

Distributed Space Conditioning for Residential Applications

M. Kevin Drost and Robert S. Wegeng, Pacific Northwest National Laboratory¹

Recent developments in miniaturizing energy systems have the potential to make distributed space conditioning an attractive alternative to central heating, ventilation and air conditioning (HVAC) for residential applications. The ability to distribute a large number of small HVAC systems throughout a residence eliminates ducting losses, minimizes cycling losses and enables zoning. Losses associated with using a central air conditioning system often consume between one-third and one-half of the output of a central heating and cooling system.

This paper summarizes recent research on miniature and microscale heat pump systems. Results to date suggest that both concepts are technically feasible. An economic evaluation of a distributed miniature heat pump system, a distributed microscale heat pump system and a conventional central air source heat pump is presented. The results show that both the miniature and microscale distributed systems have the potential to significantly reduce the cost and improve the energy efficiency of residential space conditioning.

INTRODUCTION

Residential space conditioning is an inherently distributed process that is currently done in a central fashion. The purpose of space conditioning is to provide a relatively small amount of heating or cooling throughout a residence. However, normal practice is to generate heat or chill in a central location (such as a heat pump or furnace) and then distribute heated or cooled air throughout the structure via a system of ducts. The combination of central generation and air distribution of heat and chill results in significant performance loss and costs. These include:

- **Ducting Losses**—Fan power, thermal losses through ducts, and air leakage can often consume 30% to 40% of the output of a heat pump. Losses in poorly installed ducting can be much higher.
- **Cycling Losses**—A central heat pump is sized to meet the maximum design load. In all other situations, the heat pump will only operate intermittently (cycling). While cooling, the heat pump must repeatedly cool heat pump components and ducting, only to have these components warm up when the heat pump cycles off. Typically cycling losses can reduce the efficiency of a heat pump by 10% to 15%.
- **Zoning**—Conventional air distribution systems require modulating dampers for zoning, making zoning difficult and expensive.

- **Increased Capital Cost**—The cost of ducting and ducting installation represents a significant fraction of the cost of a residential space conditioning system.

A distributed space conditioning system, where a residence is conditioned by a number of small heat pumps, would reduce each of the four penalties associated with central HVAC. Duct losses would be eliminated by eliminating the need for ducting, although some fan power may still be needed for optimum heat transfer from the distributed heat pumps. Cycling losses would be reduced by the modular nature of distributed HVAC. Increased cooling load would be provided by turning on additional heat pumps rather than cycling a single central heat pump. Multiple distributed HVAC allows zoning without additional controls or air flow modulation.

The price we pay for central HVAC is very high; a total reduction in the efficiency of the HVAC system of up to 50% and an significant increase in the HVAC system capital cost. The opportunity to reduce these losses is the primary motivator for considering distributed HVAC.

A number of conventional options exist for distributed HVAC. Base board electric heating is clearly a distributed HVAC concept, but a low efficiency one. Split condenser vapor compression cycle systems, and window-mounted air conditioners have some of the features of a distributed HVAC. Finally, the losses associated with air distribution can be reduced by considering water distribution of heat and chill.

While these conventional options have some of the features of distributed HVAC, true distributed space conditioning will require new, small and highly modular HVAC systems.

¹Pacific Northwest National Laboratory is multiprogram laboratory operated for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830 by Battelle Memorial Institute.

Recent developments in energy and chemical system miniaturization indicate that small and efficient HVAC systems are technically feasible. This paper presents an overview of technology development of small HVAC systems and presents our first evaluation of the economics of distributed space conditioning.

ENERGY SYSTEMS MINIATURIZATION

Research at the Pacific Northwest National Laboratory (PNNL) has focused on applying recent developments in microfabrication to the design and manufacturing of miniaturized energy and chemical systems. Mass production of microscale components and systems, using fabrication techniques developed for microelectronics, has the potential to make small-scale space conditioning conversion processes economically attractive, and microtechnology has matured to the point where initial applications of microsensors are reaching commercialization. Development of microscale components such as motors, pumps, and actuators is also progressing, but the combination of components into systems such as microtechnology-based heat pumps has not yet been reported in the literature.

