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HEAT PUMPS - LIMITATIONS AND POTENTIAL

by

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Power Systems Laboratory

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SUMMARY Heat pumps represent the best hope for an optimal solution to the residential heating problem. They are energy efficient-conserving scarce fuels better than all other systems, and are attractive economically. Combining heat pumps and radiant solar energy collectors promises greater conservation of scarce fuels at reasonable cost.

KEY WORDS

heat pump, heating, cooling, solar energy

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INTRODUCTION

The heat pump has been with us for many years, its' evolution governed primarily by cost and reliability considerations. Until recently the heat pump was viewed as an air conditioning unit which could be used in heating, consequently, performance tradeoffs favored cooling performance.

Interest in residential heating has been heightened by the current economic-energy climate. Traditional heating systems employing combustion furnaces (oil and gas) are currently acceptable economically but rely solely on scarce resources. Electrical resistance heating, while requiring little initial cost, results in the highest annual heating cost. However, this type of heating requires less expenditure of scarce fuels since electrical utilities presently use these fuels for only 33%* of the total energy requirements.

The heat pump, by using solar energy collected and stored in the sensible heat of the atmosphere, is able to reduce both the annual heating cost and the consumption of scarce fuels to the point where it is energy competitive with optimally sized solar systems using radiant collector panels. Advanced designs of heat pumps stressing heating performance could surpass optimum radiant solar systems; the coupling of radiant solar systems with heat pumps would result in still lower energy consumption at somewhat increased life cycle cost.

*Federal Power Commission News, June 5, 1975

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Heat Pump Efficiency

A heat pump is by definition a device which causes heat to flow from a region of low temperature to a region of higher temperature. This direction of flow is opposite to the direction required by the second law of thermodynamics so that some external energy must be added to "pump" the heat "uphill". Efficiency then can be defined as the ratio of the desired effect (heating or cooling) to the energy required, using consistent power units such as BTU/HR, KW, etc. When considering heating by a heat pump the desired effect is the thermal energy arriving at the high temperature (house). The first law of thermodynamics tells us that this energy will be the sum of that extracted from the cold region plus the energy required by the heat pump, therefore the total energy arriving at the house will always be greater than the energy required to run the device. This means the electrical efficiency, usually called Coefficient of Performance (COP), will always be greater than one.

Effect of Temperature

Intuition suggests that the larger the temperature difference over which the heat must be pumped the greater the energy required, therefore, the smaller the COP. The COP then varies with the temperatures in the system. The actual value of COP depends on the equipment used. There is an absolute upper bound to the COP between two given temperatures. The Carnot COP is given by the expression

$$COP_{max} = \frac{T_h}{T_h - T_L}$$

T_h - high temperature in absolute temperature
T_L - low temperature in absolute temperature

Consider a house maintained at 70°F in a 30°F ambient. The temperature difference is only 40°F as shown in Figure 1. Applying the above formula to these values yields a COP of 13.25. This value, however, is misleading since the actual heat pump must pump across a much wider temperature gap. In most heating systems heat is supplied at a central location and is distributed via sensible heat in the distribution fluid, e.g., via a hot air system in which house air is heated then forced through ducts to distribute heat throughout the house. The total rate of heat distributed is proportional to the product of the mass flow rate of the air and its temperature rise. Therefore, for a given heat rate the flow rate required increases as the temperature rise decreases. In a heat pump, system efficiency is increased by minimizing this ΔT, i.e. delivering air at 100°F instead of 130°F to 160°F as in combustion systems. There is a lower limit to this delivery temperature because of ducting and comfort considerations. Since at lower temperatures more air is required, significant room air velocities are generated, which in combination with the lower temperatures produce an unpleasant drafty effect.

A similar but smaller temperature change in the air blown across the outside heat exchanger is necessary to extract heat from it. These two temperature differences are necessary for any heat pump no matter how well it is designed, thus decreasing the maximum obtainable COP to the vicinity of 7.5. To transfer heat between the refrigerant fluid and surrounding air, additional temperature differences are necessary. For reasonably sized heat exchangers this difference is approximately 20°F. The total temperature difference will amount to approximately 110°F as indicated on Figure 1, yielding a maximum COP of 5.2. Real heat pumps operate at approximately half this value!

Efficiency of Real Heat Pumps

The COP of 5.2 could only be obtained by a unit operating on the Carnot cycle and employing no fan power to move air either inside or out. Figure 2 shows the degradation in efficiency caused by real equipment. The top line represents the previously calculated Carnot efficiency taking into account total ΔT. The effect of using the standard vapor compression cycle (all processes considered reversible except for expansion) is indicated by the second line. Using this same ideal refrigeration cycle but considering motor and compressor inefficiencies, the COP drops even lower, in fact very close to measured performance of existing devices. A true COP must include all electric power requirements, so the bottom line shows the effect of fan power.

The conclusion to be reached from this figure is that the improvements possible in the standard heat pump are limited and that maximum COP's at an outdoor temperature of 30°F are on the order of 4 or 5 rather than 13 as a cursory examination may suggest.

Heat Pump Capacity

One undesirable feature of heat pumps is shown on Figure 3. The heating capacity (curve labelled "Heat Pump"), the ability to deliver heat to the house, decreases with decreasing outside temperatures. This is contrary to the heat required ("Demand of House") which increases at the colder temperatures. At temperatures above the intersection of these two curves (known as the Balance Point) the heat pump can supply all the heat required, but below this point some additional energy must be supplied. For convenience and minimum cost, the supplementary heat is supplied by resistance heaters built into the indoor air handler.

Supplementary heat is added to the house at a COP of 1 thereby reducing the total COP of the system. No matter how efficiently the heat pump operates, the greater the required make-up heat required, the lower the system efficiency. This suggests that the performance of the heating system is not only a function of heat pump COP but of the size of the heat pump used (changes in the Balance Point) and the seasonal temperature distribution to which the house is exposed.

An hourly occurrence chart for the Boston area is shown on Figure 4. This shows the number of hours per season that the temperature exists in each 5°F range. This information can be translated into total heating demand by considering the heating demand at each temperature range and multiplying by the number of hours of occurrence, as shown in the lower figure. A heat pump system with a balance point of 30°F could satisfy well over half of the house demand without recourse to makeup heat.

