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A PRELIMINARY INVESTIGATION OF THREE ADVANCED WIND FURNACE SYSTEMS FOR RESIDENTIAL AND FARM APPLICATIONS

EXECUTIVE SUMMARY

by

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EXECUTIVE SUMMARY

Abstract

This report summarizes the results of an analytical performance and economic evaluation of three advanced wind furnace heating systems. The work represents an extension of previous work on wind powered heating systems and extends this wind energy application to the supply of electricity as well as space and hot water energy loads for rural residences and farms. Details of the proposed systems and the analytical modeling of the overall system and subcomponents are presented as well as typical system energy and economic performance.

Introduction

Recent detailed Wind Mission Analysis studies (1,2)* have pointed out the high potential of residential and agriculture applications for wind energy systems in the United States. Specifically, these studies estimate the potential size of the markets in these areas varying from about 9 to 10 million units. For the past several years the Energy Alternatives Program at the University of Massachusetts, Amherst has been investigating the use of wind powered heating systems (wind furances) for rural applications. In addition to the development of general digital computer based simulation models and analytical studies on wind-powered heating systems (3,4), this work has produced an operational 25 kW Wind Turbine Generator (5) and an experimental wind turbine and residential heating test facility (Solar Habitat I).

Wind energy, along with other forms of solar energy, due to its variable intensity must be stored to insure distribution to residential and farm energy loads as it is required. Unfortunately, the electrical, domestic hot water and space heating loads of a typical rural residence or farm are also variable. Thus, any well designed wind energy storage and distribution system must consider the variability of the energy inputs and outputs for the most efficient design. Also, the most efficient energy use is possible when high grade energy, such as electricity, is used for a high grade application, such as the electrical load, and similarly, when low grade energy, such as waste heat, is used for a low grade application, such as space heating. The original wind furnace system was designed to supply the majority of space and domestic water heating requirements to a single rural dwelling. From results of the analytical modeling of this system, there has almost always been an overflow of electricity which could not be used, particularly during the six warmer months.

The work to be presented in this report represents an extension of the previous work and summarizes an analytical performance and economic evaluation of three advanced wind furnace systems that are designed to supply electricity as well as space and hot water heating for rural residences and farms. As will be described next, these designs include an Improved Wind Furnace System (IWFS) and the Wind Driven Total Energy System (WDTES), Types I and II.

System Configuration and Description

The Improved Wind Furnace, shown schematically in Figure 1, includes the folllowing subsystems:

1. A wind turbine generator (horizontal axis, pitch controlled)
2. A sensible heat thermal energy storage tank (water as energy

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*Numbers in parentheses designate References at the end of the Executive Summary.

storage medium)
3. An electric power conditioner and utility interfacer
4. Switching logic and controls (not included in the Figure)

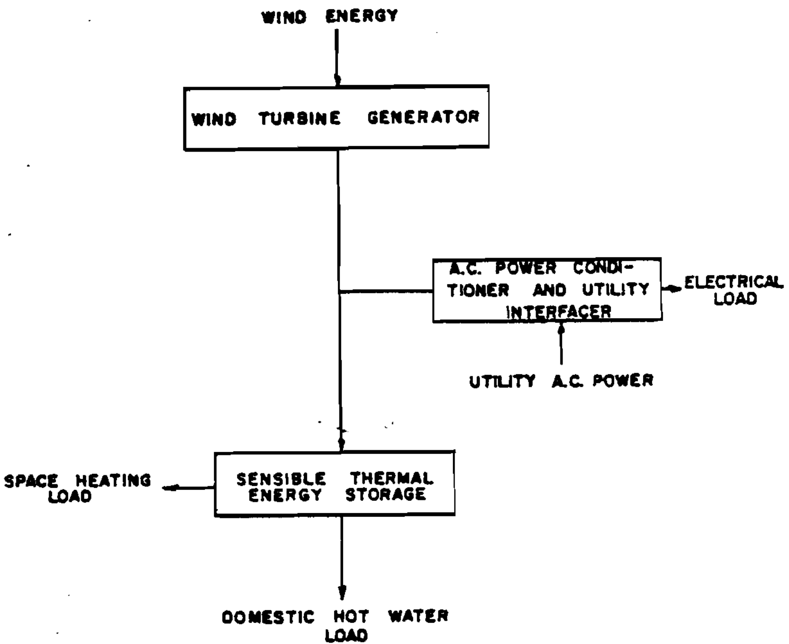

Fig. 1 - Schematic of the improved wind furnace system (IWFS)

The Wind Driven Total Energy Systems were designed to incorporate a means for supply of electrical energy, other than conventional storage batteries, at times when the wind turbine was not producing full power requirements. A systems schematic of the most general configuration WDTES, II, is shown in Figure 2. In addition to the IWFS components just described, this system includes:

1. A high temperature thermal energy storage component
2. A Rankine cycle and separate alternator power system

The Type I WDES system is similar, however, all the electrical energy output of the system is supplied from a Rankine cycle, eliminating the need for power conditioning the electrical output of the wind turbine generator.

The hourly heating and electrical loads for these systems were determined for the following three basic applications:

1. A well insulated residence (space heating load of approximately 17,000 kWh/yr)
2. An average insulated residence (space heating load of approximately 35,000 kWh/yr)

3. An "average" farm - using the average insulated house heating requirements.

A summary of the annual heating and electrical loads for these applications is given in Table 1. The hourly space heating load for the residences were evaluated using techniques previously developed for wind furnace heating systems (3). The domestic hot water load followed an assumed hourly load pattern that was based on work by Mutch (6). Depending on the application, two different models of the hourly electrical load were assumed. For the residential needs, a model adopted from the synthesized hourly electrical load of Wolf (7) was used. The average farm electrical load was modeled by superimposing an hourly electrical machinery load (about 30 kWh daily) on the average residential load to arrive at a total yearly electrical load of 16,736 kWh.

