J. ENVIRONMENTAL SYSTEMS, Vol. 19(2) 95-114, 1989-90

ASSESSMENT OF WASTE HEAT UTILIZATION TECHNOLOGIES: OVERVIEW*

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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. Some of these applications have been commercially successful, but further progress is contingent upon attracting investment, adapting to power plant operations, and resolving legal uncertainties. In this research, the crucial question of choosing which of these technologies are best suited for any particular power plant is considered. Given information on costs, climate, and the waste heat source, carefully selected trial configurations can be simulated to find the optimal design for a specific site. In this article, a procedure based on the technique known as response surface methodology is outlined. Forthcoming articles in this series will provide detailed descriptions of the models for each technology option.

INTRODUCTION

Every year, American power plants discharge about 11×10^9 GJ (11×10^{15} BTU) of low-grade, "waste" heat. This heat is rejected to the atmosphere through cooling towers and ponds, or deposited in a nearby lake, river, or

* **Editor's Note:** This issue presents the first two in a series of eight articles on uses of waste heat from power plants. In this article, a method for the site-specific assessment of technology options and a summary of findings are presented. The following article analyzes the suitability of using waste heat for aquaculture systems. Future articles will describe models for simulating the greenhouse, livestock, crop drying, and wastewater treatment components of an integrated waste heat utilization complex.

doi: 10.2190/R636-X1A9-07E7-FR89
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estuary as warm water at 15 to 43°C (60 to 110°F) [1]. This large quantity of heat is an unavoidable by-product of thermal power generation, since it is necessary to condense steam in order to complete the thermodynamic power cycle. About 50 percent of the total energy output from fossil fuel plants, and 66 percent of the total energy output from light-water nuclear plants, is lost through the condenser cooling water. Approximately 75 percent of industrial water is needed to cool steam-electric power plants [2].

The value of this thermal resource has not gone unrecognized. Suggestions for the use of this warm water include: aquaculture in which the growth of aquatic organisms is enhanced by maintaining optimal temperature; greenhouses in which temperature and humidity control are achieved by heating and evaporative cooling; soil warming to extend the natural growing season; biomass production (primarily for methane or fuel alcohol generation); water systems including water supply and wastewater treatment; livestock shelters for environmental control; food processing such as washing, crop drying, and curing; agricultural uses including frost protection and irrigation; and, district heating to provide a preheat for stream loop feedwater.

A number of obstacles exist which limit the use of waste heat utilization technologies [3]. A consequence of these constraints is that some applications have reached the commercial stage, while others remain on the drawing board. Numerous studies, demonstrations, and pilot scale projects are described in the literature [4]. Among the viable commercial projects are the following:

- International Shellfish Enterprises, Inc., in which effluent from Pacific Gas and Electric's plant at Moss Landing, California, is used to rear clams and oysters through larval development to seed size, for stocking in shellfish beds;
- Sherco Greenhouse Complex–Northern States Power has signed contracts with horticulturists to supply waste heat and sites for plastic greenhouses producing vegetables and flowers; and
- Electric Katfish Farms–Catfish (27,000 kg (60,000 lb) per year) are raised in thermal effluent at Texas Electric Service's Morgan Creek Station.

In spite of the flurry of research activity in this area, few studies have been conducted to consider the crucial question of choosing which technologies are best suited for a particular plant. Given the unique characteristics and operations of different power stations, along with the wide range of waste heat utilization possibilities, one may conclude that the technology selection process is not straightforward. There is a need for a system to aid utility managers, who are generally unfamiliar with agricultural technology, to evaluate their plants' potential as suppliers of warm water to one or more users. From the standpoint of the researcher, a method for making comprehensive assessments of site-specific waste utilization potential is long overdue. The literature in this area is very diffuse, and there is a pressing need to unify this knowledge into a common framework.

Our objective is to present a procedure which will enable investigators to find the most profitable combination of waste heat applications. Investigators can provide site-specific data, operating data, climatological data, and relevant prices to obtain an estimate of the optimal configuration for one or several locations.

The central purpose of this research has been to develop and demonstrate a selection system for the assessment of waste heat utilization technologies. This was achieved by identifying viable options, developing a theoretical framework, designing a practical selection system, documenting this system, and conducting sensitivity analyses using this system. This procedure is a major advance over the tools previously available to researchers. Once a scenario has been postulated, the design and operation of a complex under these conditions may be simulated. A wide range of alternatives can be explored in this manner. This flexibility is possible because there are two distinct sets of models. The waste heat source model is sufficiently generic to be adapted to the needs of most investigators. The various waste heat utilization models, which are self-contained but dependent on the output of the source model, are used to achieve the best combination of end uses.