If successfully developed, microtechnology-based energy conversion systems will offer at least three important advantages:

- **Modular Design**—Miniature energy systems are inherently modular and can be readily adapted to distributed space conditioning applications.
- **Cost**—Microfabrication techniques offer economies of mass production, in many cases building on mass production techniques developed for the electronics industry.
- **Heat and Mass Transfer Characteristics**—Heat and mass transport can be significantly enhanced in microstructures. Heat transport is improved by increases in the ratio of surface area to volume and by the inherent reduction of the laminar sublayer in small channels. For mass transport, each order of magnitude reduction of diffusion length reduces molecular diffusion time by two orders of magnitude.

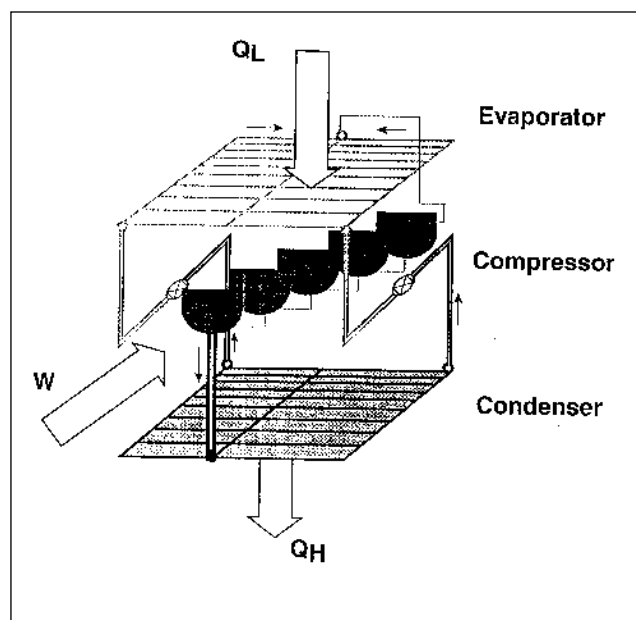
Research at the Pacific Northwest National Laboratory has focused on the development of both microtechnology-based vapor compressor and absorption cycle heat pumps.

MICROTECHNOLOGY-BASED MINIATURE VAPOR COMPRESSION CYCLE HEAT PUMP

By using the proper system architecture, collections of microtechnology-based heat pumps can allow individual microtechnology-based components to be combined and can provide a heating or cooling capacity in the kilowatt range. The sheet architecture concept is one approach. The concept involves assembling a sheet heat pump in layers, with each layer containing arrays of microtechnology-based components performing one or more process steps. In the vapor compression cycle heat pump, one external layer would contain the microchannel condenser, another layer would contain the microscale expansion valves, other layers would contain the microscale compressor, and the last layer would contain the evaporator. Internal insulating layers would be included to minimize losses caused by unwanted heat transfer between components. A schematic diagram of an individual microscale heat pump is shown in Figure 1 (Drost, Beckett & Wegeng, 1994, Wegeng & Drost 1994).

Development of an efficient microscale compressor is a significant technical challenge. An alternative microtechnology-based design involves the use of the sheet microchannel evaporators, condensers and expansion valves, but replaces the sheet of microscale compressors with a small but not microscale compressor.

Figure 1. Schematic of Microscale Vapor Compressor Cycle Heat Pump



Research at the Pacific Northwest National Laboratory and elsewhere has demonstrated the very high performance attainable in microchannel condensers and evaporators (Bowers & Mudawar 1994, Cuta et al. 1995). Single-phase convective heat transfer coefficients range between 10,000 and 20,000 W/cm²-K (1176 to 2352 Btu/hr-ft²-F) with a refrigerant pressure drop on the order of 14 kPa (2 psi). Evaporative heat transfer coefficients exceed 30,000 W/cm²-K (3528 Btu/hr-ft²-F) with a similar pressure drop. Current research is focused on demonstrating techniques for microscale air-side heat transfer enhancement and microscale compressor concepts.

MICROTECHNOLOGY-BASED MINIATURE ABSORPTION CYCLE HEAT PUMP

A simple absorption cycle heat pump is depicted in Figure 2. Although the absorption and vapor-compression cycle differ in the way compression is provided, both systems use essentially the same concepts for space heating and cooling and heat rejection.