Figure 5 shows the same house - weather combination as Figure 4 and indicates the result of using a 2 1/2 ton heat pump (which results in a Balance Point of 30°F). The area under the outermost curve is representative of the total heat required and it also indicates the input energy needed if the house were heated with only resistance heat (COP = 1). The energy required by the heat pump system is proportional to the area under the next lower curve; it includes resistance makeup heat. The lowest curve is the energy input to the heat pump alone, therefore the difference between the two lower curves indicates supplementary heat. Totals are listed on this figure and indicate that the heat pump system required 13,900 KW-hrs to supply 26,500 KW-hr worth of heat. The ratio of the total seasonal demand (26,500) to the energy required (13,900) is known as the Seasonal Performance Factor (SPF = 1.91) and is the best measure of a heat pump system's performance.

<u>Super Heat Pump</u>

On Figure 5 it was shown that although the supplementary heat is a small fraction of the total heat supplied, it is the major fraction at low outdoor temperatures and dilutes any pure efficiency increase in the heat pump itself in this range. If the heat pump could be made to provide more heat at low temperatures, reducing the supplementary heat required, seasonal performance would increase. Therefore, in seeking to improve the heat pump, our considerations include ideas for both efficiency and capacity improvements.

Several modifications to the standard vapor compression cycle were considered which could benefit either efficiency, capacity, or both. Some examples of such cycles are shown on Figure 6 along with estimated performance. The heating capacity has been normalized with respect to compressor size (displacement) and all cycles other than simple cycle are assumed to have two equally sized compressors. The assumptions governing this chart are the same as those of Figure 2, i.e., 120°F condenser, evaporator 10°F less than ambient, and all processes reversible except expansion.

<u>Parallel Compression</u>

The simplest way to increase capacity without major modification is to use parallel compressors. The two compressors, which can be of different size, can be controlled independently to accommodate differing heating or cooling loads, with a closer match between heat pump capacity and demand.

<u>Cascade</u>

The cascade cycle allows the use of two different refrigerants each suited to the temperature range over which it will operate. Since each half of the cycle must pump heat over a portion of the total temperature rise, the capacity and COP of each will increase. Since the overall COP of a cascade system is given by:

$$COP = \frac{(COP)_h \times (COP)_L}{(COP)_h + (COP)_L - 1}$$

L = low side

h = high side

each heat pump must achieve very high COP to surpass a single stage heat pump. An important advantage of this cycle is that the intermediate temperature region between the heat pumps affords an excellent area for thermal storage.

Series Compression

The decline in heating capacity at low outdoor temperatures can be reduced by placing two compressors in series. The reduced pressure ratio across each compressor reduces clearance volume effects in reciprocating units, or vane leakage in rotary compressors.

Turbocharged

The primary cause of the low temperature decline in capacity is the decrease in refrigerant density at the compressor inlet. The turbocharged cycle increases this density by using energy extracted by an expander from the discharge vapor to compress the suction vapor in a high volumetric flow, low pressure ratio precompressor.

Two Stage

The final cycle shown, the two stage, not only increases low temperature capacity but substantially increases the cycle COP over that of the simple cycle by a combination of reduced clearance volume effects (series compressors) and thermodynamic cycle improvements.

Modulated Heat Pump

The COP obtained in an actual piece of equipment depends not only on the cycle configuration and the efficiencies of each component, but on the correct sizing of these items to form the complete system. For instance, COP can be increased by inserting a smaller compressor in a given unit since the net effect is to oversize the heat exchangers and thus reduce the temperature drop across them. Naturally, heating capacity will decrease in this case. However, in Figure 3, the heat pump is seen to have excess heating capacity above the balance point so a reduction while at modest outdoor temperatures might be beneficial.

Instead of switching compressors, assume that a variable speed compressor is used which can be controlled to a desired value of heating capacity. Now by increasing or decreasing compressor RPM above or below the nominal compressor speed, the house demand can be matched both below and above the old balance point temperature (within equipment limitations). At temperatures below the old balance point temperature, system COP is increased since less supplemental heat is required while at temperatures above this point the heat exchangers are essentially oversized, thereby increasing COP. In addition, the ability of the heat pump to run continuously at temperatures above the balance point results in still higher COP and increased reliability because the effects of cycling on and off are eliminated.

On Figure 7 the effect of compressor modulation is shown for a standard heat pump in which nothing is varied but compressor speed. At high outdoor temperatures, the lowest RPM yields the highest COP because of the decreased heat flux at the heat exchangers and the consequential decrease in heat exchanger temperature difference. As the outside temperature drops the heating capacity and power requirements for the compressor at constant RPM also decrease so that at low temperatures the constant fan power impact on COP becomes significant. Therefore, at low temperatures, the higher RPM is more efficient since the fan power is a smaller fraction of total power used. It is interesting to note that when the modulated heat pump is controlled to match the demand of the house, it will follow very closely the locus of the most efficient operating RPMs. Further modifications to this heat pump such as variable speed fans, adjustable or multiple expansion devices would further increase COP.

<u>Solar Space Heating</u>

Considerable excitement exists presently among members of the HVAC industry as well as among the public about the use of direct solar radiant energy for space heating. Most people expect solar energy to supply virtually the entire heating need of a house equipped with solar collectors. Collectors now being sold and suitable for space heating are priced between 5 and 15 dollars per square foot. The cost of collectors constitutes the largest fraction of the cost of a solar heating system. It is therefore necessary to optimize the size of the collector array such that large size (and therefore cost) increases don't result in relatively small increases in usable solar heat gained.

Figure 8 demonstrates the usable heat gained for heating a given house (650 Btu/hr °F) with various size collector arrays. The area under the curve "House Heating Demand" represents the seasonal heat demand of the house. The curves marked "Solar Heat Collected" indicate collected heat for solar collectors of the indicated size averaging 35% efficiency. The area bounded at the top by the "Solar Heat Collected" curves and at the sides by the "House Heating Demand" curve represents the usable solar energy. So, for example, a 750 $ft.^2$ array satisfies approximately 65% of the building's seasonal demand, whereas a 1925 $ft.^2$ array is required for a 100% solar heated house. This estimate does not account for cold and overcast spells since the weather base used here is an average of a ten-year period. Various studies have shown that the optimal solar contribution is between 30 and 60% depending on such items as house design, climatic region and cost of alternative energy. A solar system must therefore be supplemented with a conventional heating plant, and, this heating plant must supply between 40 and 70% of the buildings heat demand.