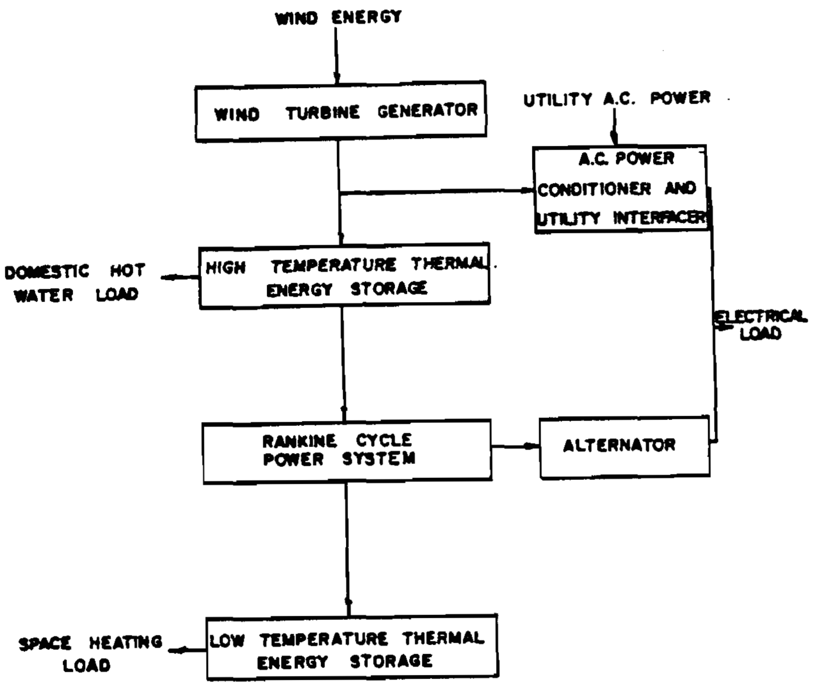

Fig. 2 - Schematic of the wind driven total energy system, type II

Type	Well Insulated Residence	Average Insulated Residence	Average Farm
Space Heating	17,166	35,383	35,383
Water Heating	3,565	3,565	3,565
Electrical	5,785	5,785	16,736
Total Annual Energy Load	26,516	44,733	55,684

Table 1 - Summary of Energy Loads (kWh/yr)

Analytical Model and Component Descriptions

The analysis of the three wind energy systems was based on a digital computer simulation of the various system energy flows on an hour by hour basis. The computer model, an extension of a previously developed model, was general enough to simulate both of the WDTES models and the IWFS model. As described in the main report, it consisted of a main program which, through its interactive format, allows the input of desired system, start-up conditions, component sizes, and output format. The main program also contained the operations switching logic and the energy distribution logic for the various loads. Subprograms included the following:

1. Data input (solar insolation, wind velocity, ambient temperature, etc.)
2. Wind turbine generator model
3. High temperature thermal storage model
4. Low temperature thermal storage and residential heating model
5. Power conditioner and alternator systems
6. Rankine cycle model
7. Electrical load requirements
8. Space heating requirements
9. Hot water heating requirements.

The basis of the assumed energy load requirements was discussed in the previous section and, as formulated, these subprograms gave the hourly energy needs of the various loads. For the wind turbine generator, the simulation subroutine that was designed to predict the performance of the 25 kW machine with three 32.5 ft diameter blades currently in operation at the University of Masschusetts (5) was used. This subroutine contains a number of analytical performance curves for machines with diameters ranging from 20 to 40 ft, and is able to simulate the performance of the wind turbine generator operating from cut-in to cut-out speeds.

The low temperature storage and residential heating subsystem models are based on previously developed models (3). A design using a well insulated water storage tank and a water baseboard heating loop was assumed.

The generator was assumed to be similar to one used in the UMass wind furnace (5), producing AC voltage of varying voltage and frequency, dpending on the wind speed. A power conditioner IWFS and WDTES, II), converting the rectified DC electrical power output to useful single phase, 60 Hz, 120/240 AC electricity was assumed to be one of two types presently available for wind turbine electrical power systems.

The high temperature thermal storage subsystem is a key element in both of the WDTES designs. An optimum sized component is important to the system performance since one that is too large will maintain a lower temperature, thus decreasing the Rankine cycle efficiency, while one that is too small could exhibit temperature fluctuations that would adversely affect Rankine cycle performance.

High temperature thermal storage subsystems have recently been designed for applications in both small and large scale solar electrical power systems (8,9,10). The modeling of such subsystems must include three basic parts: (1) the storage medium, (2) the containment system and insulation, (3) the energy transfer equipment. The high temperature thermal storage system used for the WDTES model is similar to the heat storage unit developed by Comstock and Wescott (11). This subsystem (whose size was variable) is modeled as a cylindrical storage tank containing a sodium hydroxide (NaOH) storage medium with resistance heaters for the electrical input from the wind turbine generator. A hot water coil is placed inside the tank as well as a heat exchanger coil for the high temperature side of the Rankine cycle.