The entire spectrum of waste heat utilization technologies was narrowed to fifteen options. These are summarized in Table 1, and include aquaculture (catfish, prawns, tilapia, and trout), evaporative pad greenhouses (flowers, vegetables), surface heated greenhouses (flowers, vegetables), livestock environment (broilers, swine), low temperature drying (grain storage and crop drying), and wastewater treatment (algae/clams/crayfish, anaerobic digestion/methane and water hyacinth/ethanol). An integrated waste heat utilization complex containing all fifteen options is shown in Figure 1. This complex may be adapted to a specific site by varying the extent to which each option is used. Some options may be deleted entirely at a particular site.

The procedure presented here allows the investigator to determine the optimum mix of these waste heat utilization options, based upon site-specific inputs such as the generating plant waste heat output profile, site characteristics, climatological data, and implementation costs. This has been accomplished by developing (or using available) models for describing each option and by using response surface methodology to find the optimum mix, with net present value as the measure of attractiveness of a particular configuration. The research effort has been an extensive one [5]. It is presented here as a series of papers, with this one serving as an introduction. In the following paragraphs, the focus of the research is defined and the general results and conclusions summarized. Subsequent contributions will focus on the individual waste heat utilization models and on how these models have been combined and used for optimization.

Table 1. Waste Heat Technology Options to be Considered

Options	Utilization Technology
1. Prawns 2. Trout 3. Catfish 4. Tilapia 5. Diseasonal trout/prawns	Aquaculture
6. Vegetable greenhouse 7. Flower greenhouse	Evaporative pad
8. Vegetable greenhouse 9. Flower greenhouse	Surface heated
10. Broilers (growing) 11. Swine (brooding)	Livestock environment
12. Grain storage bins	Low-temperature drying
13. Anaerobic digesters/methane 14. Algae/clams/crayfish 15. Water hyacinth/ethanol	Wastewater treatment

WASTE HEAT UTILIZATION TECHNOLOGIES

In order to keep the selection problem to a manageable size, only the most promising technologies have been considered. In this section, a brief review of the rationale used to narrow down the hundreds of possibilities to the fifteen options (Figure 1 and Table 1) is presented.

Aquaculture

Catfish and trout are excellent candidates; their culture requirements are well understood, and established markets exist for both [6]. Freshwater prawns are more difficult to raise, but can be sold at very high prices [7]. Their growing popularity among consumers and need for warmth add merit to this choice. Tilapia grow rapidly and have a reputation for being "nearly indestructible." They thrive on very inexpensive feeds, and thus have been promoted as a "protein source of the future" [8].

Lower heat requirements and reduced biological stress are possible by growing warm water species (e.g., prawns) in the summer and cold water species