Solar Boosted Heat Pumps

Figure 9 shows a schematic diagram of a solar boosted and cascaded heat pump system. The system contains: a collector array with circulation pump and liquid-to-liquid heat exchanger; a large thermal storage tank filled with water; a liquid-to-air heat exchanger with circulating pump to draw heat from thermal storage to the warm air distribution system directly when storage temperatures are above 110°F; a heat pump operating between storage and indoors when storage temperatures are between 50 and 110°F; a heat pump operating between outdoors and storage when storage temperatures fall below 50°F; and a supplementary electrical resistance heater. A major advantage of this configuration is its ability to collect more radiant solar energy with a fixed solar array than conventional systems since lower collection temperatures allow higher collection efficiencies. The figure also shows predicted seasonal performance for five electrical or electrically complemented heating systems. The solar non-radiant energy is heat extracted from outdoor air by the outdoor heat pump. Analyses were made for eastern New York State. The table shows performance of heat pumps operating at seasonal performance factors of 2 and 3. The higher efficiency heat pump (SPF = 3) does not represent equipment currently available. Rather, it represents the potential performance of an improved heat pump. The solar boosted heat pump is shown to be the most energy efficient, followed by the super heat pump and a solar heating system without heat pumps.

Figure 10 shows the results of a cost analysis for these five heating systems. Costs are broken down to annual cost of amortization of the installed system, and the annual operating cost for electrical energy required to heat a house for one season. It is interesting to note that the three systems containing heat pumps are the three least expensive to own and operate.

Figure 11 expands on the information given as Figure 10. Here annual cost of ownership and operation (excluding maintenance costs) is given to these same heating systems as a function of cost of electrical energy. The solar assisted heat pump becomes less expensive than an ordinary heat pump system if the price of electricity exceeds $0.09/KW-hr. Extrapolation of these curves shows a super heat pump, at the assumed SPF of 3 and the assumed cost increment of 60% over ordinary heat pumps, to be more cost effective than the solar boosted heat pump until the price of electricity exceeds $0.20/KW-hr.

Many arguments have recently been made about the inefficient use of scarce energy when homes are heated electrically. These arguments typically ignore the fact that US electricity generation is based on scarce fuels (oil, gas) for only 33% of total output. Therefore, even a house heated by electrical resistance heaters will, on the national average, consume less scarce fuel (oil, gas) than a house equipped with oil or gas furnaces. When one uses electrical heating in its most efficient form (heat pump heating), the use of scarce fuels is further reduced, since even current heat pumps consume approximately half as much electrical energy as resistive heaters.

Figure 12 shows the consumption of raw fuel energy for various heating systems required to supply 100 million BTUs of heat to a residence. The primary fuel for the electrical systems can of course be of any type: scarce or non-scarce. Even when one does not differentiate among scarce and non-scarce fuels, the figure shows existing heat pumps to use as little fuel as combustion furnaces. Future heat pumps (SPF=3) will require approximately 35% less fuel. The figure also shows that solar heating systems, complemented 40% by resistive heaters, require approximately as much fuel as combustion heating systems. The comparable fuel use for heat pump and solar heating systems, together with the much lower cost of heat pumps, leads to the conclusion that heat pumps are superior to solar heating systems. Only solar boosted heat pumps promise much greater conservation of scarce fuel, at a reasonable cost.

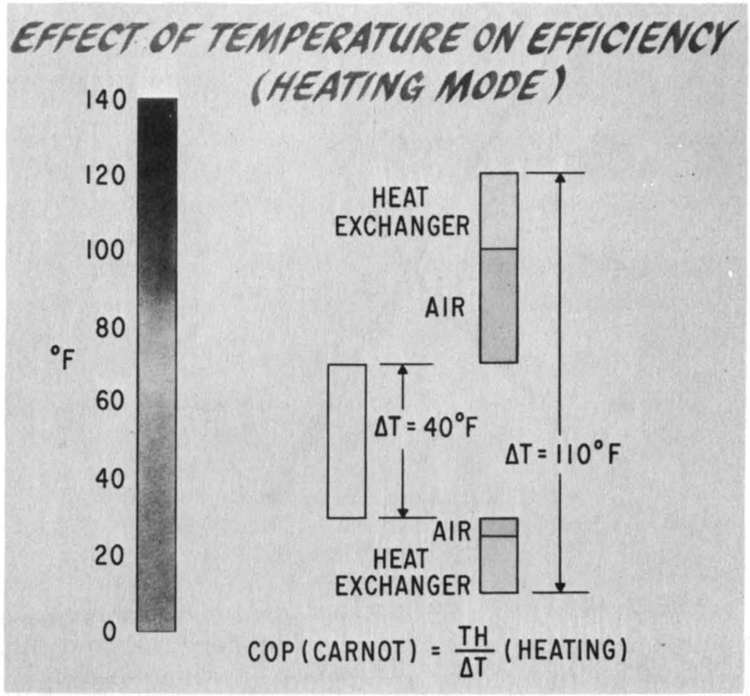


Fig. 1 Maximum heat pump efficiency calculations must be based on refrigerant temperatures rather than source and sink temperatures.

