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ASSESSMENT OF WASTE HEAT UTILIZATION TECHNOLOGIES: RESULTS AND CONCLUSIONS*

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ABSTRACT

Thermal effluent from power plants can be used to provide warmth for fish, livestock, biomass crops, greenhouses, and wastewater treatment. In this research, the crucial question of choosing which of these technologies are best suited for any particular power plant is considered. The effects of several key factors were explored through sensitivity analyses, including reliability of the waste heat source, magnitude of the source, temperature of the source, the local climate and energy prices. For waste heat utilization from power plants to be economical, thermal effluent must be available at least 75 percent of the time at temperatures of 38°C (100°F) or higher. Significant economies of scale may be obtained when the generating station is 100 MW or larger, and waste treatment services are provided for at least 500 persons.

Every year, American power plants discharge about 11×10^{15} Btu of low-grade, "waste" heat. This heat is rejected to the environment as warm water at 60 to 100°F [1]. These temperatures are too low for most industrial processes, but they are ideal for living organisms. Fish, livestock and plants grow faster at optimum temperatures, and require less nutrients. Biological waste treatment is accelerated, so a greater volume of wastes can be handled. Air flow requirements for crop drying can be reduced if the temperature of the air is elevated.

* This is the last in a series of eight articles on the utilization of waste heat from power plants. In this article, the results of our sensitivity analysis and our conclusions are presented. Earlier articles described models for simulating the aquaculture, greenhouse, livestock, crop drying and wastewater treatment components of an integrated waste heat utilization complex.

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Further efficiency improvements may be obtained by linking together several operations into a single integrated complex. This mimics the natural cycling of nutrients among plants and animals, thereby minimizing both waste disposal and feed costs. Consider the arrangement shown in Figure 1. The waste-laden effluent of the aquaculture facilities passes through a series of waste treatment ponds used for water hyacinth and algae production. The water hyacinths are harvested mechanically and fermented into ethanol, while the algae are filtered biologically by clams in the clam and crayfish pond. The renovated water is aerated and returned to the aquaculture facility.

Livestock shelters for broiler chickens and swine litters provide ample manure for the anaerobic digesters. Municipal sewage and refuse can be added as necessary to achieve the proper moisture content and chemical composition. The anaerobic digestion process yields methane gas, which can be burned to provide backup heating whenever waste heat supplies are inadequate. The liquid byproduct supernatant is treated in the algae pond, while the solid sludge portion becomes fertilizer for the greenhouses. This complex produces fish, shellfish, livestock, vegetables, flowers, ethanol, and methane for wholesale markets, and also provides waste treatment and crop drying services.

This article is the last in a series of eight articles which began with an overview of our research activities and an assessment of the options available for the utilization of low-temperature waste heat from power plants [2]. The other articles described models for simulating aquaculture facilities [3], greenhouses [4, 5], livestock shelter [6], crop drying [7], and wastewater treatment [8]. Each model included a materials balance, a heat balance, and a method for determining the flow rate of warm water required to maintain optimum temperature conditions. A detailed explanation of our research is presented in Amundsen [9].

METHODOLOGY

We began this research by identifying the sources of waste warm water, which are primarily electricity generating stations. The quantities discharged annually in the United States are enormous, and represent a vast, untapped thermal resource. Numerous beneficial uses of low-temperature thermal effluent were identified, including aquaculture, greenhouses, livestock shelters, crop drying, and wastewater treatment. The characteristics of these technologies, and the obstacles to their implementation, were explored. The evolution of feasibility studies, pilot scale projects, and modeling techniques was reviewed up until the present. It became clear that while much progress had been made in our understanding of the individual technologies, no satisfactory method had been developed for matching these technologies to specific potential sites.