Sodium hydroxide was chosen as the high temperature storage medium because it has been used to store energy up to a relatively high temperature (about 900°F) and because of its two large latent heat phase changes (solid to solid at 560°F which liberates 67 Btu/lb at a solid to liquid phase change at 600°F which liberates 70 Btu/lb). If a suitable working fluid is selected, a high Rankine cycle efficiency is possible due to the potentially large difference between the hot and cold thermal sources.

As modeled, the Rankine cycle heat exchanger has its inlet at the bottom of the tank, and temperature stratification effects should be considered in its analysis. That is, at the inlet and through the first section of the heat exchanger, the working fluid is preheated by the portion of the tank which is at the lowest temperature. As the working fluid travels up the heat exchanger, a continually decreasing amount of heat is transferred to it per unit length due to the decreasing temperature difference between the NaOH and the working fluid. Also, as the tank discharges, a phase front forms which moves vertically up the tank. This has the effect of insuring that the top section of the tank will remain at a high temperature for long periods of time, and in turn, will insure that the working fluid outlet temperature and the Rankine Cycle efficiency are high. To simulate this transient phenomena, a computer simulation based on a strip method was used to simulate differential volumes of storage material that transferred energy to the working fluid through a heat exchanger surface of finite area. Results of this analysis, showing fluid outlet temperatures for typical discharge conditions from a 250 gal tank, are given in Fig. 3.

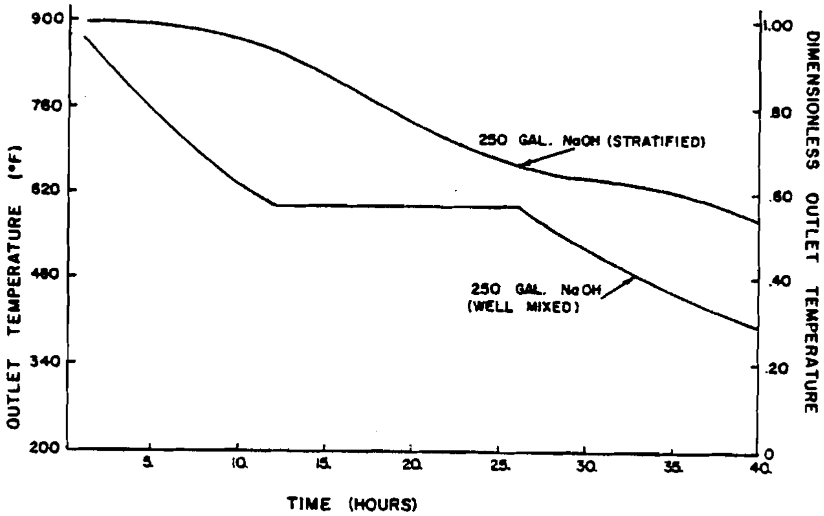

Fig. 3 - Working fluid outlet temperature from HTS system

Although the effects of stratification are quite important, they were not considered in this initial investigation of these systems due to the prohibitively large amounts of computer time for such a simulation, and the fact that a more detailed analysis of the Rankine Cycle subsystem would have been required. Instead, a well-mixed model, which represents a conservative case was used. Fig. 3 shows the comparison between the two models. Also, for purposes of analysis, the hot side heat exchanger for the Rankine Cycle is assumed to have a 50°F temperature difference across it. The domestic hot water coil is assumed to be a controlled heat exchanger which allows the water to rise to the hot water delivery temperaure of 140°F if the storage material is at 140°F or greater, and to the storage temperature if it is less than 140°F.

The Rankine Cycle subsystem is designed to supply electrical power output from the high temperature thermal energy source and reject its waste heat to the low temperature thermal energy storage subsystem (for space heating use). It was assumed that either a four or six kW output Rankine Cycle Power system was used for the residential or farm application, respectively. In recent times similar power systems have been built or proposed (12,13,14) and it is expected that such systems will become commercially available in the future. The proposed Rankine cycle subsystem consists of a preheater, a boiler (or boiler/superheater combination), a turbine, a regenerator, a condenser that rejects heat to the low temperature thermal storage, and a feed pump.

Toluene ($CH_3C_6H_5$) which is a "drying" fluid having maximum and minimum use temperatures of 750°F and -135°F respectively was chosen after a review of work by Miller (15) on the subject. The use of this fluid, readily available and having its characteristics well documented, provides for a high Rankine Cycle efficiency, if a regenerator is used in the cycle. Its characteristics as a "drying" fluid also make the design of a high efficiency turbine possible. In the WDTES scheme, the temperature of both the high and the low temperature may vary widely with time, therefore, the thermodynamic state of the working fluid in all the components of the Rankine Cycle is also a variable in time. For this reason, an in-depth investigation of the off-design performance of specific Rankine Cycle components is important for the detailed analysis of the Rankine Cycle subsystem. Since the main thrust of this work was the preliminary investigation of the general feasibility of the three wind energy systems, such an analysis was not carried out. Thus, a shorter and more readily available method of Rankine Cycle analysis was formulated based on the use of a program developed by Abbin and Leuenberger (16). This program was used to solve for cycle thermal efficiency for various steady state higher and lower cycle operating temperatures.

Since the temperature difference between the working fluid in the two heat exchangers and the storage material in their respective thermal energy storage tanks was not known, an assumption of 50°F less than the storage material temperature in the HTS and 25°F greater than the LTS storage tank temperature was made for the temperature of the working fluid at the heat exchanger outlets. Component efficiencies were assumed as

Combined alternator/generator efficiency = .95
Turbine efficiency = . 8
Regenerator efficiency = . 8
Nozzle efficiency = .95
Pump efficiency = . 5

In off-design operation, the efficiencies of these components (especially the turbine) may be affected by the variation of the storage tank temperatures. An attempt was made to show the effect of decreased turbine efficiency on system performance by introducing a Rankine Cycle efficiency factor into the model. This factor, η_{Rankine}, when set at 0.75 has the effect of reducing turbine efficiency by approximately 25% to 60%, yielding a range of WDTES performance that approximates the effects of off-design Rankine Cycle operation.