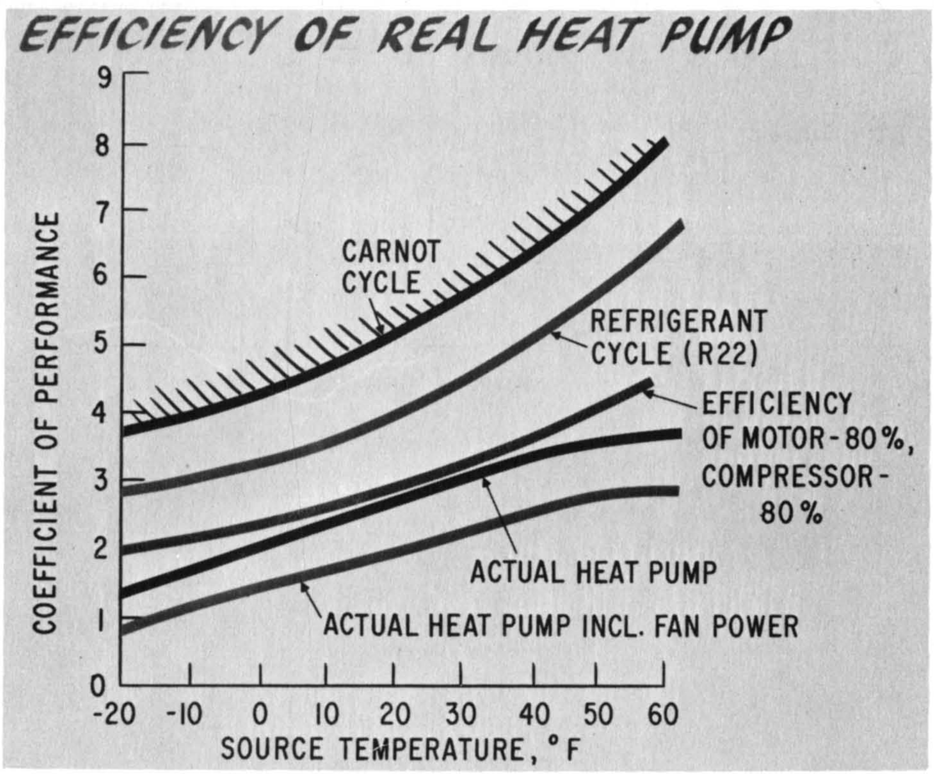


Fig. 2 Heat pump heating efficiency as it depends on source temperature for systems of different degrees of ideality.

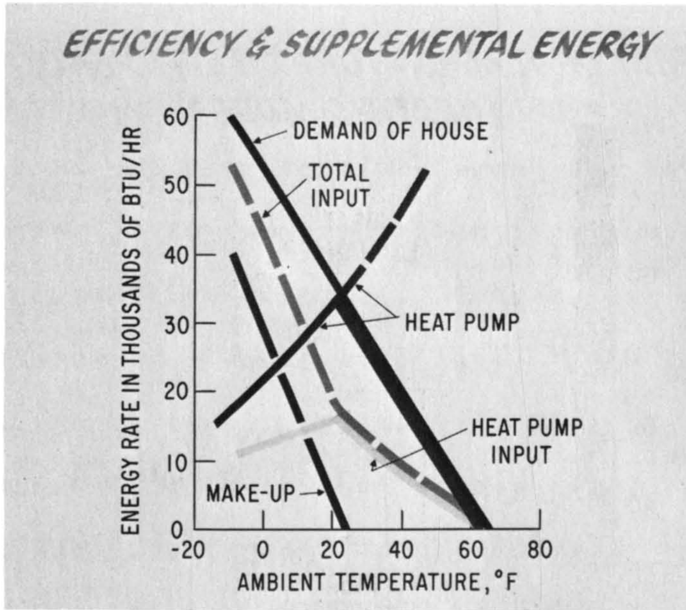


Fig. 3 Heat pump heating capacity, house demand and supplementary heat requirement as functions of outdoor temperature.

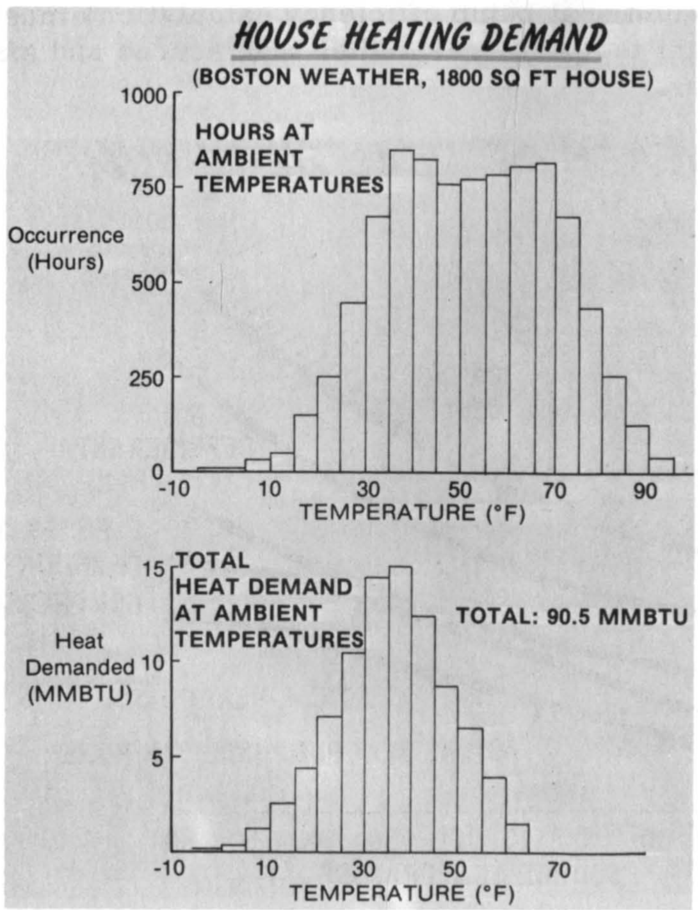


Fig. 4 Weather statistics and house seasonal heat energy demand.