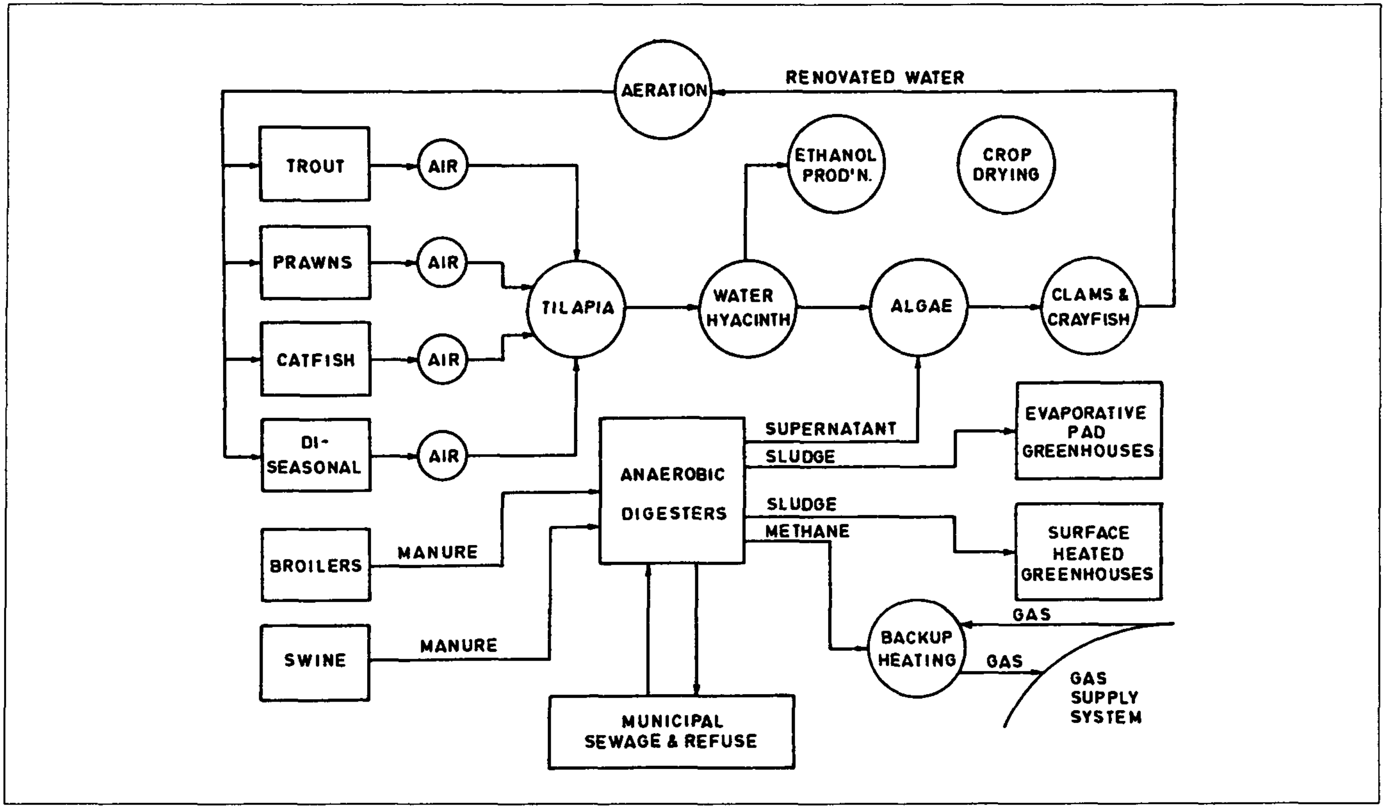

Figure 1. From graphical feedback sample packet.

Having identified which of the emerging technologies appeared to be the most promising, we set about preparing a theoretical framework for choosing among these technologies. We soon discovered that the individual options were highly interrelated when considered in unison as an integrated agro-power complex. There were too many interconnections and nonlinearities to permit the use of simple linear or brute force techniques.

The Response Surface Methodology, which is a hybrid of experimental design and regression techniques, is useful in analyzing these types of problems [10]. We were able to narrow down the range of possibilities which had to be considered by carefully selecting key points. Net Present Value (NPV) was introduced as a measure of the attractiveness of a particular configuration. For each point specified by the experimental design matrix, we could associate a particular mix of technologies at a given power plant. By conducting a simulation experiment for that particular mix of technologies, using known information for the given power plant, we could calculate the NPV of building that particular waste heat complex.

Regression was used to fit a response surface to the NPVs of the trial configurations. The maximum point on this response surface can be found using standard mathematical programming techniques. This maximum point represents the optimal mix of technologies for the given power plant.

Each option was modeled by a series of heat balance, materials balance, and productivity equations. The heat balance equations tell us how much waste heat must be added to the facility to make up for heat losses to its surroundings. The materials balances keep track of the biomass, nutrients, and waste products being circulated through the complex. The productivity functions describe the transformations of nutrients into biomass and waste products.

Weather data was generated by a simulation model which used climate information gathered over a 40-year period. These represented the ambient conditions under which the operation of the complex was simulated. The waste heat output profile of the given power plant tells us how much waste heat is available in each period. If there is insufficient waste heat, then a backup heating system covers the shortfall.

We simulated the physical flows of inputs and outputs. We used cost data to translate these physical flows into expenditures. Using the prices of the products and the quantities produced, we were able to calculate the revenue generated by the complex. The facilities were arranged on the site so as to minimize the cost of distributing waste heat to them. The initial capital investment required was calculated based upon the configuration of the plant and the size of the facilities. The NPV of the configuration was calculated by subtracting the discounted costs from the discounted revenues. This process was applied repeatedly to generate sufficient points for applying the Response Surface Methodology. Finally, we conducted several sensitivity analyses to reveal the effect of altering key factors and to aid in the development of guidelines for cost-effective waste heat utilization.

SENSITIVITY ANALYSIS

We conducted several sensitivity analyses to explore the effects of several key factors on the profitability of integrated waste heat utilization complexes. In particular, we wanted to determine the size of the power plant and the temperature of the effluent which were necessary for the complex to be cost-effective. We also examined the effects of climate and energy prices on economic feasibility. Additional factors included the reliability of the waste heat source and the size of the community receiving waste treatment services. In this section, we will present the results of our sensitivity analyses.

As our base case, we assumed that the complex was located near Philadelphia at a 100 MW plant, with 100°F water available with 100 percent reliability. We assumed that 500 persons lived near the plant, to provide a market for its waste treatment services. These assumptions were varied one at a time, to observe their impacts upon profitability.

Reliability

How does the reliability of the waste heat source affect the viability of waste heat utilization? —We compared thermal effluent streams which were available:

0% of the time (no plant at all)
25% of the time (peak load plant)
50% of the time (intermediate load plant)
75% of the time (base load plant)
100% of the time (multiple-load plant)

The profitability of complexes with 50 percent reliability or lower is marginal. There is substantially higher profitability when reliability is 75 percent or greater.

