H^+ are transported through the electrolyte in the matrix where they react with oxygen to form water, thus completing the electrochemical reaction.

Figure 2 shows how the stack is integrated with a fuel processor and power processor to form a power plant. Any one of several hydrocarbon fuels is fed to the fuel processor where in the first unit, the steam reformer, water is mixed with the fuel and then is reformed to a mixture of CO_2, CO, and H_2. In the shift converter, CO is shifted with water to provide a stream that is hydrogen-rich and low in CO. The fuel processor also contains guard beds that remove sulfur, halogens and other chemicals harmful to the fuel cell and reformer catalysts. The composition of the fuel stream emerging from the fuel processor is dependent on the fuel used, but must be high in H_2 and low in CO content for successful fuel cell operation. The remainder of the stream consists of CO_2 and a small amount of unreacted fuel, both of which are inert to the fuel cell.

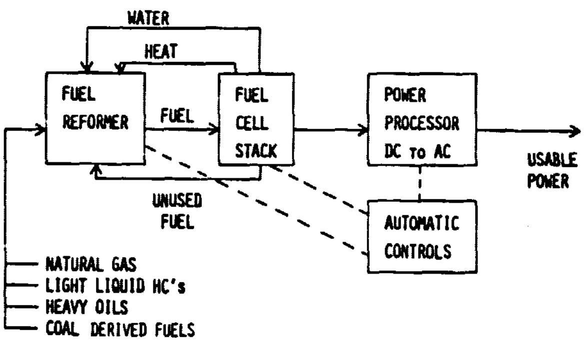

Fig. 2 Fuel Cell Power Plant.

As previously stated, in the fuel cell stack H_2 from the fuel stream and O_2 from air react to produce DC electricity, heat, and water. Water, some heat and any unused fuel are recycled to the fuel processor; water is used in the reforming and shift reactions, heat and unused fuel provide energy for the endothermic reforming reaction. Phosphoric acid was chosen as the electrolyte for first generation fuel cells because of its high temperature stability and tolerance to carbon compounds, as opposed to the alkaline electrolyte fuel cells used in the space program which required carbon-free reactants.

The power processor converts the DC power produced by the fuel cell to a power form required by the application.

The total On-Site Integrated Energy System, (Fig. 4) represents one configuration, consists of not only the fuel cell power plant but also all the associated machinery to recover waste heat from the power plant and distribute all heating, cooling, hot water, and electricity to an application.

The OS/IES by generating electricity on-site and making efficient use of by-product heat can efficiently provide heating and electric service to an application. For most applications, the total amount of fuel consumed for all heating and electrical demands will be reduced. However, since in the OS/IES case electricity is generated on-site instead of centrally, the on-site fuel consumption is generally increased.

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.

Phosphoric acid fuel cell technology has progressed in recent years to the point where power plants in the 50 kW range should be ready for commercialization in the 1980s. The potential for fuel cell power plants covers a wide range of applications, from small units for motive power, through intermediate sizes for on-site residential/commercial or industrial cogeneration and utility peaking to large multimegawatt units for utility baseload generation.

Fuel cell power plants have several features that are favorable for on-site applications including modularity, high electrical efficiency, environmental acceptability and a cooling system that encourages heat recovery.

Modularity permits rapid installation of prepackaged units with a minimum of site preparation and a short lead time. Multiple units allow the system to meet reliability requirements without the need for excessive reserve capacity. High electrical efficiency combined with heat recovery result in a maximum total energy utilization in the 80 percent range for small power plants in the range of 50 kW. Larger fuel cell power plants have a potential energy utilization of as high as 95 percent.[1] Fuel cell gas emissions are well within current EPA requirements. With heat recovery the thermal discharge to the environment is small; and because of the static electrochemical nature of the process, the fuel cell is very quiet. In general, the fuel cell would be a good neighbor in a residential area.

The above considerations, as well as other studies indicate that fuel cells show an energy savings over conventional energy systems and other OS/IES power plants.[2,3,4] The purpose of this paper is to compare a fuel cell OS/IES to a conventional system and a diesel OS/IES, then to parametrically vary the fuel cell OS/IES to determine the effect of various components and operating conditions.