In both cycles, superheated refrigerant enters the condensing heat exchanger (HX), where it undergoes constant-pressure heat rejection. The resulting condensate or mixture of condensate and vapor is then adiabatically expanded through

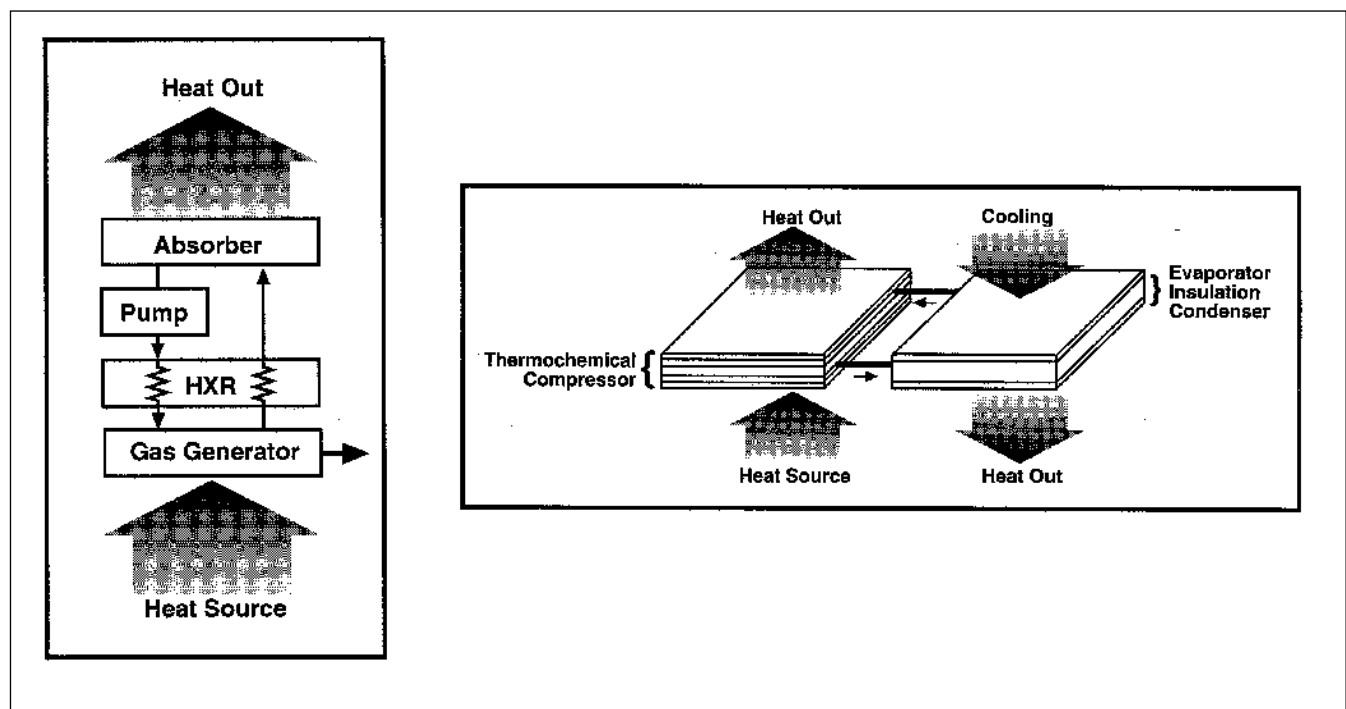
either a throttling valve or a capillary. The mixture is then routed to an evaporating heat exchanger for constant-pressure heat absorption.

Compression is accomplished in the absorption cycle heat pump through the use of a thermochemical compressor, which itself incorporates a heat engine. As shown in Figure 2, the simple thermochemical compressor consists of an absorber, a pump, a recuperative heat exchanger, and a desorber (gas generator).

An important advantage of an absorption cycle heat pump is its ability to operate with a minimum demand for electric power. Most of the energy supplied to the absorption cycle heat pump is thermal energy that can be provided by the combustion of high energy density hydrocarbon fuels. There are many variations on the cycle arrangement shown in Figure 1, and significant efficiency improvements can be expected from a detailed cycle optimization.

Thermochemical compression lends itself to miniaturization. Absorption and desorption (gas generation) are functions of the surface area-to-volume ratio and, therefore, should show better performance as scale decreases. Also, high-capacity absorption and desorption will require high cooling/heating rates with minimum approach temperatures, and these conditions can be obtained in microchannel heat exchangers. In addition, the efficiency of thermochemical compression is largely a function of the recuperative heat exchanger effi-

Figure 2. Absorption Heat Pump Cycle



ciency. Here again, our previous development work with microchannel heat exchangers builds positive expectations for a compact, highly efficient device.