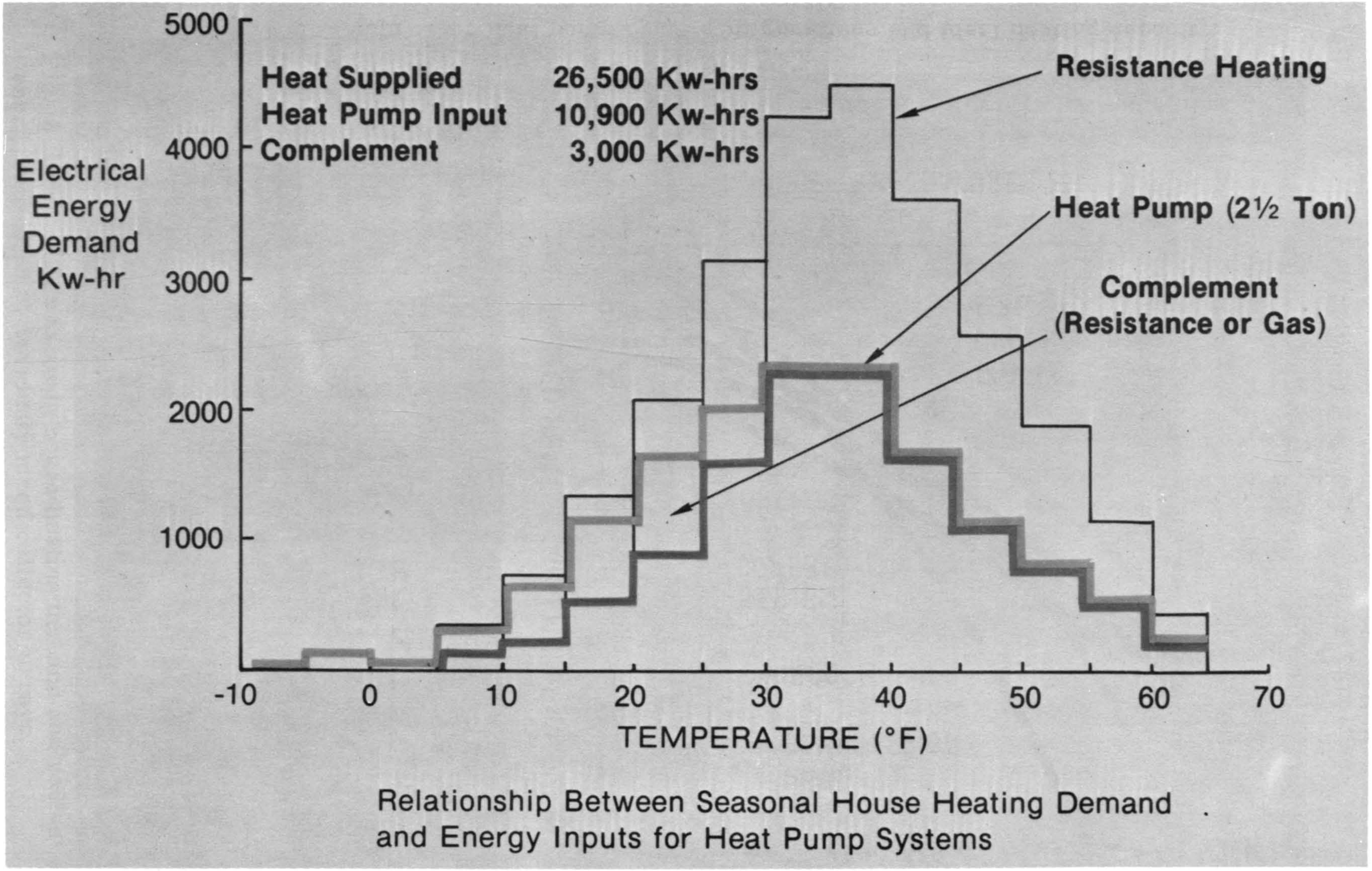


Fig. 5 Relationship between seasonal house heating demand and energy inputs for heat pump heating systems.

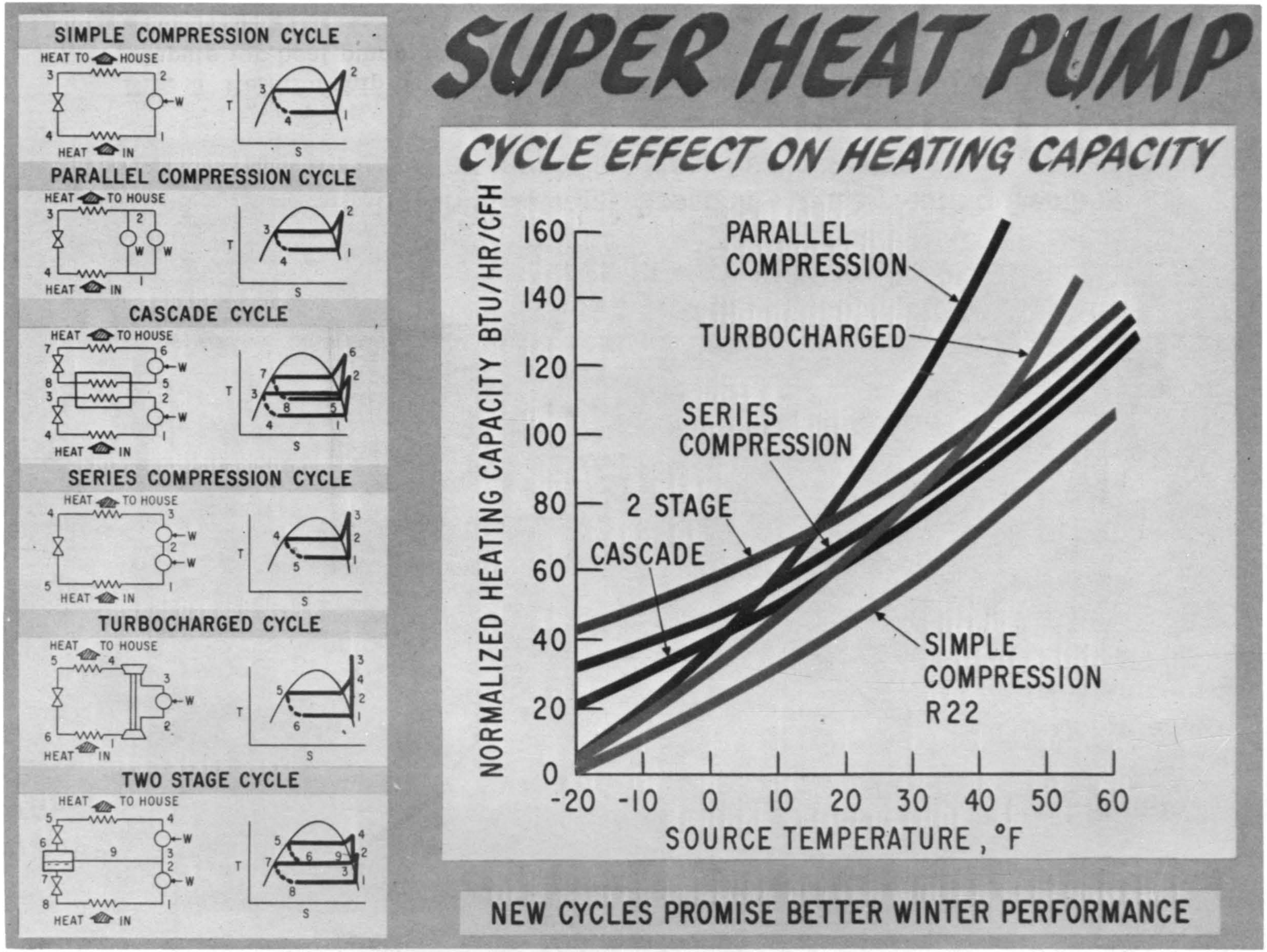


Fig. 6 Multicompressor heat pump cycle configurations and ideal heating capacity.