Application Description

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[5] as a participant in the HUD-MIUS program.

The 500-unit apartment complex consists of 20 buildings situated on 11 acres. 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 construction 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, D.C., Minneapolis, Minnesota, Houston, Texas and Las Vegas, Nevada were chosen as representative of four significantly different climates.

Figure 5 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 domestic hot water demand is based on supplying water at 60° C (140° F) and the space conditioning demand is based on a 23° C (74° F) set point and 50 percent relative humidity.

Space heating and cooling demands are supplied via two-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. The system's major performance assumptions are summarized in Table I. Systems were designed to meet 95 percent of the historically observed extremes.

The primary fuel for this study was assumed to be coal as illustrated in Figures 3 and 4. For the conventional system, coal was used directly in a coal/steam central station power plant. 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 delivered to the site.

The quality of clean synthetic fuels from coal is expected to be equivalent to comparable petroleum fuels.

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 to \$5 per million BTU).

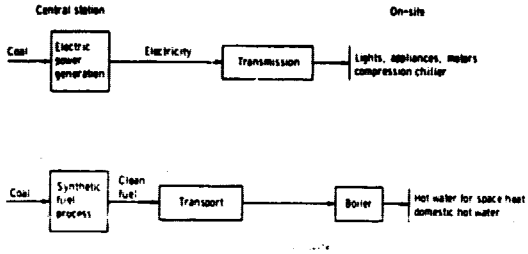

Fig. 3 Conventional system.

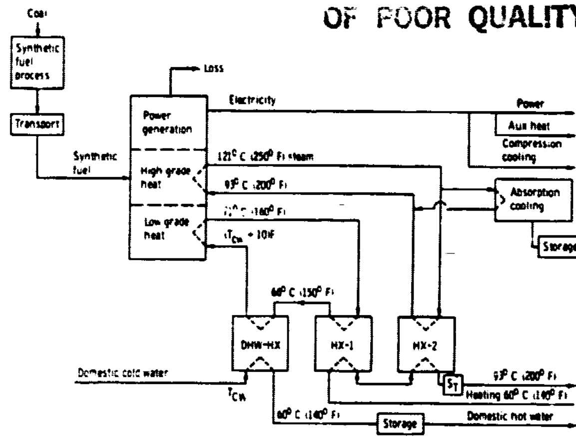

Fig. 4 On-site integrated energy system.

TABLE I. - PERFORMANCE ASSUMPTIONS

COAL-TO-ELECTRIC CONVERSION EFFICIENCY	32.5% (HHV)
COAL-TO-SYNTHETIC FUEL CONVERSION EFFICIENCY	65% (HHV)
FUEL CELL OUTPUT (USED IN COMPARATIVE ANALYSIS ONLY)	38% ELECTRICITY (LHV) 24% 71° C (160° F) WATER 20% 121° C (250° F) STEAM 18% LOSS
DIESEL OUTPUT	33% ELECTRICITY (LHV) 17% 71° C (160° F) WATER 22% 121° C (250° F) STEAM 28% LOSS
PACKAGE BOILER EFFICIENCY	80% 121° C (250° F) STEAM (LHV)
CENTRAL COMPRESSION CHILLER COP	4.5
UNITARY COMPRESSION CHILLER COP	2.1
ABSORPTION CHILLER COP	0.65
HEAT PUMP	1.5 - 2.8
ELECTRIC RESISTANCE HEAT	75%
STORAGE	100%
RATIO OF LHV TO HHV - SYNTHETIC LIQUID - SYNTHETIC GAS	0.94 0.90
SYNTHETIC FUEL TRANSMISSION EFFICIENCY	98.5%
ELECTRICITY TRANSMISSION EFFICIENCY	92%

(HHV) BASED ON THE HIGHER HEAT VALUE
(LHV) BASED ON THE LOWER HEATING VALUE
COP = COEFFICIENT OF PERFORMANCE

Section I - Comparative Analysis

This first section is a comparative energy use analysis between a conventional system and two OS/IES, one diesel the other fuel cell powered. The energy analysis is used to calculate a break-even cost for the fuel cell system.