There is not much difference in the NPV between 75 percent and 100 percent reliability. This is because the aquaculture modules have substantial thermal inertia due to the high heat capacity of the water. They can perform nearly as well with brief interruptions as with a constant supply of heat. This makes less backup heat necessary per hour of interruption as compared with less reliable conditions.

Energy Prices

Which is more favorable to this type of waste heat complex: high energy prices or lower energy prices? —Figure 2 shows that higher energy prices lead to lower NPV's for the waste heat complex. This is disappointing, because waste heat utilization is generally seen as a weapon against higher energy prices. Of course, to fully appreciate the effect of higher energy prices, a study should be made of the effect of higher energy prices on the alternative means of production. Such a study would be very complicated to perform, because the technical coefficients do not remain constant and there are many secondary impacts.

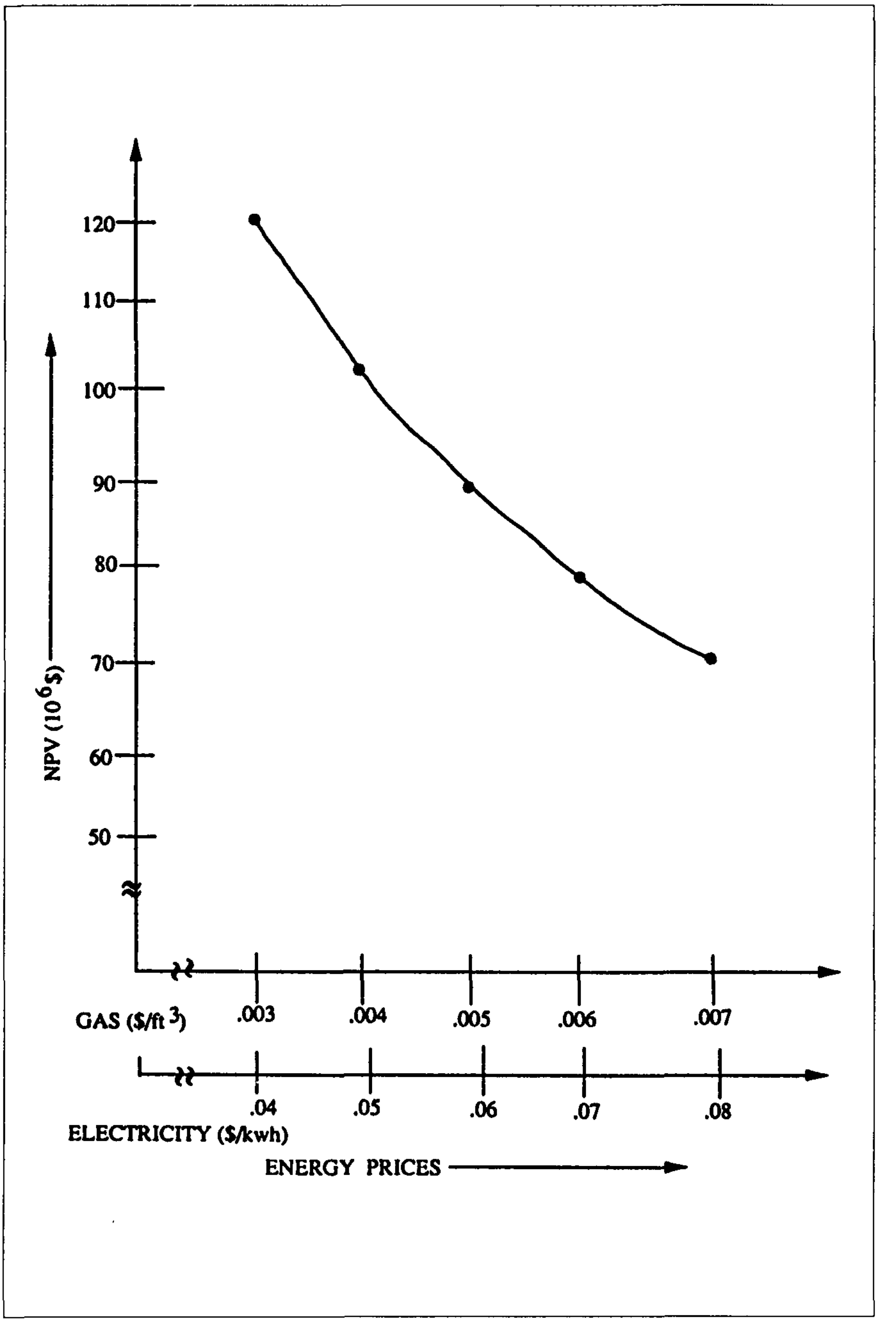

Figure 2. Energy prices: from graphical feedback sample packet.

While the waste heat complex is recovering and utilizing thermal losses, it also consumes a great deal of electricity and natural gas. The complex is surprisingly energy-intensive. Electricity is needed to circulate the large volumes of water and drive the ventilation fans. Gas is consumed by backup heating. Although revenues from the sales of digester gas also rise as energy prices increase, they are not enough to cover the growing expenditures on energy.

It was originally thought that the presence of an energy product (digester gas) would make the NPV nearly neutral to energy prices. However, the energy expenditures are about ten times the revenues from digester gas sales. Ethanol revenues were insignificant compared with gas revenues, so their contribution was small. When energy prices rise, the increased costs overwhelm the moderate increases in revenue.