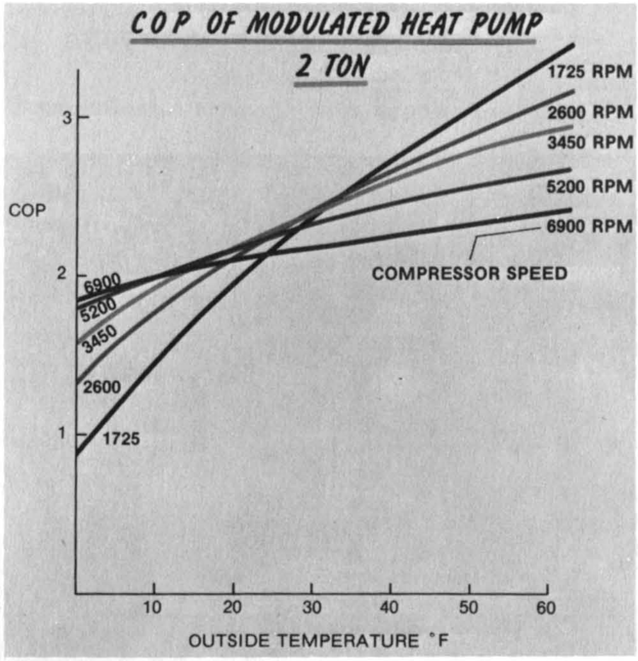


Fig. 7 Heat pump heating efficiency as a function of outdoor temperature for various speeds of the speed modulated compressor.

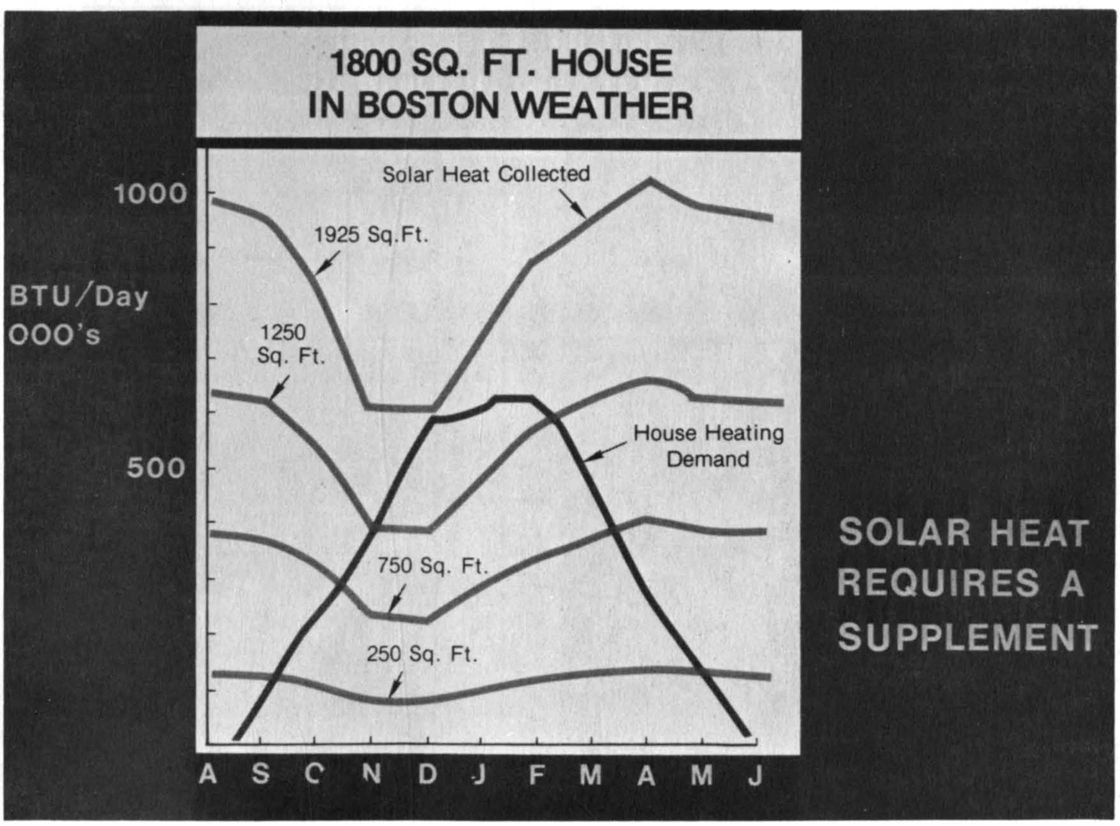
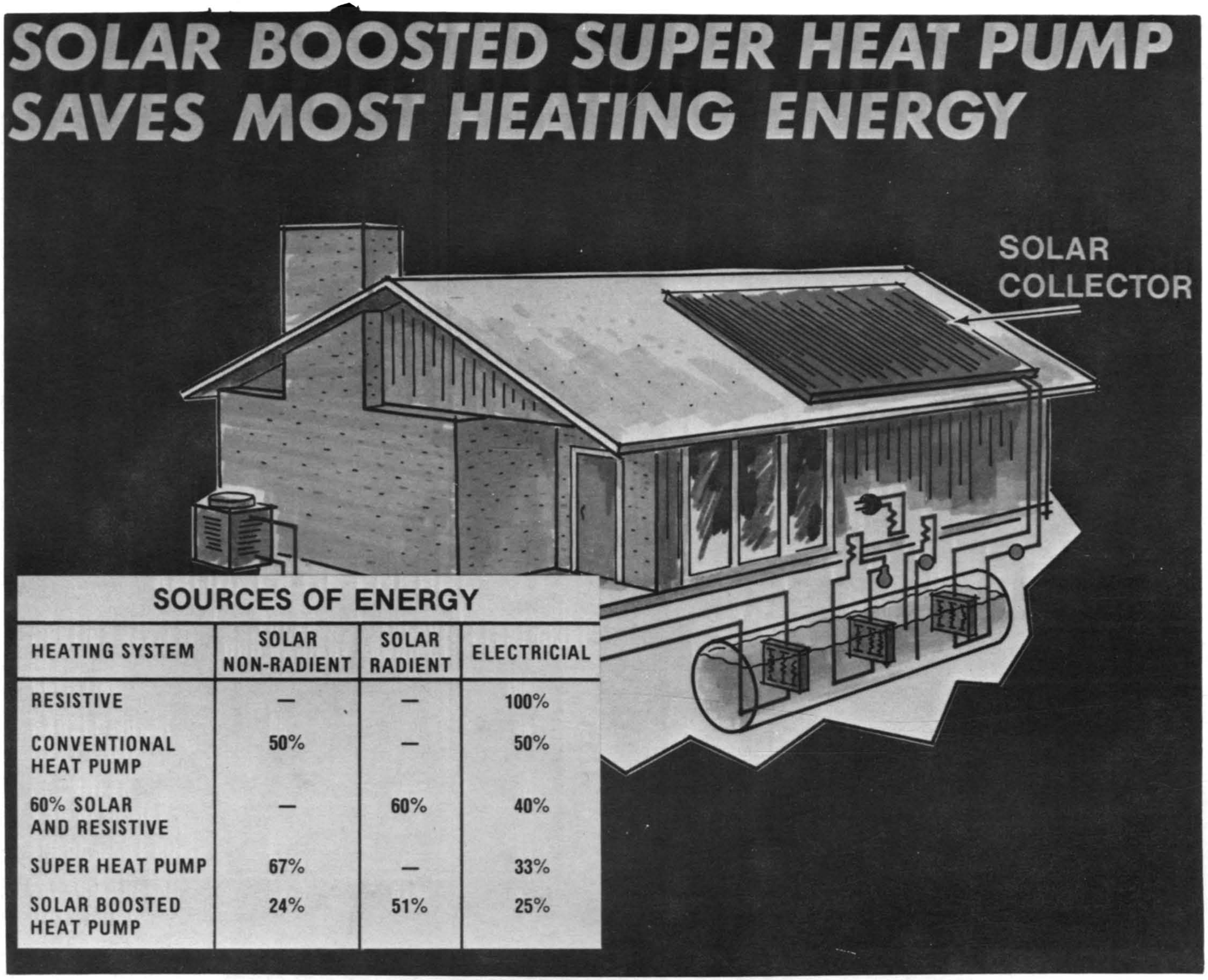