Systems' Descriptions

Conventional Energy System

The conventional energy system (illustrated in Fig. 3), supplies all of the normal electrical demands with electricity purchased from a central utility. 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. Energy conversion efficiency and transportation losses for all components are listed in Table I.

On-Site/Integrated Energy Systems

The general configuration of the on-site/integrated energy systems is illustrated in Fig. 4. 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 power plant is fueled with a coal-derived synthetic fuel, as described for the conventional on-site boiler.

The on-site power plant 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 power plants 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 power plant 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-produce 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 power plant 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 comparative analysis. 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 power plant.

The diesel power plant 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 power plant 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 I) represent average operating conditions at a load factor of 80 percent, which is readily achievable with four engines.

The fuel cell operating characteristics, given in Table I, are based on phosphoric acid fuel cells currently being developed.

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.

Energy Analysis

The results of the energy analysis are summarized in Figure 5. 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 percent 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 5 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. 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 power plant, fuel and electric transmission losses, and on-site power plant and boiler losses. The total bar graph therefore represents the total annual coal consumption required to meet the consumer demands.

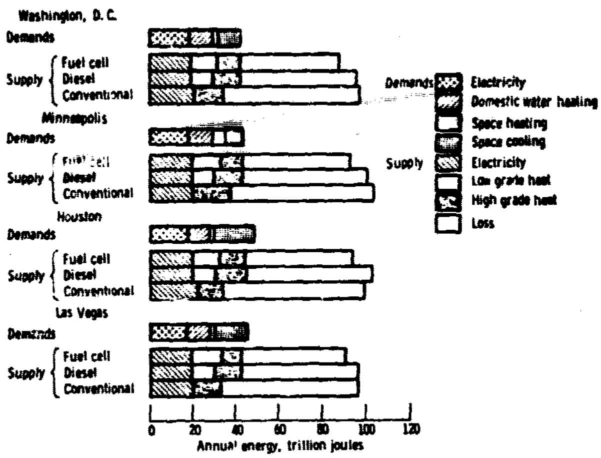

Fig. 5 Energy comparison.

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 percent 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 percent of the coal's higher heating value while the diesel and conventional systems utilized about 45 percent of the coal's heating value.

The OS/IES worked well for this application. 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 percent. 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

Economic comparisons are made on the basis of supplying the energy demands of the Washington, DC apartment complex only. 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 percent 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[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 percent 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 power plants 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.[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 6, 7 and 8. Figure 6 compares the diesel and fuel cell systems, Figure 7 compares the conventional and fuel cell systems, and Figure 8 is a composite that shows the most economic system given a price of fuel and electricity.

In Figure 6(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 to $5 per million BTU) and a range of capital cost from $275/kW to $375/kW. Figure 6(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 power plant costs, including fuel processor, power conditioner and heat recovery equipment fall within this range.[7,8]

Figure 7(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 7(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 8 superimposes Figures 5(b) and 6(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 $490/kW to be economically attractive. Figure 8 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.

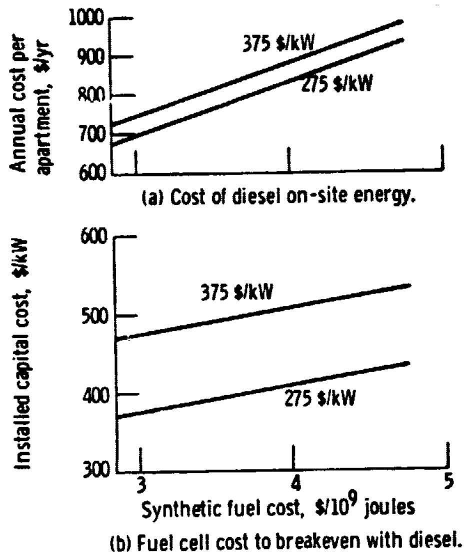

Fig. 6 Cost comparison with diesel.