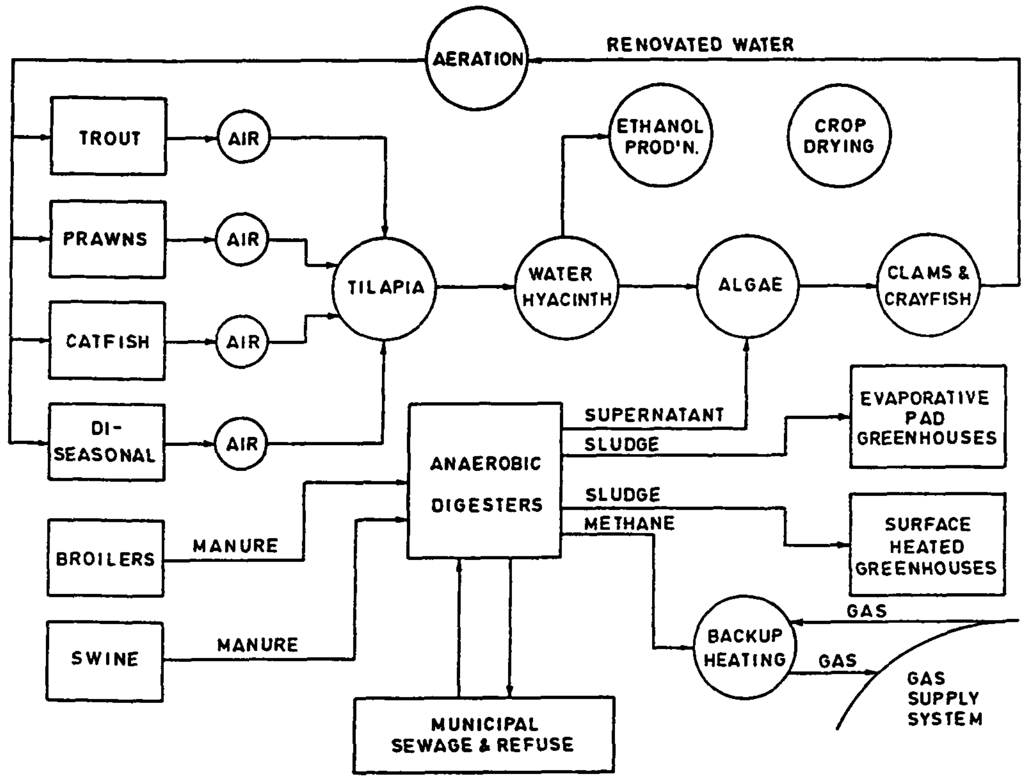

Figure 1. Spectrum of integrated waste heat utilization options.

(e.g., trout) in the winter. This diseasonal approach has been advanced by Guerra, Godfriaux, and Sheahan, among others [9].

We have eliminated from further consideration carp which suffer from very low market prices, and perch and striped bass, which both have proved very difficult to culture [7]; and, eels, which are highly susceptible to disease, parasites, and pollution [10].

Wastewater Treatment

Algae ponds are an established means for nutrient recovery. When combined with anaerobic digesters, they provide effective waste treatment at a relatively low cost. Water is oxygenated and odors are eliminated [11]. Algae have also been included based on their value as a low-cost food for salable clams and crayfish. However, waste-grown algae are considered to be unpalatable and unsanitary for direct human consumption [12].

While both water hyacinth and duckweed are amazingly prolific, the high water content and excessive surface area requirements of the duckweed make it less desirable than the water hyacinth. A water-hyacinth-based ethanol production process will be considered, along with production of methane gas by anaerobic digesters. Ethanol and methane gas are both valuable fuels.

These biological treatment procedures are applicable to most animal wastes. Even the undigested food ("paunch") removed from animal stomachs, which is a major disposal problem at meat-processing plants, can be successfully treated by these biological means [13].

Greenhouses

The options here are two-fold: first, what type of greenhouse to build; and second, what sort of plants to raise in them. While many different greenhouse designs have been tried, the evaporative pad-heated and surface-heated greenhouse have received the most attention. Evaporative pad-heated greenhouses use direct-contact heat exchangers. Specifically, air is forced through spongy pads which are constantly supplied with warm water. Surface-heated greenhouses use a film of warm water, which is trickled over the outside of the greenhouse, to heat the interior. This seems a bit wasteful, but when warm water is plentiful, this can be the most cost-effective means of temperature control.

The choice between the two greenhouse types is not clear-cut. The overall cost of each type is somewhat dependent on site-specific factors such as effluent temperature and waste heat reliability. Prevailing weather conditions may have a major impact. Therefore, both of these heating methods will have to be considered.

Among the types of vegetables which may be grown in the greenhouses, tomatoes, leaf lettuce, and cucumbers all have high wholesale value per acre-year.

However, the high temperatures required by cucumbers for full growth make them the least attractive of the three. The varieties of tomato and lettuce which were developed in warm, humid areas perform best under wet, steamy greenhouse conditions [14]. As for flowers, orchids, roses, and chrysanthemums are all in great demand. All three of these flowers have been grown successfully in greenhouses for many years. For the purposes of this study, the tomato and hybrid tea rose have been selected because they are in consistently high demand; they are widely reported on in the literature; their prices are relatively stable; and, their market is relatively uniform throughout the United States.

Livestock Environment

Animals frequently have different temperature requirements for their reproductive and growing-out stages. Poultry do not need high temperatures in order to lay eggs [15], but their weight gain is significantly accelerated by supplemental heat as they are grown to broiler size. Conversely, swine do not require supplemental heat to grow at an acceptable pace [16], but can not brood their young in uncontrolled environments. Therefore, environmental control is advisable for broiler growing and swine brooding, but not for broiler brooding and swine growing. Cattle generally do not need any supplemental heating at all [17], and so are not further considered in this research.