Each of these technologies consume the same energy which they ordinarily would expect for fuel for space heating. However, when operated without waste heat (0% reliability) they are unprofitable or only marginally profitable. Most of the positive NPV we see follows from increased yields and savings on space heating, which justifies the cost of delivering the waste heat.

Waste Availability

Is access to an adequate supply of waste nutrients essential to the success of an integrated complex? — External wastewater and municipal refuse, along with the fish and livestock wastes, provide the nutrients for the digesters and treatment ponds. These in turn generate revenue by supplying methane, ethanol feedstock, and food for the clams and crayfish. A waste treatment fee can be charged to the community, which is clearly a type of income dependent on external waste sources.

A community produces about 143 gallons/person-day of raw sewage [11] and 6 pounds/person-day of municipal refuse [12]. Since waste production is roughly proportional to the population, we can use population as a surrogate for waste availability in this analysis.

Five possible situations were considered. The complex may receive the waste of:

50 persons (plant employees only)
500 persons (a village or shopping center)
5,000 persons (a town, military base, or airport)
50,000 persons (small city or part of a large city)
500,000 persons (large city or several small cities)

Figure 3 shows how population affects the overall NPV, from a waste availability standpoint.

As the population increases above 500 persons, the diminishing returns to scale are clearly evident. Note the log scale on the bottom of Figure 3. This shows how

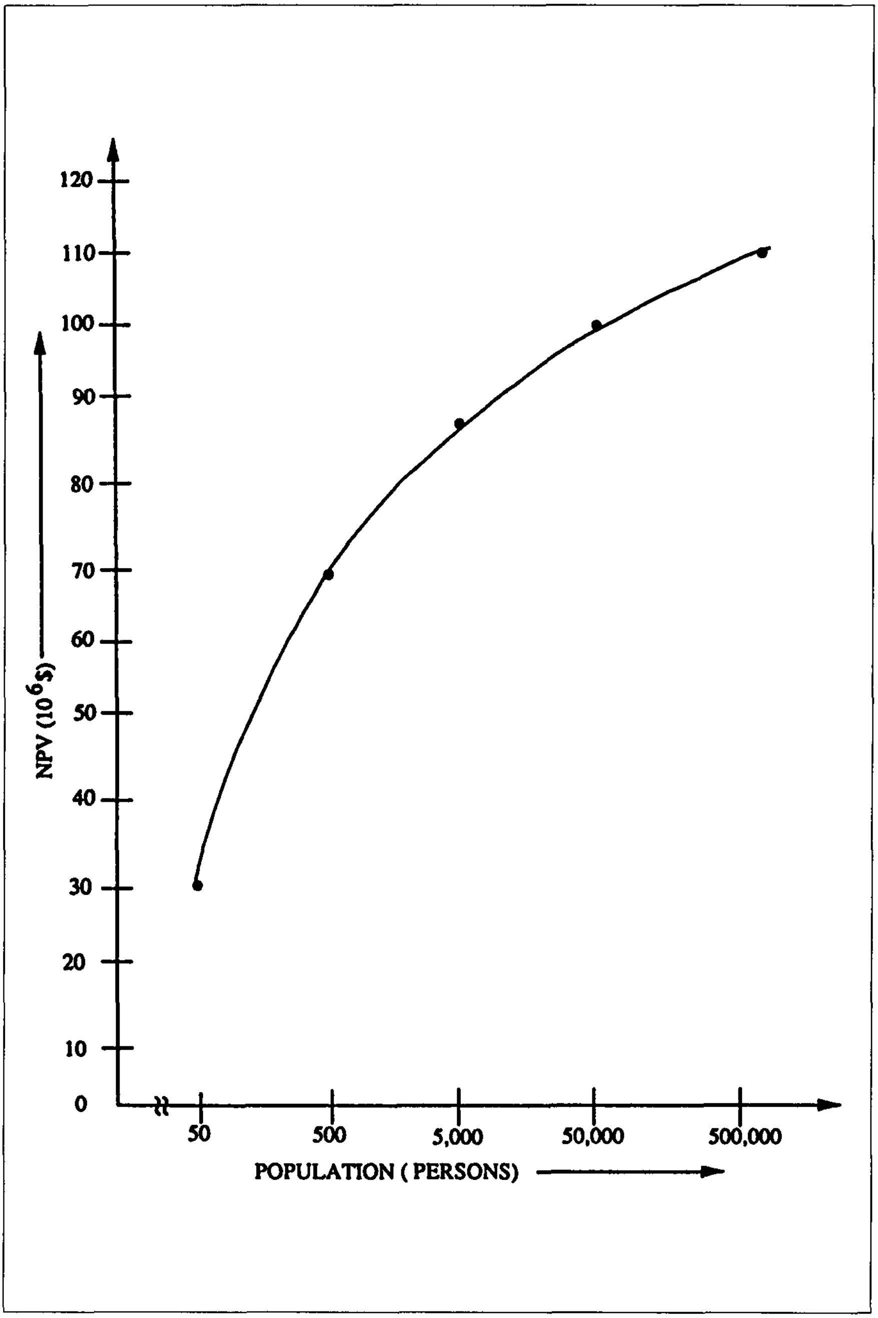

Figure 3. Waste availability: from graphical feedback sample packet.

slowly the NPV increases when we look at large populations. Beyond the 5,000 mark, there is little room to expand the digesters and other treatment facilities to handle the additional load. The value of the waste treatment continues to rise as the population density increases, but the quantity of waste treated can not be augmented.