Fig. 8 Relationship between house heating demand and radiant solar energy collected by variously sized collector arrays.



SOURCES OF ENERGY

HEATING SYSTEM	SOLAR NON-RADIENT	SOLAR RADIENT	ELECTRICIAL
RESISTIVE	—	—	100%
CONVENTIONAL HEAT PUMP	50%	—	50%
60% SOLAR AND RESISTIVE	—	60%	40%
SUPER HEAT PUMP	67%	—	33%
SOLAR BOOSTED HEAT PUMP	24%	51%	25%

Fig. 9 Solar boosted cascaded heat pump system and seasonal sources of heat energy delivered to house.

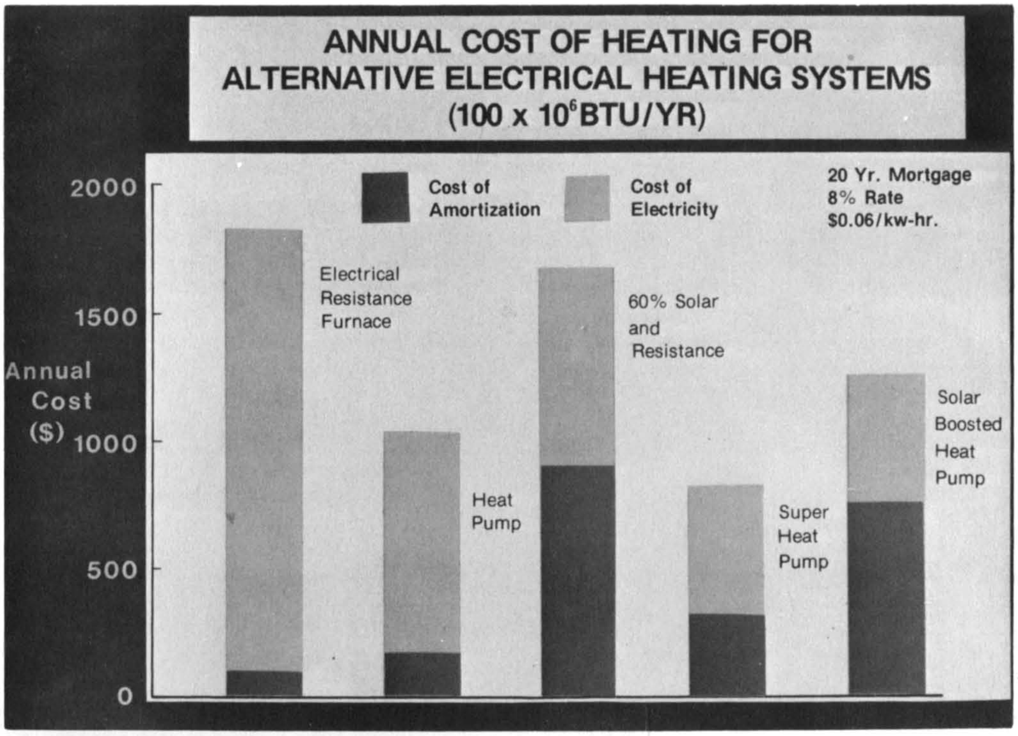


Fig. 10 Annual cost of heating for alternative electrical or electrically complemented heating systems at $0.06/KW-hr.