The Pacific Northwest National Laboratory has demonstrated all of the microscale components for a microtechnology-based absorption cycle heat pump, except the gas generator. As discussed above, microchannel evaporators and condensers have been successfully demonstrated, and a range of designs for a microchannel absorber have been tested with the results confirming the high absorption rates predicted through microscale mass transport enhancement. We plan to demonstrate a complete prototypical, hybrid lithium bromide thermochemical compressor, using a small but not microscale liquid pump, in 1996. Currently PNNL is developing a compact microchannel combustor that can be used as the heat source for the microtechnology-based absorption cycle heat pump. The microchannel combustor is being developed for the Department of Defense's Defense Advanced Research Projects Agency (DARPA).

ECONOMIC EVALUATION— METHODOLOGY

The objective of the economic evaluation is to determine the market entry potential of the microtechnology-based compact heat pump and a true microscale heat pump. The evaluation is limited to electric cooling options and compares the cost and performance of a conventional central electricity driven vapor compression cycle heat pump system with cost and performance estimates of comparable distributed vapor compression cycle heat pump systems.

APPLICATION CHARACTERISTICS

Cost and performance characteristics of both the central system and the mini systems are based on a 1,500 ft² single family dwelling. An average United States climate has been assumed, with a resulting maximum heating or cooling load of 36,000 Btu/hr for the conventional, central system and 25,200 Btu/hr for the distributed microscale system. The 35% reduction in cooling load for the distributed system is caused by decreased cycling and distribution (duct) losses, as well as a lower overall load expected because of improved zone temperature control. The estimate of the impact of distributed cooling on cooling load was taken from data comparing base board electric heating (a distributed heating system) to central electric heating (Miller et al. 1991).

CHARACTERISTICS OF THE CONVENTIONAL CENTRAL HVAC SYSTEM

To compare the proposed microscale pump system with existing "standard" systems, it was necessary to select a

heating/cooling system that was representative of those typically installed in American households. Vendors contacted as part of this study indicated that a 3-ton split-system central heat pump would normally be installed in a typical residence. Although the maximum cooling and heating loads for an average residence are substantially lower than the 3-ton capacity of this system, it is typical to install an oversized system. This is because the consumer usually wants a system that will result in minimal "lag" time, or time required to cool (or heat) the house to the desired temperature from a higher (or lower) temperature.

A primary difference between the conventional system and the microscale system is installation cost. Based on contacts with local HVAC vendors we estimated that approximately 70% of the installed cost of the conventional system is for the ducting materials, ducting installation labor, and piping between the inside and outside units. The installed cost of the conventional system was estimated by local vendors to be approximately \$6,000, including profit. When comparing the conventional system to the microscale system, a 50% profit margin was assumed, resulting in a \$4,000 "pre-profit" cost as a basis for comparison.

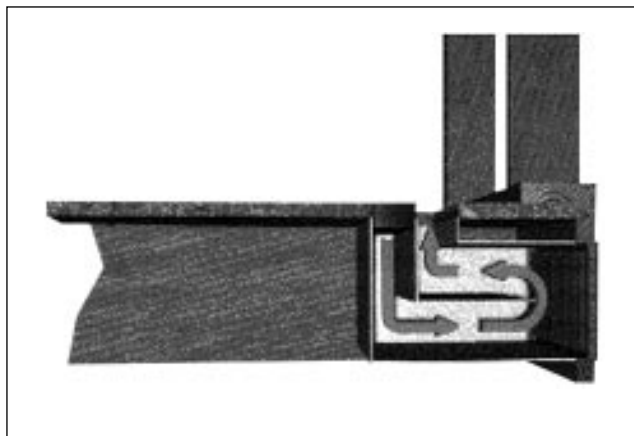
Based on reviewer comments, it appears that there is a significant variation in the cost of ducting and ducting installation based on type of construction (custom versus track home), region and building practices.

Future research should include an investigation of the sensitivity of the economic results to alternative assumptions concerning ducting capital and installation costs.

CHARACTERISTICS OF A DISTRIBUTED SYSTEM

The basic concept for the distributed heat pump system is shown in Figure 3. The system configuration has the unit

Figure 3. Distributed Heat Pump Concept



mounted between the floor joists in a residence. The condenser (when operating in cooling mode) would be mounted flush with the outside wall, while the remainder of the system would be mounted in the floor itself. A simple ducting system and small fan would circulate interior air across the face of the evaporator to enhance the interior air-side heat transfer. In addition, a thermostat system would allow the user to adjust the temperature set point for each unit. An average of 10 of these units would be required to meet the heating and cooling load.