The wastewater represents "free nutrients" in much the same way as the waste heat represents "free energy." Each has its greatest beneficial effect when the other is present in sufficient quantities.

Source Magnitude

How does the size of the source affect viability? Is there a profitability threshold? — Sources of waste warm water at different levels of magnitude were tried:

0.1 MW (commercial laundry)
1 MW (food processing plant)
10 MW (compressor station on gas pipeline)
100 MW (small power plant)
1000 MW (large power plant)

Figure 4 shows the results of these trials.

Sources smaller than 10 MW had very low NPV's. Their complexes were not large enough to take advantage of the economies of scale. The shortage of waste heat held them to a few acres or less in size. The NPV increased tenfold going from 10 MW to 100 MW. This slower growth in the NPV was due to increasing costs of warm water distribution and water recirculation. As modules are placed further and further from the waste heat source, a greater and greater share of the revenues are needed to transport the water for long distances.

Effluent Temperatures

Are these technologies feasible for low-temperature sources, or are high-temperature sources needed? — Waste heat streams were examined at 20°F intervals:

60°F		Process effluent
80°F	Once-through	
100°F	Closed-cycle	
120°F		
140°F	Compressor station	

It is difficult to associate a specific temperature level with a particular type of facility. Warm water at 100°F can be found at once-through plants, closed-cycle plants, or at various factories.

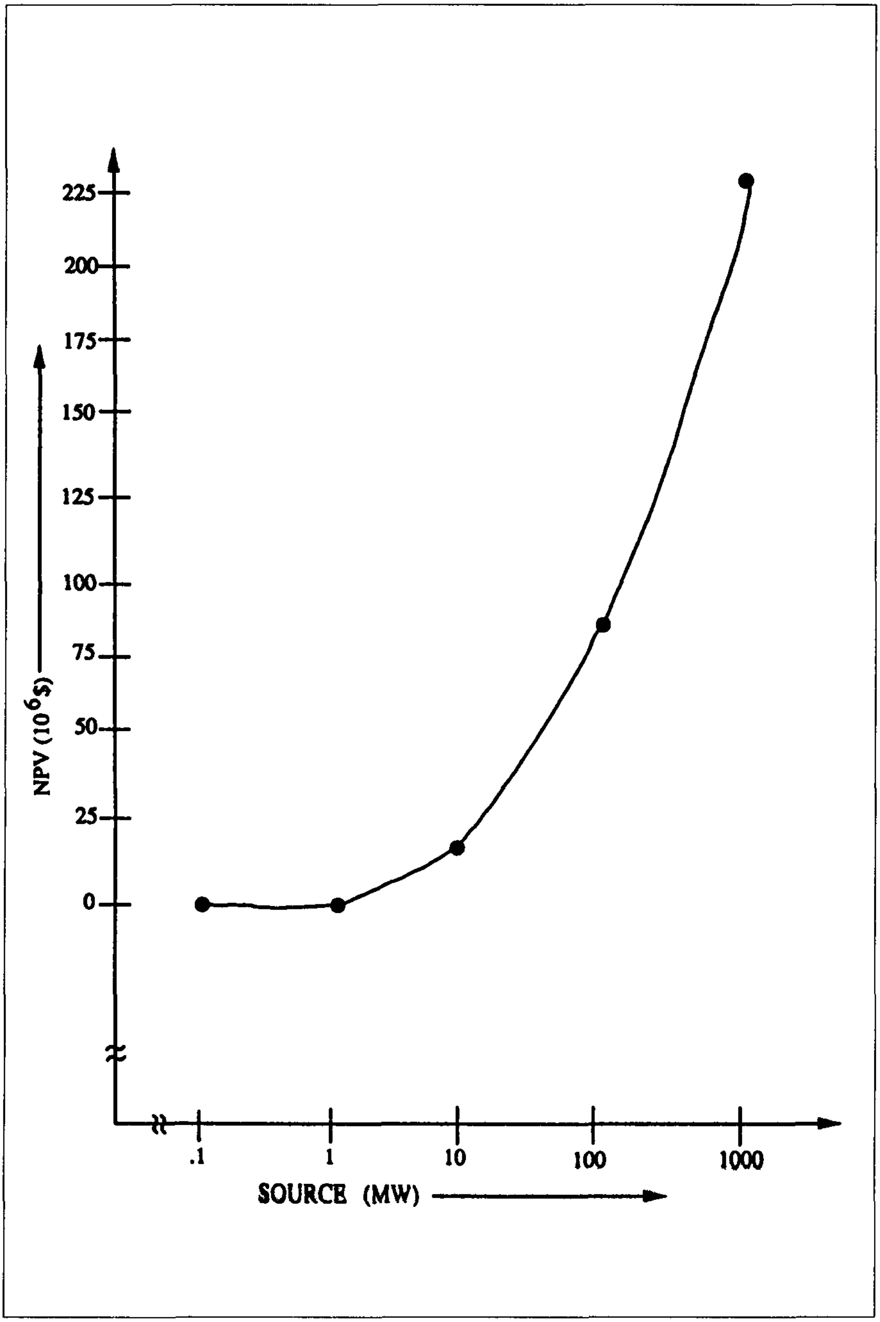

Figure 4. Size of the waste heat source: from graphical feedback sample packet.