Energy Performance Results

Using the previously described analytical model, a series of computer runs simulating the yearly performance of the three systems in a New England setting (using Bradley Field wind data) were performed. Since the number of independent variables was quite high, the effects of all system parameters capable of being varied in the digital computer simulation could not be studied due to time and computer usage restraints. Thus, key parameters were identified and varied to give insight into system performance. These included: (1) the heating and electrical loads, (2) low temperature thermal storage size, (3) high temperature thermal storage size, and (4) Rankine Cycle efficiency factor. Although turbine blade diameter is a key system variable only the 40 ft size was considered. It was assumed that a single wind turbine with this size blade (on a 60 ft tower) was well-suited to match the loads under consideration and represented the largest sized economical unit for a residence or farm.

With the three different heating and electrical loads, variation of the previously described parameters yielded a multitude of performance information on such desired energy parameters as auxiliary space and water heating, electrical, or total auxiliary energy requirements, as well as other system parameters (average storage temperatures, Rankine Cycle operating temperatures, etc.). A fully summary is beyond the scope of this paper, and is contained in the main report. Some typical results emphasizing major points, however, will be presented in this section.

Figure 4 presents the total auxiliary energy requirements for the well insulated residence using the WDTES system with 100 and 75% values of Rankine cycle efficiency. Compared to the total energy requirements for this system (25,516 kWh/yr) it can be seen that the effect of the Rankine Cycle efficiency parameter on total auxiliary energy requirements is small. As will be shown in the next graphs, a tradeoff exists between electrical and thermal heating output when this parameter is varied. These results also show that a high temperature storage (HTS) size of about 100 gal is optimum for this configuration and operating load.

Figures 5 and 6 present the fractions of space heating and electrical loads to be supplied from auxiliary sources for each of these systems applied to the well insulated residence. It can be seen, that once the improved wind furnace system's low temperature storage (LTS) subsystem reaches 2000 gal, this system can supply more space heating energy that the WDTES systems. However, the IWFS requires a much larger amount of auxiliary electrical energy input than the WDTES system, and, due to its configuraiton, this value is fixed regardless of energy storage size.

Figure 7 gives a comparison of three types of systems for the farm aplication. These results show that, for a high temperature storage size of about 250 gal, the WDTES, Type II system out-performs both the IWFS and the WDTES, Type I system (which is not suited for this particular application). Detailed calculations also revealed that large temperature flucuations in the Rankine Cycle made HTS sizes less than 100 gal impractical.

Economic Analysis

The high initial costs of the systems under study must be weighed against the savings in energy use, with respect to conventional systems, to justify their implementation. Total costs for the conventional and non-conventional systems were considered to include component costs and fuel costs. Annual price escalation rates of 6% for electricity, 7% for oil, and 8% for natural gas (17) were assumed for the 20 year amortization period. The component economics model for the wind energy system was based on an initial capital outlay in 1977 for a prototype system or a mass-produced system (if this were possible today) with its lower costs. The non-conventional energy systems, as well as the conventional heating systems were assumed to be paid for during 20 year periods with an annual interest rate of 8%. The possibility of selling excess electrical energy back to a utility was not included.