Two versions of this concept were evaluated. The first involves the use of a small linear compressor, while the second assumes that a true microscale compressor was available. Figure 3 presents the microscale compressor version of the system. Both systems make use of microtechnology-based heat exchangers for the condenser and evaporator. The next section describes the microtechnology-based heat exchanger, followed by a discussion of the two compressor concepts.

HEAT EXCHANGERS

While conventional systems use standard fin-tube heat exchangers for the evaporator and condenser, the microscale system is envisioned as using small, microtechnology-based plate heat exchangers capable of a high heat flux. To reduce tube-side resistance to heat transfer, the heat exchangers use a large number of microscale channels. Traditional manufacturing processes capable of fabricating arrays of microchannels are relatively expensive. The microchannels must be fabricated using a process capable of relatively high precision and low cost. A machining process such as milling would typically be used in this case. However, milling costs are prohibitively high for producing large volumes of low-cost heat exchangers. A laser metal-cutting process capable of cutting microchannels is relatively inexpensive. This technology is rapidly maturing, resulting in less cost reduction for large volumes than might be achieved for other, less mature, technologies.

An alternative process for manufacturing the heat exchangers involves producing arrays of microscale channels or fins on the heat exchanger base sheet using spray deposition technology similar to that used in ink jet printers. Cost assumptions used in this paper for spray deposition techniques are based on existing ink jet technology. It is assumed that the relationship between heat exchanger material cost (2024 T6 aluminum) and spray deposition process cost is similar to the relationship between paper cost and printing cost using an ink jet printer. Production costs for a small volume of heat exchangers is large, because of the high research and development (R&D) and capital costs that would be required to develop this technology. However, as

these R&D and capital costs are amortized over large volumes of parts, the unit cost decreases rapidly and approaches the cost of the aluminum itself.

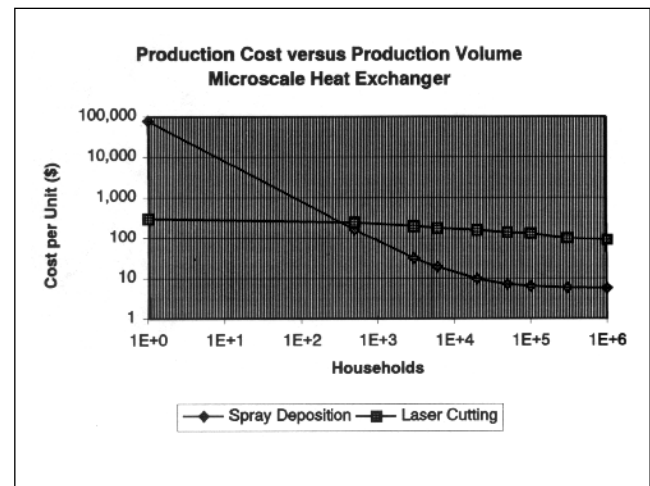
Figure 4 shows the estimated production cost of the heat exchangers using these two processes for a range of production volumes. Note that laser cutting is less expensive for small volumes, but spray deposition has the potential to be significantly less expensive once the technology is developed and high production volumes are achieved.

COMPRESSOR

Two compressor alternatives were evaluated. The first involves a small, commercially-available linear compressor used in conjunction with the microscale heat exchangers described above. This type of compressor is currently available, with wholesale prices ranging from \$40 to \$50. The second alternative is to produce a sheet-type heat pump using microfabrication techniques.

The microscale compressors are assumed to be fabricated on a sheet of magnetic material that undergoes eight etching and seven masking/coating process steps. Technologies used to produce the microscale compressor sheet are similar to those currently used to manufacture other microscale components such as gas sensors and accelerometers. While the size of the compressor would be significantly larger than for microscale sensors, the materials used (e.g., copper) would be less expensive than the silicon used for the sensors, and the scale of the etched microstructures would be larger than that for microscale sensors, which are typically in the 2 to 5 micron range. It is believed that the larger microstructures would have less demanding tolerance requirements, which would tend to lower manufacturing costs. For this paper, it is assumed that the initial costs of the compressor would be

Figure 4. Heat Exchanger Economies-of-Scale



an order of magnitude higher than currently-available sensors of similar manufacture, and that economies-of-scale similar to those for existing microscale components would be realized. This results in a first cost of roughly \$2,500 for the compressor, with a cost reduction factor of roughly 25 for large volumes of production. Figure 5 shows the estimated unit cost versus volume of production.

