21-45-23

VI-A-3

EXPERIENCES WITH A COMPUTER-BASED STUDY ON WASTE HEAT USAGE FOR INTEGRATED AGRICULTURAL PURPOSES IN MICHIGAN

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ABSTRACT

A computer based study to assess the feasibility of agricultural utilization of reject heat from a nominal 1000 MWe power plant began in September 1973 by an interdepartmental team at MSU. This paper reviews and interprets the results of this systems study. Components used include numerical models representing three agricultural subsystems: pond heating for catfish culture, field warming for vegetable production, and greenhouse heating for ornamental flowers as well as models for the power plant thermal discharge and a cooling reservoir for the dissipation of heat not usable by the agricultural subsystems. The components of the system were integrated by optimizing a net present value criterion. Ownership-management options for operating the agricultural subsystems are suggested. This paper presents impressions on the usefulness of the factors included in the methodology used. Future research needs for this methodology are outlined.

INTRODUCTION

Over the last decade there have been numerous conferences to assess the potential for and problems with utilizing reject heat in beneficial ways. The early conferences usually had two separate components: (1) a collection of technical papers with each paper on a specific aspect of waste heat utilization, and (2) a concluding statement or set of recommendations reiterating the diverse factors that need to be considered in a unified assessment. When discussions were held at Michigan State University (MSU) in September 1973 to institute a feasibility study on waste heat utilization in Michigan, the consensus of opinion was that (1) adequate technical data for Michigan conditions could be developed from the results of field experiments conducted elsewhere, and (2) that a computer based approach could be used to get a low cost, rapid, overall assessment. The key feature of the proposed study was the interaction over the duration of the study by the small but multidisciplinary group. The group would be forced--by the necessity of developing mathematical models and analysis techniques--to isolate the dominant factors in previous research.

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The tentative organization of the study was defined in the following way. The candidate agricultural uses of waste heat were selected from systems studied by others [1,2] with guidance from Dr. Larry Boersma [3] including preprint material from his research then in progress [4]. Adequate data seemed to be available to model pond warming for freshwater fish culture, greenhouse heating, soilwarming for vegetable production, and several uses. Because the initial goal in the computer study was to develop an analysis "tool", the study was limited to these three agricultural uses. The work by Boersma's group [4,p.243] showed that important parameters in several components of a combined waste heat system could be defined, but they did not have time available to develop an integrated system. A combined system is one consisting of several components that are independent. An integrated system is one where the size of the components, or their arrangement, or their operation is chosen to optimize a criterion. Previously Price [5,6] had integrated the sizes of three components (fish pond, greenhouse, and recreational lake) in a system using the criterion of maximum overall size of the component uses. It was optimized by a sensitivity study involving heat dissipation models and actual weather data. It was suspected that the cost of transporting the enormous quantity of low temperature water to the components of the agricultural system might be an important parameter [7,8]. Also a detailed economic analysis of the cost and revenue in the agricultural components would certainly be important to agribusiness [9]. Finally, a net present value criterion was taken as the criterion that would be used to integrate the three agricultural subsystems.

The eleven university personnel involved with the project for varying periods of time presented their preliminary conclusions based on this criterion in December 1975 [10]. During the first part of 1976, two of the personnel continued to made refinements on the study [11].

Examples could be given of papers in ther literature where waste heat computer models were used for the following goals: (1) development of mathematical models that accurately represent the collected experimental data for specific agricultural uses, (2) development of detailed design specifications for a specific subsystem, (3) approximate evaluation of an informative criterion, and (4) computational procedures to optimize some criterion. The essence of the MSU study involves the last two items. Informative information includes: cooling system net present value, enterprise shadow prices, agribusiness net present value, and environmental concerns.

Separable programming and a net present value criterion were a useful way to study the agricultural utilization of reject heat.

NET PRESENT VALUE

Net present value (NPV) is used by the electric utility industry to compare alternative conventional cooling systems. It is used to justify decisions on the cooling system to their investors and to state regulatory agencies.