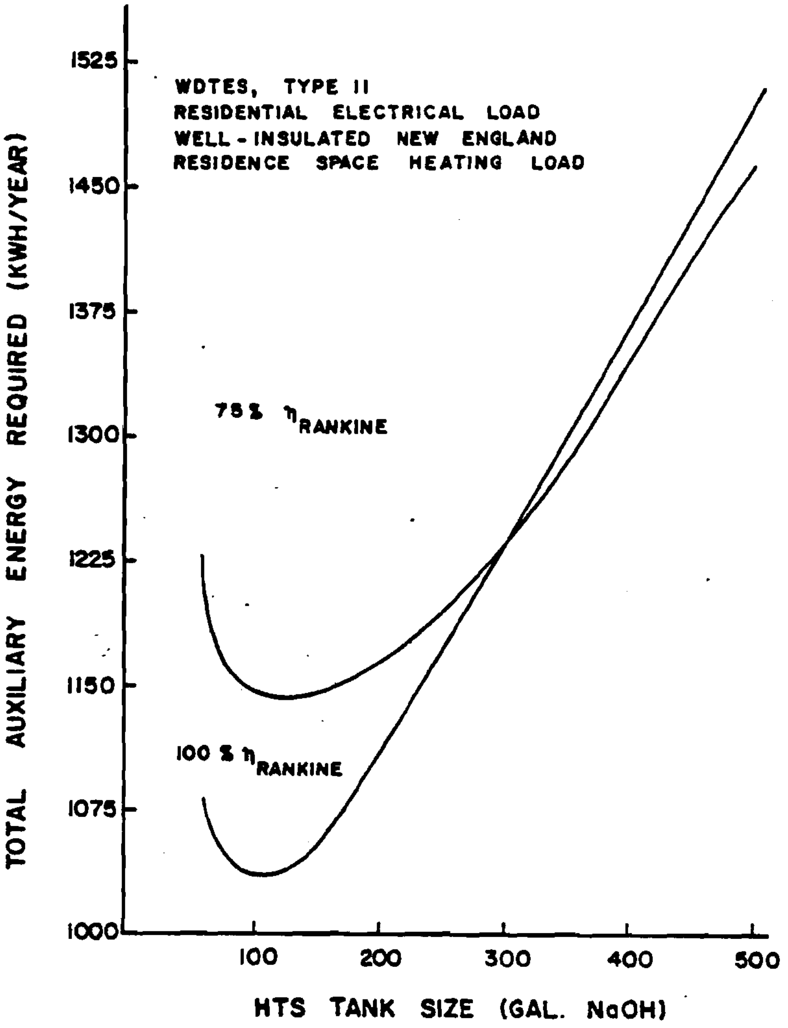

Fig. 4 - Total auxiliary energy required in a function of HTS tank size for both 100% and 75% Rankine cycle efficiency values.

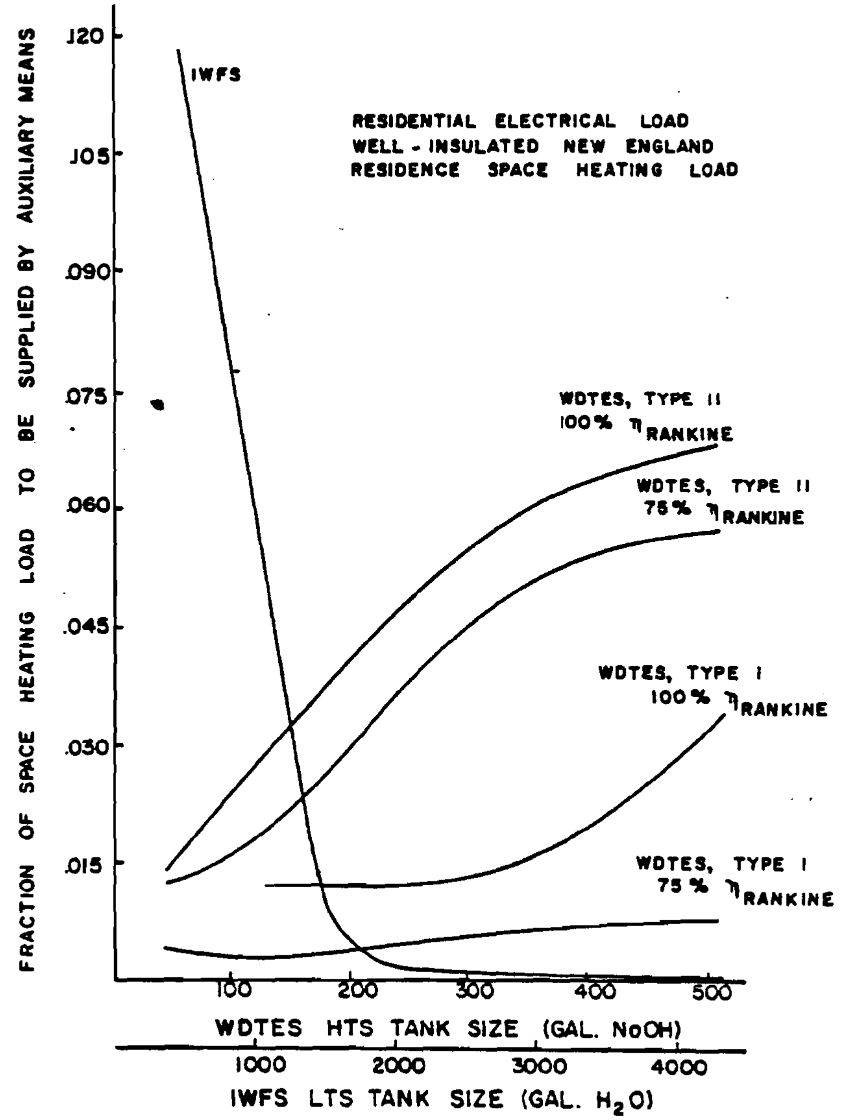

Fig. 5 - Fraction of auxiliary space heating loads as a function of WDTES HTS tank size or OWFS LTS tank size.