Industrial Processes and Food Processing

These applications are too numerous to evaluate individually. Also, there is a limited need for any given type of facility; one rhubarb factory per state is more than enough. Unfortunately, nearly all of these applications require supplemental heating. This cuts heavily into the potential profits from waste heat utilization. For those applications where low-grade heat is needed, the facility often has sufficient thermal effluent from its own operations which it can use instead. Processing operations are better viewed as sources of waste heat than as potential recipients.

One major exception is crop drying. Many crops can be dried successfully at low temperatures. In addition, nearly all regions of the country require grain drying and storage. Therefore, the option of low-temperature grain drying and storage has been included.

SOURCE OF WASTE HEAT

For the purpose of this analysis, waste heat will be defined as the thermal energy contained in the water discharged from industrial plants. Waste heat at temperatures below 49°C (120°F) is generally referred to as low-grade, low-quality, or low-temperature waste heat, while high-grade, high-quality, or high-temperature waste heat is in the vicinity of 82°C (180°F). Most cogeneration facilities use high-quality waste heat. These applications, which include steam loops and pre-heating for hot water supply, are well understood. They differ considerably from low-temperature applications which are the focus of this research. Relative to high-grade waste heat, little attention has been paid to the possibilities of using low-grade waste heat. Nearly all thermal effluent is produced by electric generating stations as condenser cooling water.

There are two basic types of cooling systems which are employed by power plants: once-through and closed cycle. In a once-through system, water which has been pumped from a nearby lake, river, or estuary is passed through the condenser where it removes heat from the turbine exhaust steam, causing the steam to condense to a liquid. Enormous quantities of water—about 600,000 gallons per minute for a 1000 MW fossil-fired plant—are required [18]. Virtually all of the water is returned to its source, so this is regarded as a non-consumptive use. However, the water is 6–17°C (10–30°F) warmer than it was originally. It is this temperature rise which a waste heat utilization project aims to exploit.

Closed cycle systems maintain a supply of water on-site and re-use this water repeatedly. In practice, there are evaporative losses which require that new water be added during each cycle as make-up; this is on the order of 2.5 percent of the water being circulated [19]. Water is also lost during periodic flushing-out of solids, which is known as blow-down.

Before being returned to the condenser, the water must be cooled; there are several mechanisms for achieving this. Cooling ponds, spray cooling, or cooling towers may be used. They will effect a drop in temperature ranging from 18 to 21°C (32 to 38°F) [20]. The notion here is to use this warm water on its way to the cooling facility. Because of environmental concerns, recent trends have been away from once-through systems and toward closed cycle systems.

Magnitude of Potential Energy Recovery

About 50 percent of the total energy output from fossil fuel plants, and 66 percent of the total energy output from light-water nuclear plants, is lost through the discharge of about 11×10^9 GJ (11×10^{15} Btu) of waste heat every year. This is more than enough energy to heat every home in America [21]. The implications of using even a small fraction of this heat are enormous. Approximately 15 percent of the total United States energy consumption is discharged by power plants in the form of waste heat. Even if only 10 percent of this amount were utilized, an annual savings equivalent to more than 250 million barrels of crude oil would result [22]. Of course, comparisons like this can be misleading. A barrel of crude oil has a higher value than a ton of lukewarm water containing the same energy. When oil is burned, it can provide a much larger temperature difference, and thus do work with a much higher overall thermodynamic efficiency.

The question which we ought to ask is whether there are some instances in which we are now using a high-quality fuel such as oil where we could be using waste heat instead. In a world with limited supplies of energy, it is not wise to burn kerosene to heat a greenhouse to 16°C (60°F) when a nearby power plant is releasing 26°C (80°F) water into the local river. Note that this statement is made strictly from the standpoint of energy availability, and does not consider some important issues such as whether it would be cost-effective for the greenhouse to switch from kerosene to waste heat.

While it is an attractive concept, there certainly are some fundamental problems with the idea of using waste heat to satisfy all of our low-temperature thermal needs. For example, once-through systems in particular put out cooler water in the winter than in the summer, whereas most demand for low-temperature heat occurs in the winter. The delta-T of, say, 10°C (18°F) will raise the water from 21°C (70°F) at the intake to 31°C (88°F) at the outlet during the summer, but from 5°C (41°F) to only 15°C (60°F) during the winter. This underscores the need for a technology selection algorithm which will account for seasonal fluctuations in waste heat supply and demand.