FAN, CONTROLS, AND ACCESSORIES

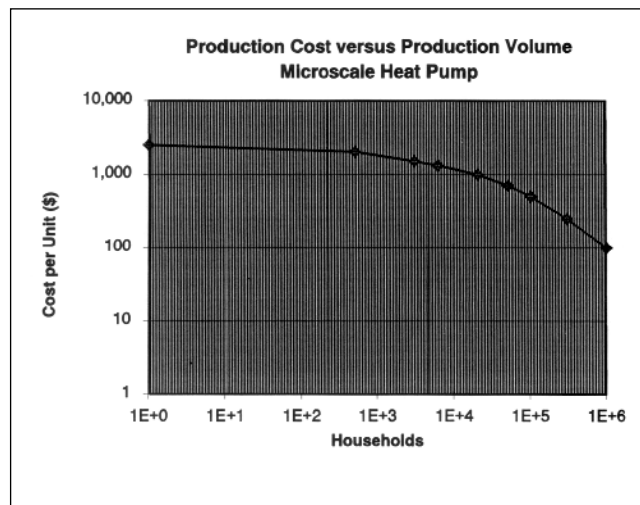
A small, inexpensive fan costing roughly \$9 would be required in the system ducting to move air across the inside heat exchanger and provide some mixing of the air within the room. The mini heat pump system would also require a reversing valve, piping, and other miscellaneous accessories to connect the various components of the system. An estimate for the combined cost of these components, and an assumed assembly cost, are included in the overall cost estimates presented below.

RESULTS

As detailed above, the potential competitiveness of the distributed heat pump systems using microtechnology is heavily dependent upon the manufacturing techniques used, as well as the production volume that can be achieved. Figure 6 shows the estimated cost of the four alternative systems for a production volume suitable for 5,000 residences per year, representing the relative costs for very low production rates. The characteristics of the four alternative distributed systems are described on Table 1.

Figure 7 shows the same comparison, but for a production rate suitable for 100,000 residences per year. Note that the

Figure 5. *Microscale Heat Pump Economies-of-Scale*



central system cost does not decrease because this system is already in large scale production. The capital cost of the systems is presented separately from the life cycle electricity costs to shown the relative energy savings of the microscale systems. An average electricity rate of 8.1 cents/kW and a lifetime of 15 years were assumed.

CONCLUSIONS

Distributed space conditioning has the potential to significantly improve the performance and reduce the cost of residential space conditioning. Recent technical developments suggest that miniature and microscale distributed heat pumps are technically feasible and may be an attractive option for distributed cooling. Results suggest that these systems have the potential to reduce energy consumption in residential space heating and improve economics.

ACKNOWLEDGMENTS

The research discussed in this paper was funded by the U.S. Department of Energy through Laboratory Directed Research and Development funding.

REFERENCES

- Bowers, M.B. and I. Mudawar. 1994. "High Flux Boiling in Low Flow Rate, Low Pressure Drop Mini-Channel and Micro-Channel Heat Sinks." *International Journal of Heat and Mass Transfer* 37(2):321–332.
- Cuta, J.M., W.D. Bennett, C.E. McDonald and T.S. Ravigururajan. 1995. "Fabrication and Testing of Micro-Channel Heat Exchangers." *Reprinted from Microlithography and Metrology in Micromachining*, 2640:152–160. Austin, Texas: SPIE—The International Society of Optical Engineering.
- Drost, M.K, M. Beckett and R.S. Wegeng. 1994. Thermodynamic Evaluation of a Microscale Heat Pump. *In Proceedings of the International Mechanical Engineering Congress and Exposition HTD291*. Chicago, Illinois: American Society of Mechanical Engineers.
- Miller, N.E., M.A. Williamson, S.A. Bailey, R.G. Pratt, G.M. Stokes, W.F. Sandusky, E.W. Pearson, and J.R. Roberts. 1991. *Characterizing Thermal Performance from High Resolution End-use Data: Analysis*. PNL-7590 Vol-2. Richland, Washington: Pacific Northwest National Laboratory.
- Wegeng, R.S and M.K. Drost. 1994. "Developing Miniature Energy Systems." *Mechanical Engineering*, September 1994.