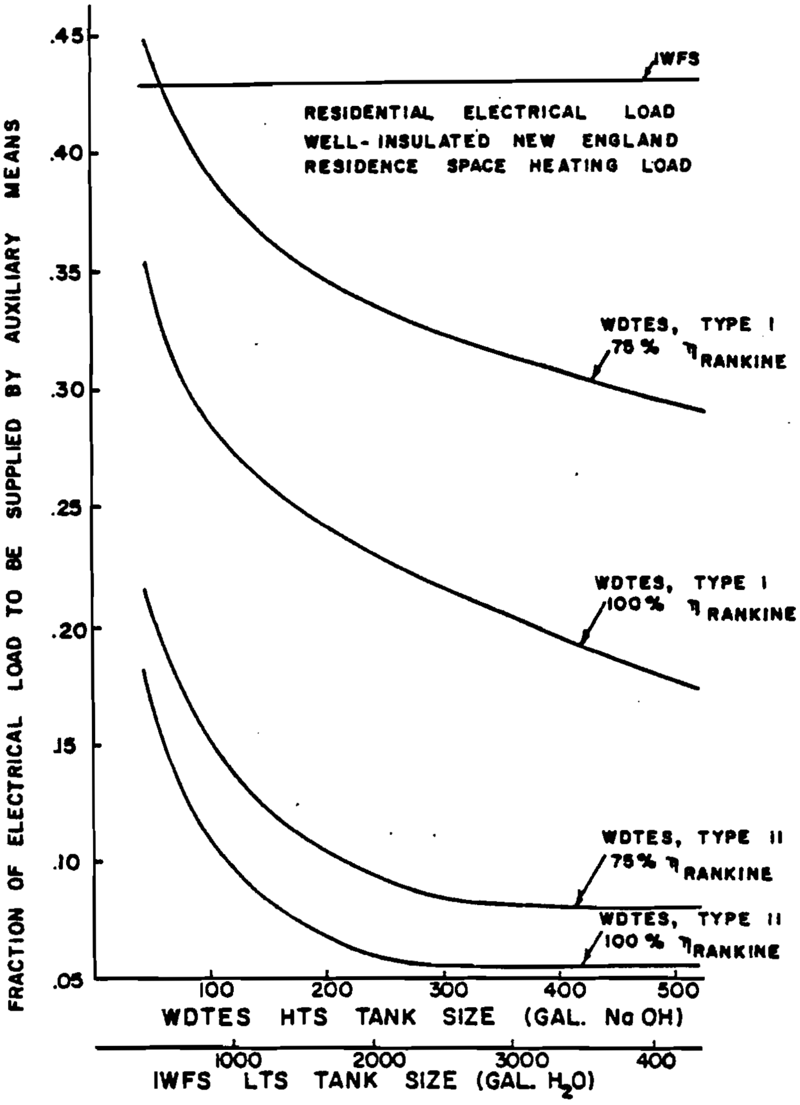

Fig. 6 - Function of auxiliary electrical load as a function of WDTES HTS tank size or IWFS LTS tank size.

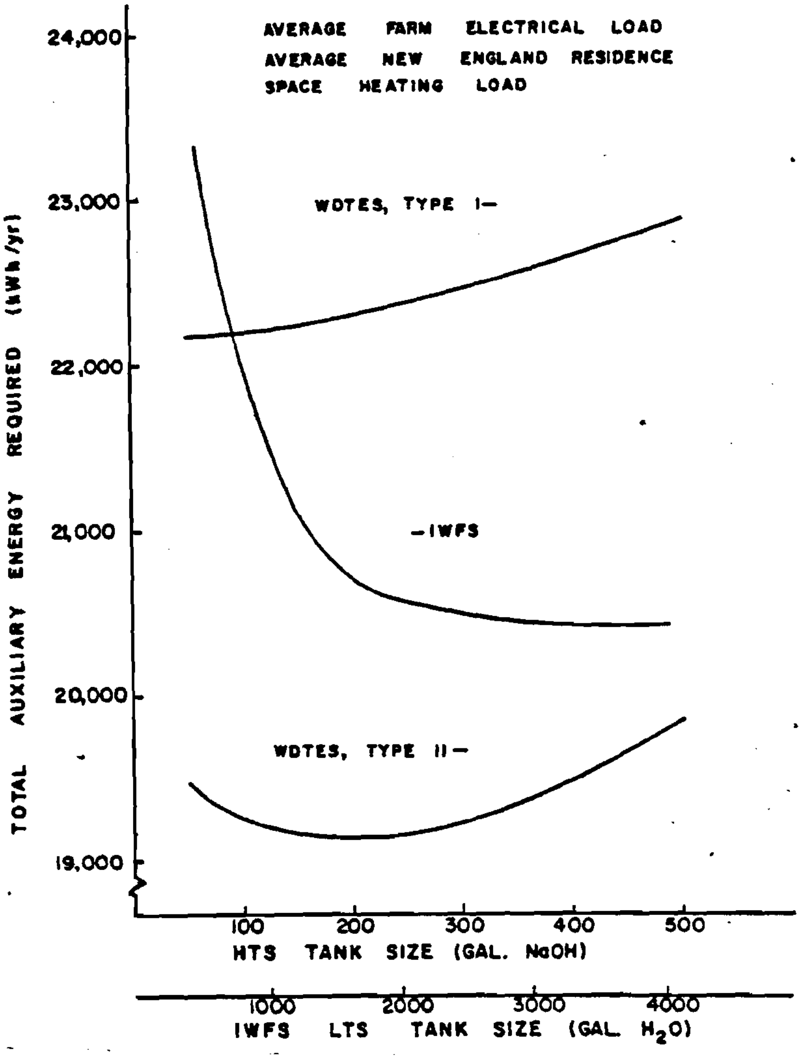

Fig. 7 - Comparison of systems for farm application.

Costs of the wind turbine generator, the low temperature thermal storage and the conventional systems (based on work in Refs. 4 and 5) were adjusted to reflect changes in the consumer price index. Costs for the high temperature thermal storage, the Rankine Cycle, and power conditioner (rectifier and inventer) were unique to this study. The NaOH material cost was estimated from Refs. 9 and 10, and the costs of the other HTS components were estimated on the basis of past UMass wind furnace experience.
The costs of the two different power conditioner (rectifier and inverter) were unique to this study. The NaOH material cost was estimated from Refs. 9 and 10, and the costs of the other HTS components were estimated on the basis of past UMass wind furnace experience. The costs of the two different power conditioner systems were estimated from representative manufacturers technical data. A preliminary estimate of the Rankine Cycle power system costs was obtained from Ref. 18, however, Barber (19) has recently estimated much higher costs for small Rankine power systems. It should be pointed out that state of the art Rankine systems are not presently commercially available, at least at the lower cost levels of Ref. 18. Specific details of the various subcomponent costs and other variables pertinent to the economics analysis are given in Ref. 6.