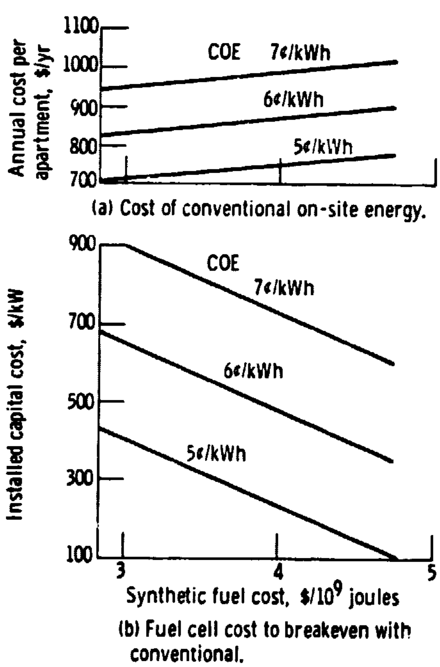

Fig. 7 Cost comparison with conventional.

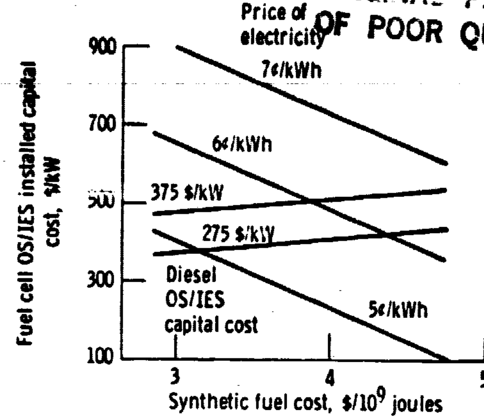

Fig. 8 Synthetic fuel cost, $/10^9 joules.

Section II - Parametric Analysis

This second section is a parametric analysis that compares the resource use and economic effects of changing fuel cell power plant operating characteristics and total energy system components.

System Description

Power plant electrical efficiency, thermal efficiency, the ratio of high to low quality heat, and percent heat lost were varied. In an actual fuel cell these characteristics could be a result of varying operating temperature, operating pressure, catalyst loading, cell components, method of fuel processing, or heat recovery scheme to mention only a few.

Four fuel cell power plant designs were selected as representative of options available to a manufacturer. Specific operating characteristics are listed in Table II.

TABLE II - FUEL CELL PERFORMANCE ASSUMPTIONS

[Natural or high BTU gas as fuel]

Fuel cell A high heat efficiency	40% electricity 35% 160° F water 15% 250° F steam 10% loss
Fuel cell B base case	40% electricity 36% 160° F water 9% 250° F steam 15% loss
Fuel cell C low heat efficiency	40% electricity 31% 160° F water 4% 250° F steam 25% loss
Fuel cell D low electrical efficiency	35% electricity 40% 160° F water 10% 250° F steam 15% loss

Fuel cell B is the base power plant and is a best guess of the actual operating characteristics of a first generation phosphoric acid fuel cell. Fuel cell A can be thought of as a high thermal efficiency version; it has the same electrical efficiency as B but recovers more heat and heat of a higher quality than B. Fuel cell C is the low thermal efficiency version, having the same electrical efficiency as fuel cell B but recovering less heat and heat of a lower quality than fuel cell B. Fuel cell D is the low electrical efficiency version, with the same amount of unrecoverable heat and same high to low quality heat ratio as fuel cell B.

The OS/IES designs were constrained by two ground rules: (1) the system must be completely independent, neither importing nor exporting electricity to a utility grid nor generating heat by direct combustion, and (2) waste heat from the fuel cell must be used to the maximum practical extent.

Within these ground rules eight promising systems were defined.

System 1 may be illustrated by Figure 4 and is the same system used in the comparative analysis, only without storage.

System 2 differs from System 1 only in that the absorption chiller will accept feedwater as low as 88° C (190° F). These low temperature units have the same COP as the high temperature units but are necessarily larger to extract the same amount of heat from lower quality feedwater.