One must also recognize that the flow of waste heat may be interrupted frequently. While utilities run their least expensive base load units as much as possible, there are still scheduled outages for maintenance and forced outages because of equipment failure. Nuclear units must be shut down for refueling. Peak load units are expensive and so are shut down whenever possible. Therefore, a station with several different units will provide a more steady supply of waste heat, since rarely will all of the units be shut off at the same time.

Types of Sources to be Considered

Most waste heat projects have little effect on the operations of the host power plant. First of all, plant operators are understandably reluctant to make any major changes in plant operations, unless these actions can be taken without cost and without disrupting normal procedures. Second, these projects use only the heat in water which has been disposed of or set aside for cooling anyway. Third, most of the projects currently underway use only a small percentage of the heat that is rejected by the power station. After the initial construction, the main issue requiring coordination is the plant's chemical treatment schedule; even this becomes a minor consideration if heat exchangers, rather than direct contact with the growing environment, are used [7].

Thus, we are primarily interested in when the water is available, at what temperature, and in what volumes. The type of plant is of little concern to us, except as it affects the levels of various contaminants in the water.

In practice, most industrial plants have tightened up their water usage considerably by "cascading" hot water through processes requiring successively lower temperature until it becomes quite cool and is discharged or used consumptively. These conservation measures have eliminated much of the heat release which once existed [23]. Nearly all water containing waste heat is found at electric generating stations, where the cooling requirements are so immense and the secondary applications of low-grade heat currently so uncommon.

Some researchers, such as Olszewski, Hildebrand, and Reed, have proposed benchmarks [24]. They concluded that 27°C (80°F) is the minimum water temperature required for economic feasibility of waste heat greenhouses. This rule of thumb is useful as a means of targeting specific plants for assessment, but ignores factors such as land availability, market proximity, and duration of waste heat output. These constraints, along with the climate, will vary considerably from location to location, and require the detailed attention which this research is intended to expedite.

Some existing cooling ponds at generating stations may be used for aquaculture or waste treatment with little or no modification. However, some ponds may have good steady-state performance (high heat dissipation overall), but poor transient performance (ability to damp short term temperature fluctuations) [25]. Fish are quite sensitive to temperature perturbations, which may inhibit their growth or even kill them. While a detailed analysis of the suitability of existing cooling ponds is beyond the scope of this research, such uses ought to be considered as part of the overall evaluation.

The cost of cooling facilities avoided by relying on the cooling properties of waste heat facilities should also be included; plants with unmet cooling needs are more attractive, of course, than those in which no such savings are anticipated.

INTERFACING BETWEEN POWER PLANTS AND WASTE HEAT SYSTEMS

Technical Obstacles

Although mechanical cleaning (brushes or abrasive spheres) and thermal cleaning (water flow reversal) techniques have been tried, chemical defouling is a more efficient and less expensive means for removing deposits in power plant cooling systems. Unfortunately, many of these chemicals are highly toxic to fish and other organisms which may be integral components of waste heat utilization technologies. For example, areas with sustained chlorine concentrations higher than 0.02 mg/L generally have no fish population, even though much higher concentrations (0.5 mg/L) can be survived for short periods of time (e.g., fifty minutes by trout) [26].

While once-through systems rely on chlorination, closed-cycle units use biocides and corrosion inhibitors which may include chlorine dioxide, ozone, bromine chloride, acetate, n-dodecylquandine, n-dodecylquandine hydrochloride, chlorophenols, quaternary amines, organometallic compounds, chromate plus zinc plus phosphate, phosphate scale inhibitors, and copper corrosion inhibitors [20]. A comprehensive evaluation of these substances is beyond the scope of this research; however, it is clear that waste heat supply interruptions due to these cleaning operations will have to be considered.

A number of technical constraints related to the use of green plants have been identified. Aquatic plants have a very high water content; their bulk has limited the development of harvesting methods [27] and processing techniques [28]. While the warm, humid environment of the waste heat greenhouse is conducive to plant growth, it also encourages the more rapid growth and spread of plant diseases [29]. Cold tolerance is also reduced [30].