An analytical model was developed to compare the economics of the proposed systems with conventional heating and electrical energy supply systems. Using results obtained from the previously discussed system energy performance model, the economic potential of each prototype or mass-produced system was determined for each of the residential or farm applications. Typical results from this analysis for the well-insulated residence and the farm application are shown in Figures 8, 9, and 10. All systems are compared on the basis of an average (over a 20 year period) annual cost which included both fuel and capitcal costs (loan payback plus interest charges). As discussed in the previous section, key system performance variables were the high and low temperature storage system sizes.

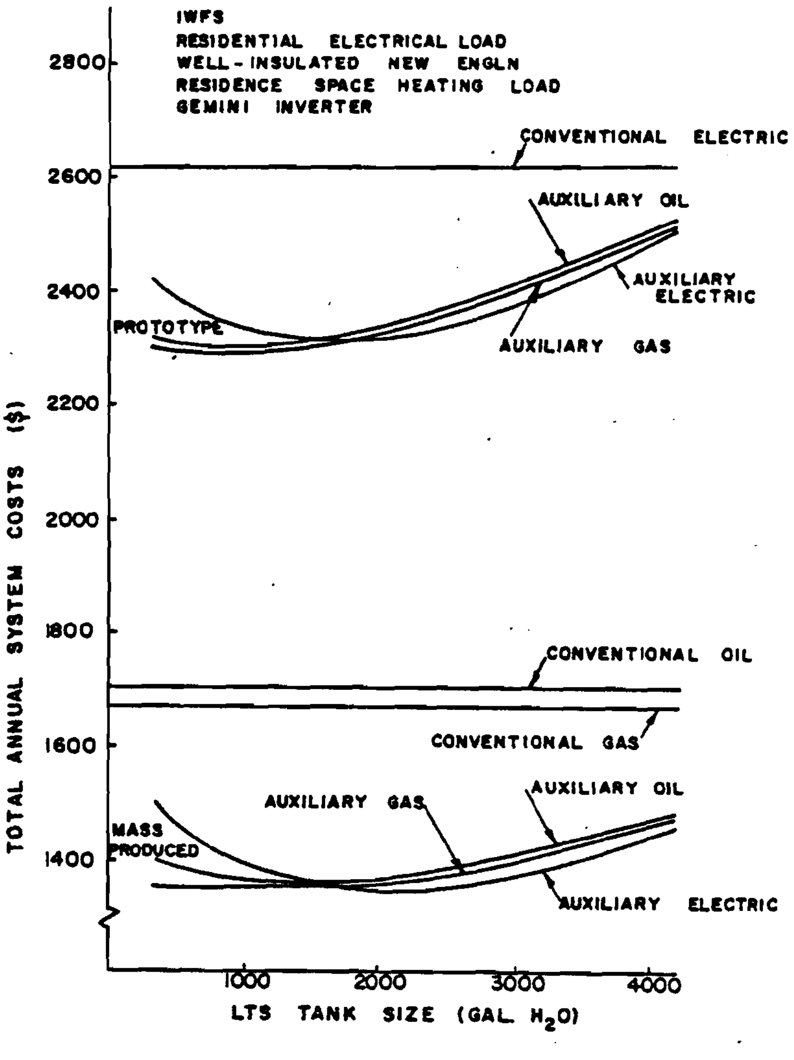

Fig. 8 - Total annual IWFS system costs as a function of LTS tank size for conventional, prototype, and mass-produced systems.

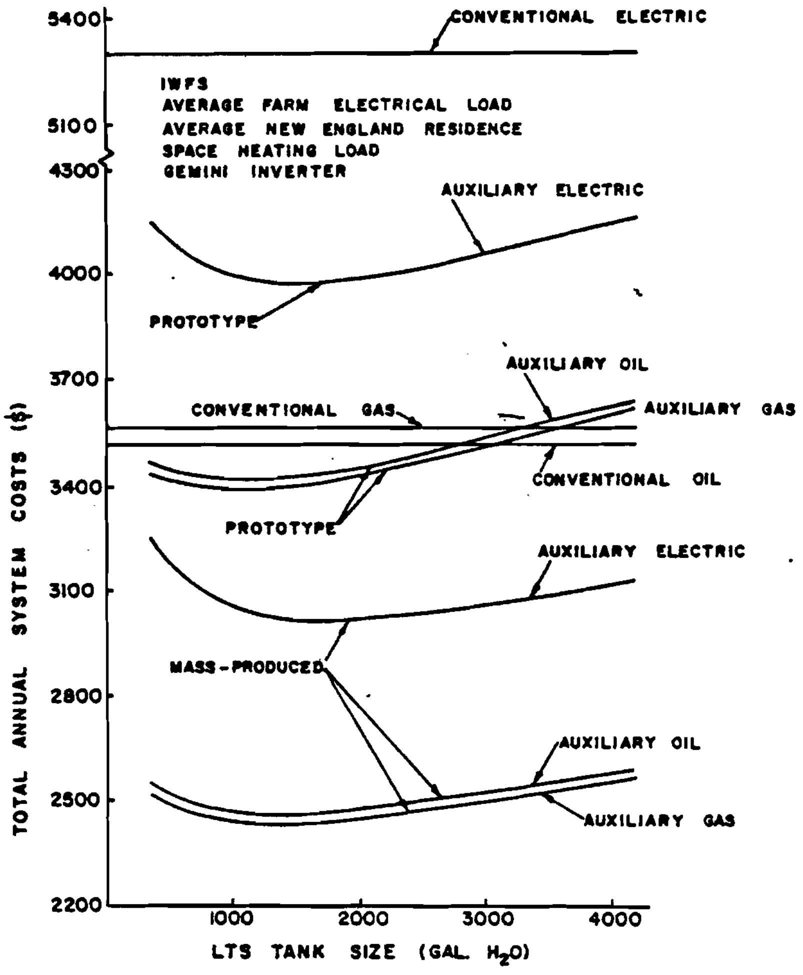

Fig. 9 - Total annual system costs as a function of LTS tank size for conventional, prototype and mass produced systems.