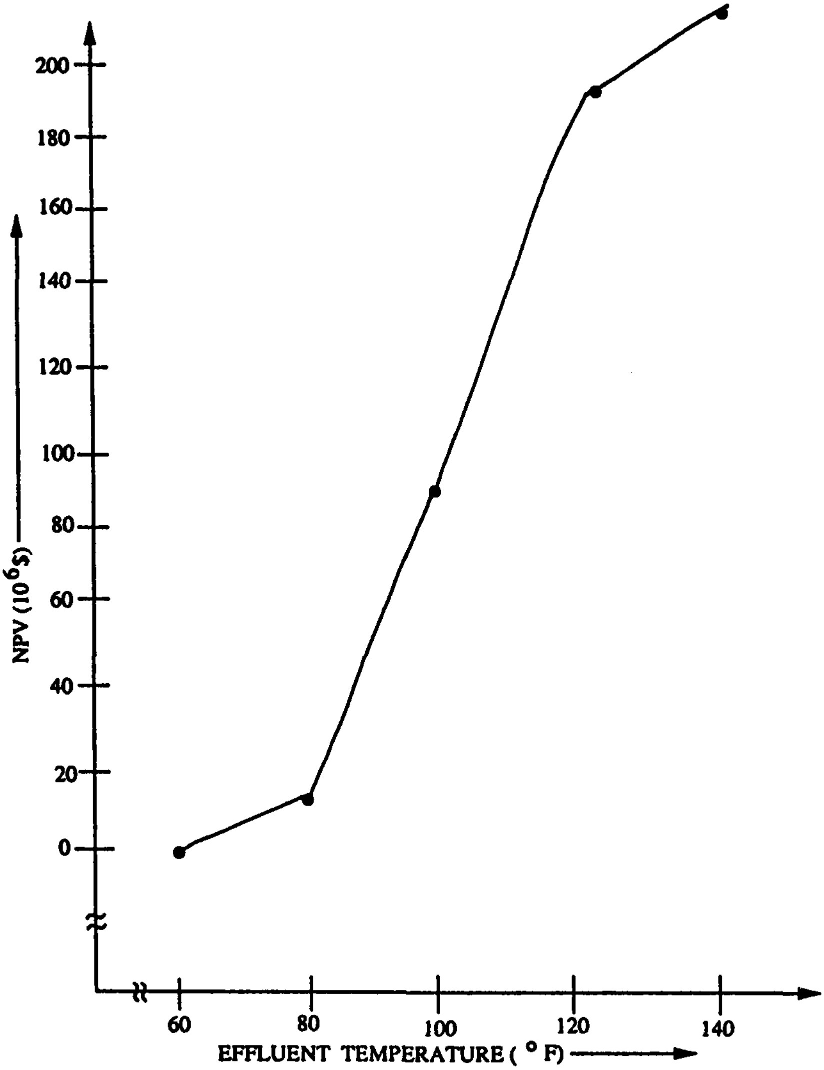

Figure 5. Thermal effluent temperature: from graphical feedback sample packet.

The effluent temperature depends on the ambient temperature of the water supply, the design of the plant, the utilization of the plant, and the point in the cycle at which the warm water is removed. The possibilities are numerous even for a single plant. Fortunately, for the moment we are only concerned with the temperature of the effluent and not the type of source which it came from.

Figure 5 shows an S-shaped curve as the NPV increases for higher temperatures. At 80°F and below, the complex has to struggle to break even. The NPV skyrockets dramatically as the effluent temperature increases from 80°F to 120°F. There are diminishing returns for effluent temperatures above 120°F.

At 80°F and below, tremendous quantities of water are required to maintain the desired growth temperatures. The supply costs are much higher, since the flows and distribution system capacity must be much larger. Above 100°F, flow requirements are much more manageable. Above 120°F, supplemental heating is nearly eliminated, and the complex can expand to take advantage of economies of scale.

The evaporative pad greenhouses are particularly susceptible to low effluent temperatures, even though plants only require 70°F or less. This is because of their direct-contact mode of heat transfer, which must overcome evaporative cooling. Their supplemental heating becomes too expensive.

Climate

How does climate affect the complex? What are the effects of heat, cold, and humidity? — Weather tapes were constructed for five cities which represent the major climate zones of the United States:

Minneapolis, MN	(North Central; continental)
Denver, CO	(Rocky Mountain; alpine)
Philadelphia, PA	(Northeast; maritime)
Atlanta, GA	(Southeast; subtropical)
San Francisco, CA	(West Coast; mediterranean)

Using the same 100 MW, 100°F, 100 percent reliable source under each set of climate conditions, the NPV-maximizing integrated complex was determined for each type of climate. Figure 6 shows these NPV results plotted by the mean winter temperature of each location.