Modern biological and chemical treatment methods have been demonstrated to be effective enough to prevent most of the potential health problems associated with direct human consumption of products produced in wastewater [31]. There has also been concern that warm water encourages the spread of amebic meningoencephalitis. At least two types of amebae (*Naegleria fowleri* and *Acanthamoebae* spp.) have been identified which are associated with thermal discharges and cause fatalities after entering the bloodstream. *N. fowleri* enters through the nostrils of swimmers, but may be controlled by chlorination. *Acanthamoebae* spp. are highly resistant against chlorination, and are difficult to control [32].

Olszewski and Bigelow found that half of all nuclear stations have enough land to utilize all of their reject heat, and that in general land constraints are not the limiting factor [33]. A 1000 MW plant would require 400 ha (1000 ac), on average, for complete use of its effluent.

Economic Factors

Financiers are reluctant to invest in unusual activities such as aquaculture, where laws are ambiguous, professionals are few, and much of the technology is untested. The assets of the enterprise are often meager, the equipment very peculiar, and the land of marginal value or even underwater. Distributors seek a constant, year-round supply of uniformly high quality goods, preferably in large quantities; it is difficult to get the fish to cooperate. Commercial producers usually have to develop their own customer base among restaurants and stores [34].

In addition, aquaculturists must compete with producers who catch their fish from lakes and streams without feeding costs, and greenhouse owners must compete with growers who ship their produce from Florida and Mexico without the cost of building greenhouses. Thus, the additional costs of running these intensive culture systems must be less than the cost of transporting the item from the area where it is easiest to produce. Alternatively, the waste heat culturists may produce an item which is of better quality and freshness; consumers will pay a premium for such food [35].

Transportation costs may also work against the culturist, as when the power plant is remotely located or when growers must convey their crops for great distances to be dried at the plant. Labor, security, and construction costs will be higher than those required for traditional agricultural enterprises [7].

Operators who decide to locate at a power plant must often make a sizeable investment, or a long-term commitment, in order to justify the considerable expense of retrofitting the plant discharge system, constructing a distribution network and other facilities, and the opportunity costs of dedicating the land to a new purpose. Johns *et al.*, concluded that it is not cost effective for most greenhouse operators to relocate, since the fuel savings typically provide an internal rate of return of only 9.7 percent over twenty years, when moving costs are considered [36]. Emerging technologies may change this; an example would be the development of spray-on rubberized liners, which has revolutionized the construction of new ponds suitable for aquaculture [37].

On the other hand, consider the Japanese greenhouse industry. It was crippled in 1974 by the combined impact of higher energy costs for heating and ventilation, and new regulations regarding the disposal of the PVC and polyethylene sheeting used in the construction of temporary greenhouses. The 110,000 metric tons (121,220 short tons) of plastic must be discarded and replaced every year; careless dumping led to the new laws requiring operation of melting-down or smoke-free-burning plants which have increased operating costs substantially [38].

Reliability of the waste heat source is another crucial consideration. Intermittent operation and periodic contamination of the water with biocides may require that a backup heating system be installed. Olszewski calculated an initial investment cost of $4 million with annual operating costs of $400,000 to backup the waste heat output of a 1000 MW plant [39].

Legal, Attitudinal, and Policy Aspects

Most aquaculture laws exist at the state level, and reflect the traditional conflict between farmers, fishermen, and aquaculturists. In many states, aquaculturists can not receive clear title to the water bottoms which they are tending, and so their shellfish beds remain fair game for fishermen. Many state statutes are simply out of date; for example, all fish in Louisiana are property of the state. This raises legal questions when fish are cultured, stolen, or escape [34].

Many utilities have at least one attorney working full-time on water regulatory problems [40]. Many waste heat project operators cannot afford such considerable expenses, and it is difficult to locate experts in this field [41].

The federal Food, Drug, and Cosmetic Act (FDCA) restrictions on food additives do not apply if heat exchangers separate plant effluent from the growth media; if heat exchangers are not used, some chemicals and pipe residues may be absorbed, for which FDCA provisions are vague. The Delaney Clause, which prohibits any addition of radionuclides to food, must be adhered to by those utilizing nuclear plant effluents [42].