Figure 6. Cost Comparison—5,000 Households

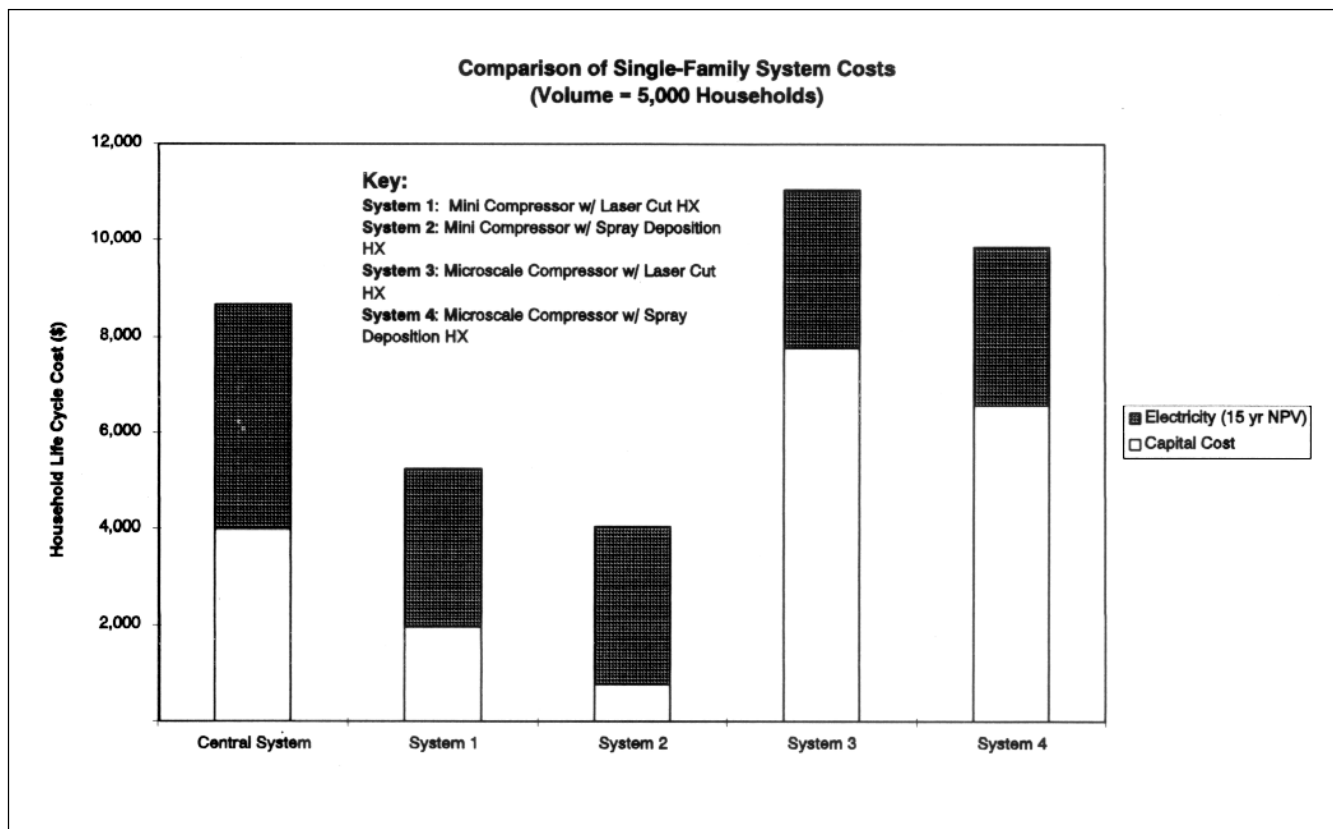


Table 1. Characteristics of Alternative Systems

	Configuration	Heat Exchanger	Compressor
Central System	Split system heat pump	Conventional fin-tube	3-ton reciprocating
System 1	Joist mounted distributed	Laser-cut mini-fin	1,200 Btu/h reciprocating
System 2	Joist mounted, distributed	Spray deposition mini-fin	1,200 Btu/h reciprocating
System 3	Joist mounted, distributed	Laser-cut mini-fin	Microscale sheet
System 4	Joist mounted, distributed	Spray deposition mini-fin	Microscale sheet

Figure 7. Cost Comparison—100,000 Households