The warmer the winter, the higher the NPV. In Minneapolis, large quantities of warm water must be circulated to withstand the brutal winters. In San Francisco, optimal temperature control is possible with meager waste heat inputs. Northern cities such as Minneapolis are also hurt by inadequate levels of sunshine. The lower insolation reduces the productivity of flowers, vegetables, water hyacinths, and algae. The solar gains are also decreased. It seems that, like many other enterprises, integrated waste heat utilization complexes will perform better in the Sunbelt. Nevertheless, there are some major advantages to locating in the Snowbelt. Fresh-picked gourmet vegetables are likely to be in short supply in Northern

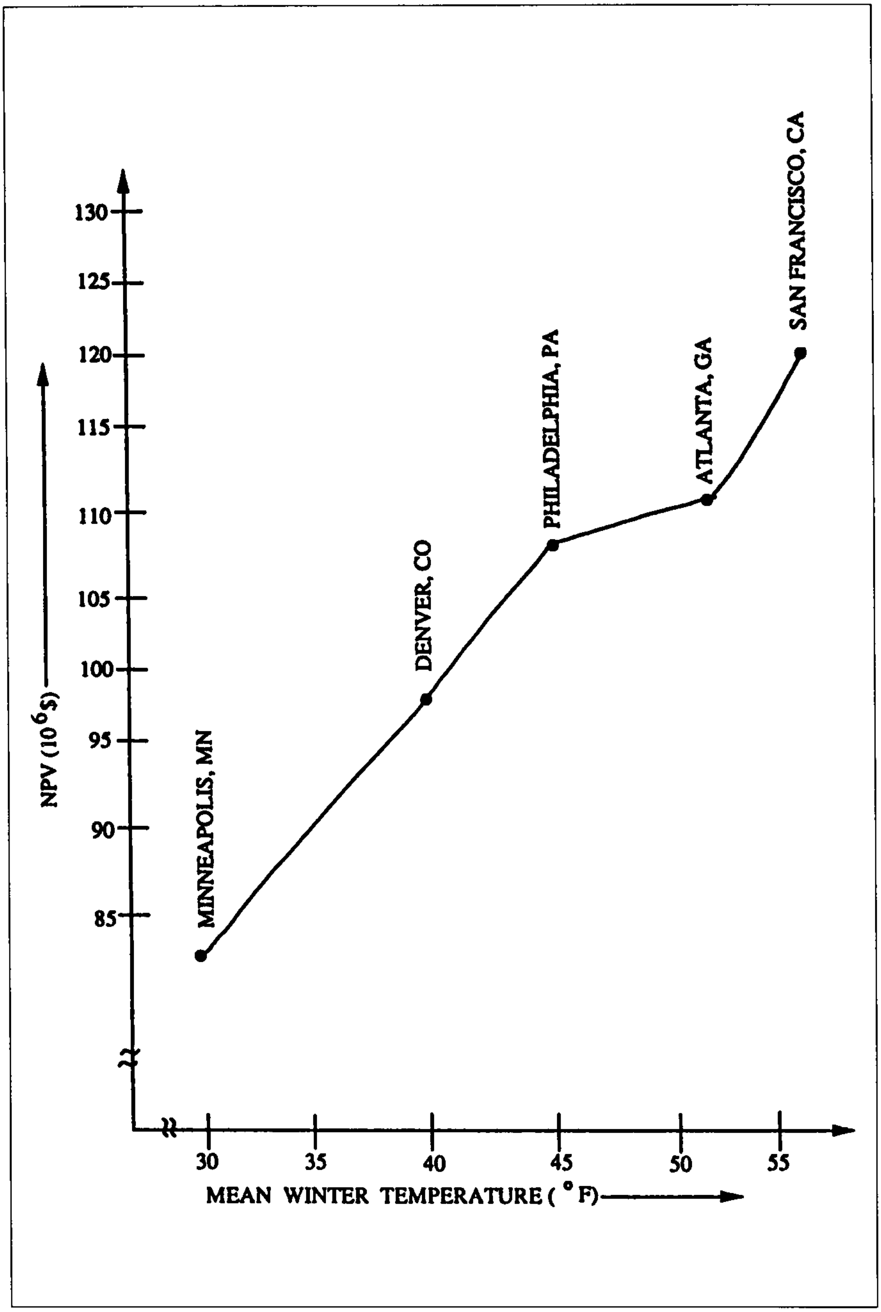

Figure 6. Mean winter temperature: from graphical feedback sample packet.

cities in the winter. A full evaluation would require the sort of detailed market analysis which is sorely lacking in this field.

There are other climate-related effects. Low temperature grain drying is greatly inhibited by the presence of high humidities. The grain takes more time to dry, and deteriorates more rapidly in storage. The viability of trout production falls precipitously as we move towards regions with high summer temperatures. Trout need cold water, and hot summers eliminate half of the year from production. One solution is to raise freshwater prawns, which are tropical shellfish, instead of trout during the summer months.

Site Configuration

How should the technology options be arranged on the site? Is there a discernible pattern? —The technology options are placed on the site in such a way that the overall piping and pumping costs are minimized. The most generic situation can be achieved by placing the source at the center of zones arranged as concentric rings. The zones contain larger and larger areas as one moves further away from the source. The "source" at the center of the site is the distribution point to which