Uncertainty also clouds the regulatory treatment of revenues and expenditures by the utility on waste heat projects [43]. It is difficult to anticipate potential problems with untested technologies, which complicates the drafting of sales agreements and contracts [44]. On the positive side, local residents may view these projects more favorably than cooling towers [45]. Public acceptance of food grown in effluent has not been a serious problem [46].

METHODOLOGY

Models describing the behavior of each of the subsystems (see Figure 1) have been developed. In general, these have been derived or adapted from models previously described in the literature. The details of the submodels are the subject of later reports in this series. The submodels are used to simulate the operation of each of the technologies. For a given technology, we estimate the outputs resulting from a given set of inputs, and, from this, we calculate the profit which that technology contributes to the overall profit of the complex, when operated at that level of output. (See Figure 2.)

Each option is modeled by a series of energy balance, mass balance, and productivity functions. For example, the aquaculture energy balance equation would keep track of the waste heat being added to the raceway to make up for the heat losses to its surroundings. The amount of feed added to the water must equal the mass of the fish harvested and the fish wastes combined. How much of the feed becomes fish tissue and how much becomes waste products is determined by the productivity function. The energy balance equations depend on the raceways and ponds, not on the species living in them, whereas the productivity functions are different for each species.

The greenhouse and livestock shelter models likewise require functions describing their heat exchangers, since the amount of heat exchanged depends on variables such as the temperature difference between the warm water and the air. The water hyacinth/ethanol option requires a hyacinth production model and an ethanol production model, since two distinct processes are involved.

Linkages

These components cannot operate independently. They all rely on a central distribution network to provide them with warm water for heating. There are also interconnections between facilities. Likewise, the submodels are closely linked. For example, as water is recirculated through the aquaculture facilities, the wastes of the fish raceways become nutrients for the water hyacinth and algae ponds. These in turn provide clarified water to be returned to the fish