Systems 3 and 4 are analogous to Systems 1 and 2, respectively, with the addition of hot water storage. Storage is used in the spring/fall season when no heating, but possible cooling is required during the day, and heating is required in the evening. Excess hot water available during the day is stored for use during the evening hours. The small cooling loads would require only one chiller. This would be a compression machine; the fuel cell by-product hot water would go to storage instead of feeding the absorption chiller. Hot water storage would require insulated tanks capable of storing 93° C (200° F) water. Power plant operation would still be controlled by electrical demand, but use of by-product heat could be deferred until needed.

System 5 uses a central heat pump to supplement heating provided by fuel cell by-product heat. The heat pump also supplements cooling provided by high temperature absorption chillers. System 6 is like System 5 with the use of low temperature absorption chillers.

System 7, like System 5, uses a heat pump to supplement heating by fuel cell by-product heat. Unlike System 5 where the heat pump supplies all the make-up cooling, in System 7 only the capacity required for winter is installed; no additional capacity is added for the summer peak. Peak cooling capacity, above that which can be satisfied by heat pumps, is satisfied by more efficient compression chillers.

System 8 again satisfies heating demand with by-product heat and electric resistance heating. Cooling demand is satisfied, more conventionally, by individual compression air conditioners. These are less efficient than central units. And since they provide cooling directly there is no means of using by-product heat in absorption chillers.

Although Systems 2-8 are not illustrated, their layout can be visualized by making the changes described above to Figure 4. Component performance assumptions are listed in Table I.

Energy Analysis

Results of the energy analysis for selected parametric cases are shown in Figures 9-11. All values represent the annual fuel used on-site to supply electric power, space conditioning, and domestic hot water to the full 500-unit apartment complex. In the parametric study it is not necessary to take the energy inputs back to a coal pile as a common starting point, since all on-site systems are common at their fuel input point. Going back to the coal pile would also distort the fuel savings on-site by adding conversion and transportation inefficiencies to the calculation. The figures are in units of trillion joules and are based on the lower heating value of the fuel which is assumed to be either natural gas or high BTU coal derived gas.

Figure 9 compares the annual fuel usage, which is a measure of the energy efficiency for each of the eight service supply systems. Throughout this discussion System 1 (electric resistance supplemental heat, high temperature absorption and supplemental compression air conditioning) coupled with fuel cell B will be referred to as the base OS/IES. For the Washington location this system uses 63.0×10^{12} J/yr (60.1×10^{9} BTU/yr). By going to a low source temperature absorption chiller a 4 percent fuel economy is realized. Systems 3 and 4 incorporate short-term thermal storage into Systems 1 and 2, respectively. System 3 saves 2 percent of the fuel required by System 1. This savings is mostly from storing low-quality heat during periods where cooling is required. Systems 5 and 6 incorporate a heat pump for supplemental heating in winter and supplemental cooling in summer. In order to incorporate a heat pump for both supplemental heating and supplemental cooling a system must sacrifice its very high efficiency compression chiller. This is not fuel conserving in most cases. System 5 requires 8 percent more fuel than base System 1. This can be explained by looking at the relative efficiencies of the three supplemental space conditioning devices. The heat pump COP is larger than the electric resistance COP that it replaces for supplemental heating (i.e., smaller power requirement for the same heat production); but for supplemental cooling the heat pump COP is much smaller than the compression chiller COP that it replaces (i.e., larger power requirement for the same account of cooling). For the Washington area the relative supplemental cooling/supplemental heating demands (along with ambient conditions that affect heat pump performance) are such that the increased summer power requirements outweigh the decreased winter power requirements. This situation is reversed in colder climates.

The situation also changes somewhat in System 6 where low temperature absorption chillers are used. The low temperature chillers satisfy a higher percentage of the cooling load thus reducing the supplemental cooling/supplemental heating demand ratio to a point where Systems 2 and 6 have approximately the same fuel requirement. In Systems 5 and 6 the comparison between low and high temperature absorption chillers point out two results. First, this is the strongest case for inclusion of low temperature absorption chillers and, second, but perhaps more significant, this shows the need to evaluate different system combinations in light of location. The building industry cannot "zero in" on one particular OS/IES design and expect it to be the most energy efficient in all locations and applications.