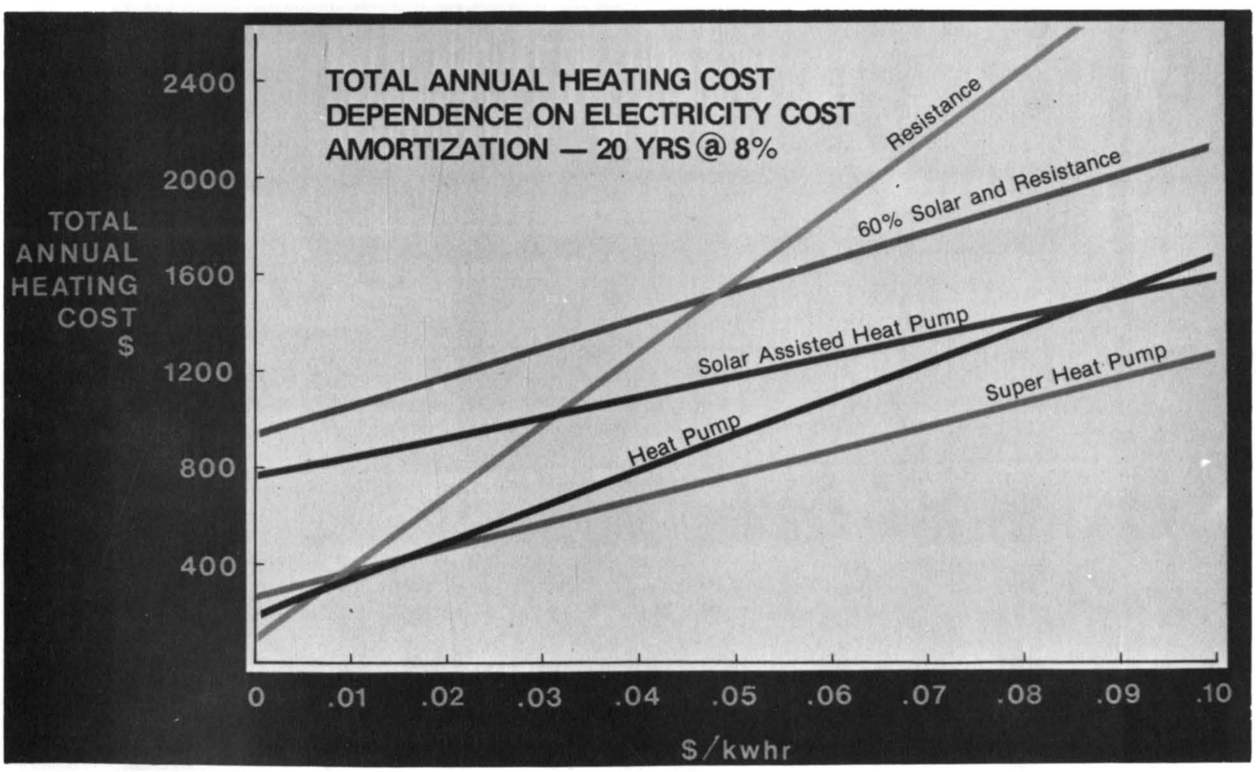


Fig. 11 Annual cost of heating for alternative electrical or electrically complemented heating systems as functions of the cost of electricity.

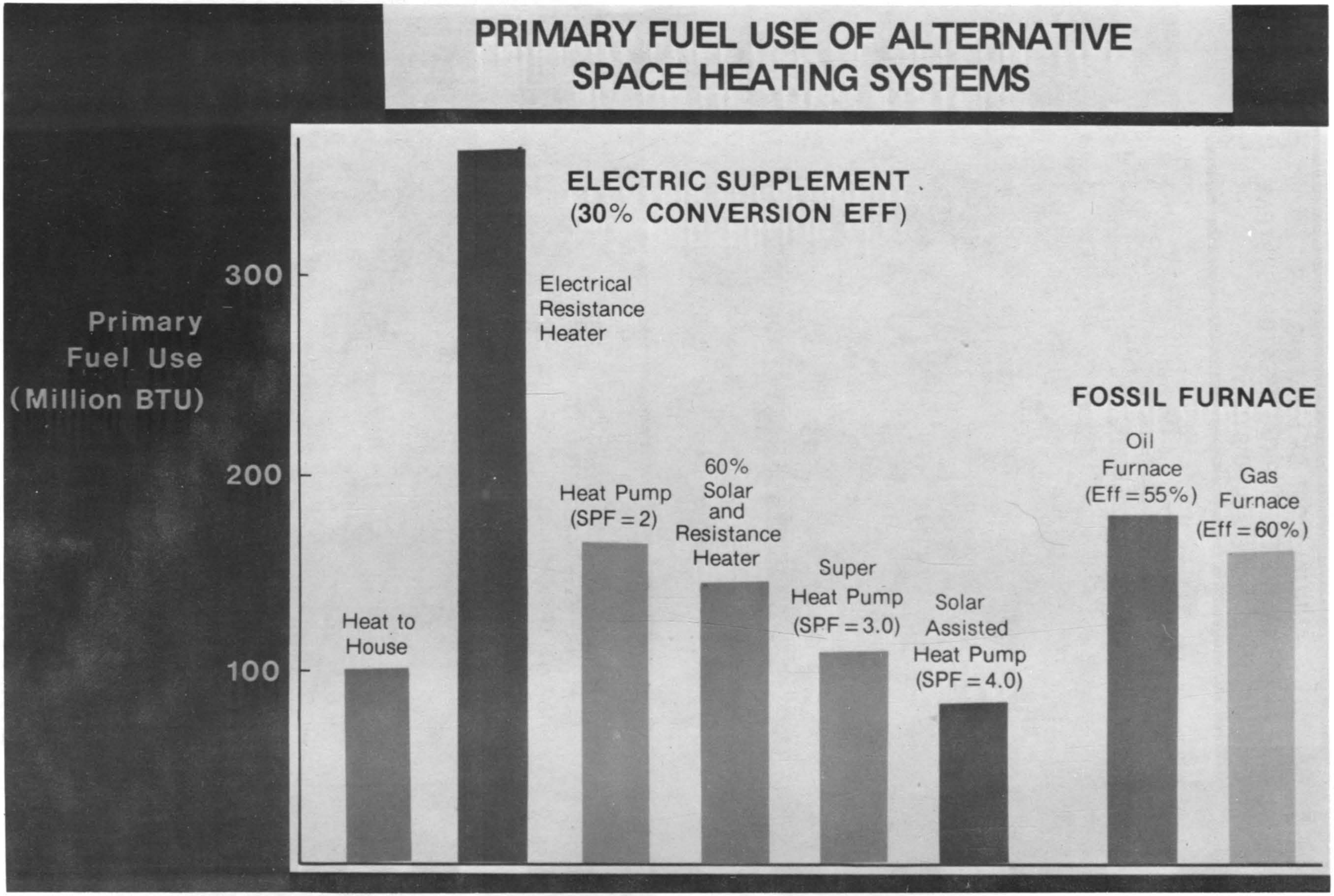


Fig. 12 Primary fuel use of alternative space heating systems.