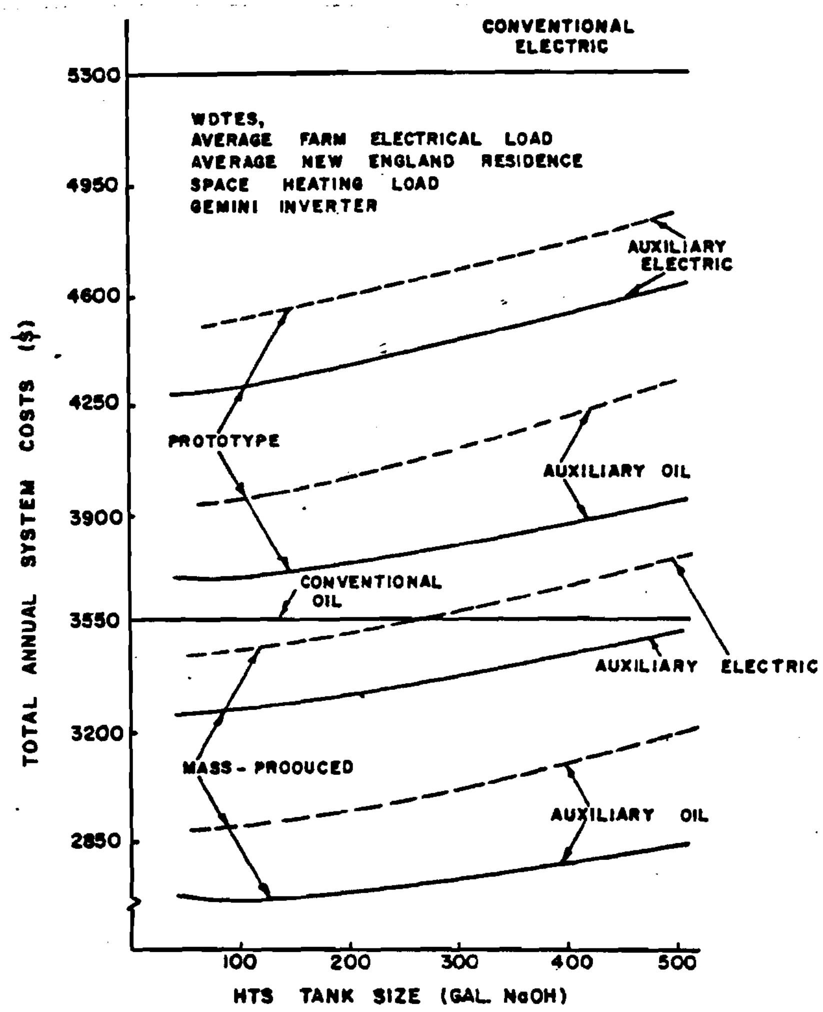

Fig. 10 - Total annual system costs as a function of HTS tank size for conventional, prototype and mass-produced systems.

Conclusions and Recommendations

Optimum system configuration and component sizes for each of the three applications can be made either on the basis of minimum auxiliary energy requirements or minimum annual system costs.

For the well-insulated New England residence, results shown in Fig. 4 indicate that the minimum total auxiliary energy requirements occur when the WDTES, Type II scheme, with a 100 gal HTS is used. This system would supply over 95% of the 26,516 kWh total energy loads of the home, even with a turbine efficiency of 60%. However, it is not economical to use such an expensive energy system. As shown in Fig. 8 the minimum annual system costs (over $300 with respect to conventional gas systems) for this application occur when the mass-produced IWFS model with electrical auxiliary and a 2000 gal LTS is used.

With the average New England residence the WDTES, Type II scheme represents the most energy efficient model of the three, allowing about 73% of the total residential energy requirement of 44,733 kWh to be supplied. Again, though, the mass-produced IWFS provides the least expensive (over $700 annually with 1000 gal LTS and auxiliary gas use) means of energy supply.

In the average New England farm setting, again the WDTES, Type II proved the most efficient, supplying some 66% of the 55,684 kWh total farm energy requirements (with a 250 gal HTS). Results from the economic analysis (see Fig. 9) showed that the annual savings over conventional gas costs by using a mass-produced IWES with a 1000 gal LTS and an auxiliary gas system, is almost $1000.

Two avenues of research, both analytical and experimental, should be followed to continue the work of this initial investigation. On the experimental side, a well-instrumented pilot plant operation should be carried out in order to determine the analytical program's overall validity and use as an engineering tool. Future analytical studies should consider other (perhaps larger sized) applications of the IWFS and WDTES schemes using varying or multiple WTG sizes. Other modifications might include the use of conventional battery storage systems in order to decrease storage tank sizes and utility electrical requirements. More detailed subsystem analyses should include a detailed study of high temperature tank stratification, coupled HTS and Rankine Cycle interaction, and an off-design performance of the Rankine Cycle. Finally, there is a need for continued economic analyses as subcomponent prices become more predictable, and the economic potential of these systems should be studied with respect to any major government alternative energy funding or tax incentives plan.

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