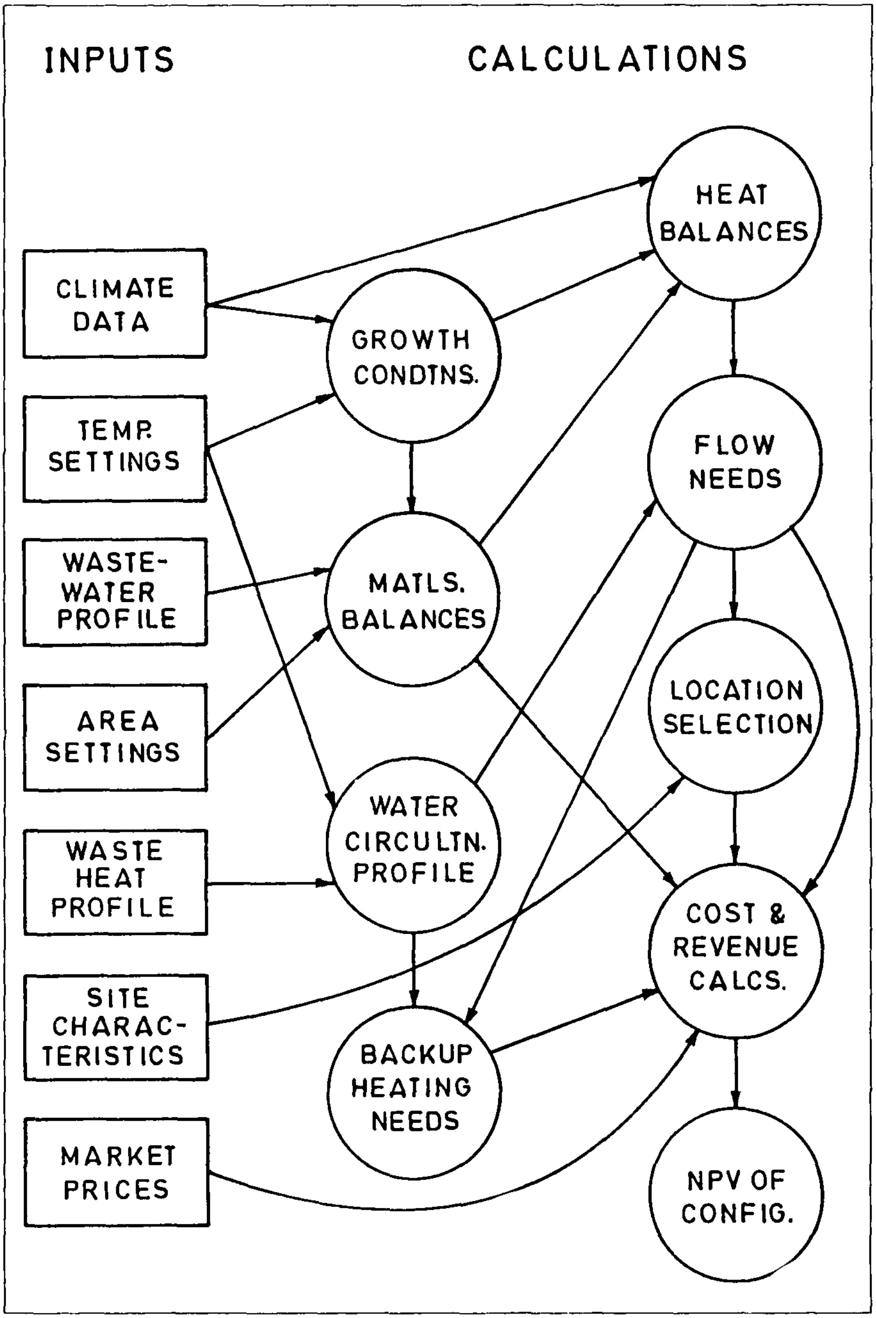

Figure 2. Overview of waste heat utilization assessment methodology.

rearing operations. The wastes of the livestock facilities are treated by the anaerobic digesters. The methane produced by these digesters can be burned to provide backup heating for the whole complex, or sold to the outside world (see Figure 1).

Methodology for Technology Selection

For a given technology, the size which yields the largest net present value (NPV) is selected. The situation becomes complicated as the number of options is increased because the options are interrelated and because the linkages between the options introduce several non-linearities. For example, the size of the aquaculture facilities relative to the size of the methane digester facilities determines the BOD (biochemical oxygen demand) concentration of the influent to the algae ponds. The size of the algae ponds is a non-linear function of the BOD concentration. Also, the size of the methane digester facilities is a non-linear function of the proportions of manure from the livestock facilities and wastewater from outside the complex. The power requirements of the aeration facilities are not a linear function of the relative sizes of the aquaculture facilities. Lastly, the location assignments have a major impact on the heat distribution costs and hence on the overall NPV, but the best location for each option depends strongly on the mix of options being considered.

Therefore, we must deal with the entire waste heat utilization complex as a whole. It is relatively simply to calculate the NPV of the entire system, once we specify the group of technologies to evaluate. Now, the results of one option may serve as inputs to another (see Figure 1). For example, the BOD output of the aquaculture and methane digester facilities determines the design of the algae ponds, and thereby the costs of the ponds. The effect is complicated by the presence of the water hyacinth, which removes some of the BOD contained in the aquaculture outflow as it passes through on its way to the algae ponds. It should be clear that these individual options are hopelessly entangled. Even if we look at five different sizes of each option, we would have to repeat the process $5^{15} = 30{,}517{,}578{,}125$ times. This is because for each size of each option, we would have to try every possible combination of the other options along with it to make sure that we didn't overlook the optimal configuration (the setup with the highest NPV).

Response Surface Methodology (RSM) enables us to tackle this problem. Instead of trying every conceivable possibility, we try a few judiciously selected configurations. We then fit an equation to the results using regression. This gives us an approximation to the NPV for every possible configuration. We can maximize this equation using standard mathematical programming techniques, and find the region which yields the highest NPV. If desired, a second response surface analysis can be used to pinpoint the optimum with greater accuracy. A concise introduction to RSM is given by Law and Kelton [47]. An exhaustive treatment can be found in Myers [48].

Weather data are generated by a simulation model which uses climate information gathered over a forty-year period [49]. These data constitute the ambient conditions under which the operation of the complex is simulated. The waste heat output profile of the given power plant tells us how much waste heat will be available in each period. If there is insufficient waste heat, then a backup heating system covers the shortfall.

SUMMARY AND CONCLUSIONS

Using net present value as a measure of the attractiveness of a particular configuration, response surface methodology was used to determine the optimal mix of waste heat utilization technologies for a given power plant. The details of the model, the simulation technique, and the sensitivity analyses will be presented in later contributions in this series. The conclusions anticipate the results presented in these contributions and take the form of guidelines for waste heat utilization. These include:

1. Waste heat should be available at least 75 percent of the time 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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