System 7, with heat pumps, compression and high temperature absorption chillers saves some (1.4 percent) fuel when compared to System 6 but the added complexity would probably outweigh any fuel savings.

System 8 results in the greatest amount of fuel usage, 23 percent more than System 1, and is an indication of the savings that are possible using recoverable powerplant heat.

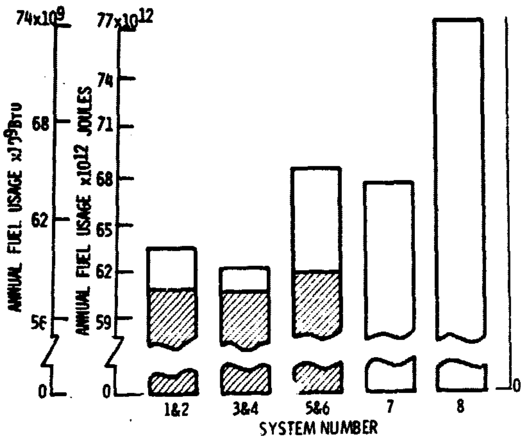

Fig. 9 Fuel usage dependence on system. Washington location and power plant B.

The Washington climate is temperate; any harsher climate should magnify the results of the energy analysis of the Washington area. The climate effect is shown for selected systems in Figure 10. Systems 1 and 2, in general, show a smaller climatic effect than Systems 5 and 8. This is because Systems 1 and 2, in general, have a higher overall efficiency than Systems 5 and 8. The only exception is System 5 in Minneapolis where the supplemental heating gains outweigh the supplemental cooling loss as previously discussed. Houston and Las Vegas show greater benefits from storage since they have greater demands for both heating and cooling in the same day. The high fuel demands for Houston and Las Vegas in Systems 5 and 8 are due to the lower air conditioning COP with the large air conditioning loads. To a lesser extent System 8 in Minneapolis and Washington is also affected by the low air conditioning COP. The increase in fuel consumption is not so large as in Houston and Las Vegas because the air conditioning load is small.

Figure 11 compares the four fuel cells for Systems 1 and 2 in the four locations. Fuel cell B is the best guess of actual first generation phosphoric acid fuel cell performance, and will be used as the basis for most comparisons. First looking at the Washington location only, a comparison of fuel cells A and B for System 1 shows that gaining five points in heat recovery in fuel cell A yields a 4 percent reduction in fuel consumption, while losing five points in electrical efficiency in fuel cell D results in a 7 percent increase in fuel consumption due to the high COP of electrically driven

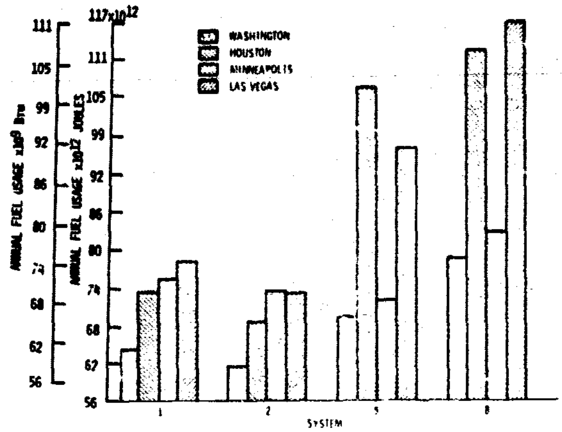

Fig. 10 Fuel usage dependence on location and system. Power plant B.

devices. The fuel cell thermal/electric ratio is a good indicator of the utility of an absorption chiller that can use a low temperature (110° C) source as can be seen by the unshaded portion of each of the bars in Figure 11. The fuel cell with the highest thermal/electric ratio (i.e., D) shows the most effect of low temperature chillers.

Figure 11 also shows that location has some effect on fuel cell power plant choice but the effect is not as large as the effect of system choice (Fig. 10). The only trend is that Houston and Las Vegas, with their high air conditioning demand, are more sensitive to electrical efficiency while Minneapolis with the high heating demand is more sensitive to heat efficiency.