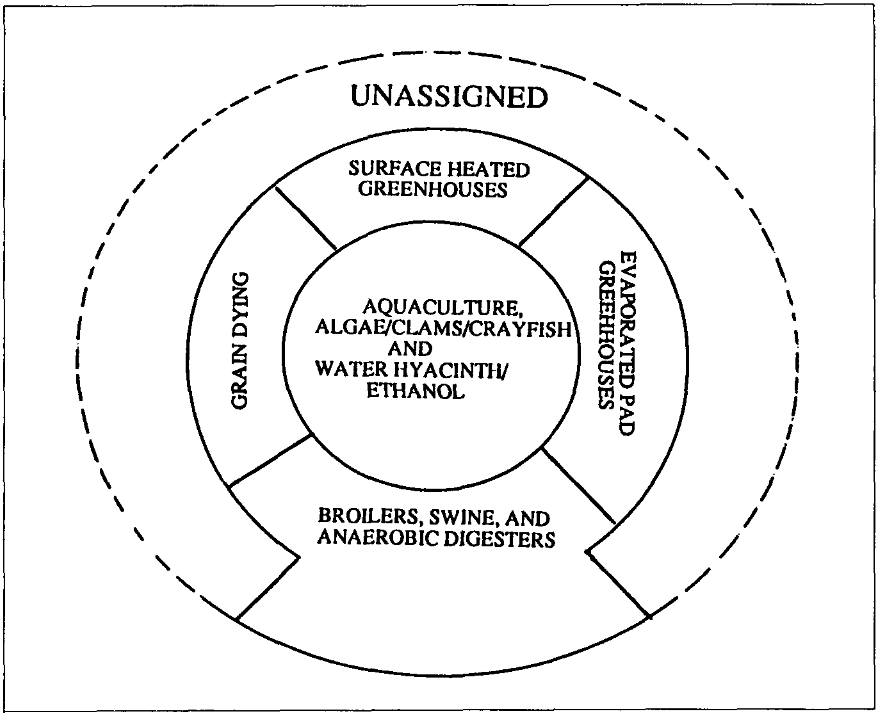

Figure 7. Site configuration: from graphical feedback sample packet.

the warm water is delivered; it is not necessarily the location of the power plant. The piping cost calculation allows for several supply pipes for each zone. They should radiate like spokes on a wheel, to minimize the distance between each technology module and its main supply line.

The site was assumed to be a bowl-shaped depression with a 5 percent slope. This leads to a slight elevation differential between the central distribution point and each of the zones. Since the water must be pumped in two directions, the absolute value of the difference in elevations is what matters. This makes the outward appearance of the topography somewhat arbitrary; a group of plateaus or a constant tilt would have served just as well. Note that the elevation within each zone is assumed to be uniform. Figure 7 shows the optimal site configuration for a 100 MW power plant in the Philadelphia area. The wastes of a community of 5000 persons are available to the facility. The thermal effluent is 100°F and 100 percent reliable. There are 100 acres of land available.

The aquaculture facilities, which include the fish raceways, the algae ponds, the clam/crayfish ponds, and the water hyacinth/ethanol modules are concentrated at the center of the site. Recall that these aquaculture and pond waste treatment technologies are all interconnected and so are considered as a group for the purposes of siting.

At the fringes of the site are the grain drying modules, the greenhouses, and the broiler and swine shelters which are accompanied by the anaerobic digesters. The broiler and swine shelters, along with the anaerobic digesters, extend into the outermost zone, which is largely unoccupied.

The positioning of the technologies is determined by their flow requirements. The aquaculture facilities and the waste treatment ponds require large amounts of water because their surfaces are exposed to the atmosphere (with the exception of the water hyacinth ponds). The greenhouses, the grain drying, the livestock shelters, and the anaerobic digesters are enclosed and insulated, so they have lower flow requirements.

The reason why the flow requirements determine the positions is simple. The pumping and piping costs are all proportional to the flow requirements. By placing the high-flow modules close to the central delivery point and the low-flow modules far from the central delivery point, the warm water distribution costs are kept at a minimum.

CONCLUSIONS

The beneficial use of thermal effluents has an intuitive appeal. Rather than increasing ecosystem stress due to thermal pollution, we are able to derive tangible benefits in the form of increased food production. However, quantifying these benefits has proved elusive.

We identified aquaculture, greenhouses, livestock shelter, crop drying and wastewater treatment technologies which could benefit from the application of waste heat. In order to evaluate which options are best suited for specific power plant sites, we developed simulation models for each technology.

We explored the interconnections between these technologies and discovered extensive non-linear relationships. In order to analyze the profitability of integrated waste heat utilization complexes under various conditions. We applied the Response Surface Methodology (RSM). This enabled us to determine the optimum configuration for each site, in spite of the large data requirements and complicated models.

We conducted some sensitivity analyses in order to examine the performance of an integrated complex under various conditions. As a result of numerous simulation experiments, we have formulated the following guidelines for waste heat utilization:

1. Waste heat should be available 75 percent of the time or more in order to avoid excessive backup heating costs.
2. The complex should provide waste treatment for at least 500 persons to bring in additional revenue and supply nutrients for biomass production.
3. A 100 MW generating station is large enough to support a complex which is able to take advantage of significant economies of scale.
4. Effluent temperatures of 38°C (100°F) or higher are needed to keep thermal effluent flow requirements down to practical levels.
5. Grain drying should be excluded in climates with a mean relative humidity above 65 percent.
6. Trout production should be discontinued during hot summer months but a warm water organism can be grown in its raceway until cold weather returns.
7. Heated aquaculture ponds should be located near the point of waste heat delivery, while enclosed structures may be located further away. The exposed water surfaces lose heat rapidly and require higher thermal effluent flow rates as compensation. Distribution costs are minimized by placing high-flow aquaculture facilities closest to the source of the thermal effluent.

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