Economic Analysis

The second part of the parametric study was an economic analysis in which the breakeven cost of selected fuel cell power plants was calculated. The breakeven cost was based on the fuel savings of a power plant/system combination compared to fuel cell B in the same system. If fuel usage was the only consideration the fuel cell with the highest electrical efficiency coupled with maximum heat recovery would be the power plant chosen. In general, though, any increase in electrical efficiency or heat recovery efficiency is accompanied by an increase in capital cost. The manufacturer of OS/IES equipment must strike a balance between the lower first cost of a lower efficiency machine and the yearly fuel savings of a more efficient, though higher first cost machine.

Figure 12 shows the incremental capital cost allowed by fuel savings. Fuel cells A, C, and D are compared to fuel cell B for System 1 in the Washington location only.

No assumptions were made concerning the cost of power plant B; all that is shown is the maximum additional cost of the more efficient fuel cell system A and the minimum cost reduction for the less efficient fuel cell systems C and D. For example, at a fuel price of $38/10^9 joules at most a $50/kW premium can be paid for fuel cell A. This is about 10 percent of the power plant cost according to recent price projections that range from $400/kW [7] to $625/kW. [8]

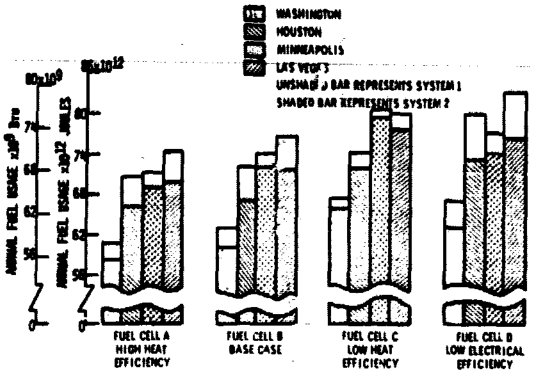

Fig. 11 Fuel usage dependence on power plant and location. Systems 1 and 2.

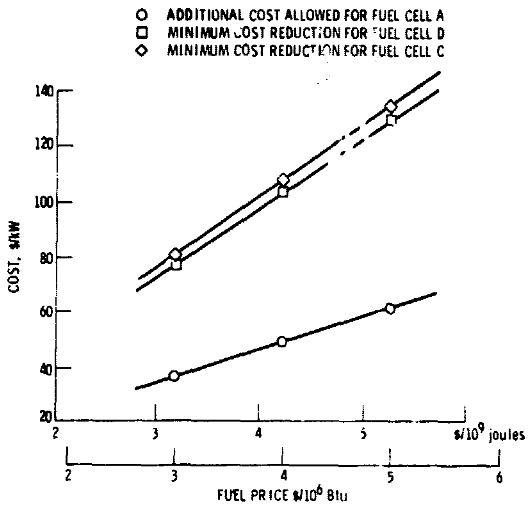

Fig. 12 Incremental breakeven cost, relative to fuel cell B. Washington location; system 1; and 13 percent fixed charge rate.

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 percent 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. The fuel cell OS/IES capital costs could be 30 to 55 percent greater than the diesel OS/IES capital costs for the same life cycle costs. The life cycle cost of a fuel cell OS/IES would be lower than that for a conventional system as long as the cost of electricity is greater than $0.05 to $0.065/kWh. The parametric study indicated that OS/IES system component choices are a major factor in annual fuel consumption; the least efficient system using up to 25 percent more fuel than the most efficient. Central air conditioning, thermal storage, and heat pumps lead to minimum fuel consumption while individual compression air conditioning units (which tend to break with the integrated energy concept) lead to the highest fuel consumption. The projected range of fuel cell operating characteristics has less of an effect (up to 12 percent) on fuel consumption than system component choices. In general the fuel cell with the highest electrical efficiency has the lowest fuel consumption.

Due to fuel cost alone, the most efficient fuel cell (power plant A) can absorb a $50/kW premium at a $3.8/10^9 joules ($4/10^6 BTU) fuel price.

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