The net present value method accounts for the time value of money in combining the investment in initial capital and annual costs. The NPV was used as the criterion that was optimized to define the size and temperatures of the agricultural subsystems. For the agricultural subsystems the net present value is of the form:

$$Z^{**} = \sum_{j=1}^{S} A_j \left[\sum_{i=1}^{n} \left(\frac{R - C}{(1 + r)^i} \right)_{ji} - K_j \right] \qquad (1)$$

where

Z^{**} = Net present value of the integrated subsystems, positive terms j for properly chosen subsystems,
S = Number of subsystems, agricultural plus reservoir,
A = Area or size of subsystem j, acres
R = Annual gross revenue for subsystem j,
C = Annual cost for subsystem j,
r = Discount rate or opportunity cost for capital,
K = Initial capital outlay for subsystem j,
n = Life of project or planning horizon, years,
i = Index for time,
j = Index for subsystem.

While this objective function is usable for determining the optimal subsystem sizes, it does not allow comparisons with conventional cooling methods because it does not account for the cost in transporting the warm water to the subsystems. The NPV for the water transport system is of the form:

$$Z^* = -\sum_{i=1}^{n} \frac{P_i^*}{(1 + r)^i} - K^* \qquad (2)$$

where the additional variables are

Z^* = Net present value of water transport system, or of conventinnal cooling system, always negative.
K^* = Capital outlay for water transport system,
P_i^* = Makeup power and other annual costs for water transport.

The same form for Z* is used to compute the net present value of conventional cooling, with different suitable values for P* and K* of course. For the integrated agricultural system, Z = Z* + Z**.

The optimal integrated system contained 100 acres of tomato fields, 160 acres of catfish ponds, a 350 acre cooling lake, and no greenhouses. Bakker et al. [10] concluded that the NPV for this integrated agricultural system makes it competitive with conventional cooling methods. The slightly revised NPV comparisons from Meekhof [11] are shown in table 1. The NPV for the integrated agricultural system is less negative than the corresponding value for conventional cooling. Although the NPV is positive for each agricultural system, the value for the cooling reservoir has a slightly greater magnitude and is negative. When the NPV for the water transport shown in table 6 is included the total NPV is about as negative as that for a conventional cooling tower.

SHADOW PRICES

One of the programming techniques used to optimize the integrated system was linear programming (LP). The LP output gives shadow price information useful to agribusiness in decision making.

Shadow prices for activities (subsystems) indicates the effect on NPV of expanding the size of an enterprise. Shadow prices for constraints indicate the effect on the NPV for all subsystems of removing marketing and other constraints. Positive values are an indication of what entrepeneurs would pay for one additional unit. Table 3 [from 11] gives sample shadow prices for the optimal system. The negative value for waste heat in September indicates that adding a subsystem operating in that month would be desirable. The magnitudes of the other shadow prices show that the fish enterprise resource is the major limiting factor. An explicit constraint in the LP program limited the catfish enterprise to less than 160 acres.

Several resources are limited in the waste heat system and are represented by explicit and implicit constraints in the LP problem. Available markets limit the sizes of the tomato and catfish enterprises. The total quantity of waste heat is limited by the size of the electric power plant, assumed to be 1000 MWe. Because the reject heat is used to keep the subsystem temperatures above specified levels, the heat dissipation considerations discussed later imply (1) the maximum size of each subsystem is limited, and (2) a reservoir is required for both supplemental cooling after water is cooled below the specified temperature level and as a place to dump reject heat directly from the power plant when no subsystem can use it. Reservoir size required for this cooling is shown by month in table 2.

The LP output gives cost of forcing in activities. This serves to rank the relative profitability of enterprises and gives the order they would come into the system if more waste heat were available. More waste heat would become available if the sizes of subsystems currently included in the system were reduced. Table 4 [from 11] shows the greenhouse enterprise is less desirable than other possible enterprises including more units of soilwarming and fish culture operated at "non-optimal" temperatures. Greenhouses are undesirable because the capital and annual costs given in table 5 are higher than that for other systems, while their rate of heat dissipation occupies a middle position.

INSTITUTIONAL ARRANGEMENTS

Institutional aspects involve the contractural arrangements for the personnel to manage the waste heat system and for the capital to construct and operate the system. Possible options are listed in table 10. Costs incurred by a body seeking fee simple acquisition include payment of interest and principal on bonds raised to finance purchase of the land, administrative costs, cost of compensating the affected communities for property taxes foregone where land is purchased by a tax exempt body and leased back for agriculture-aquaculture. Should the utility company decide not to fully control the total integrated system and not raise the capital for one or all the separate subsystems, it can enter a contractual agreement with private entrepreneurs to supply waste heat water.

The options are limited by two positions held by the electric utility industry [12]: (1) reliability in the operation of the heat dissipation system is essential because the cost of plant shutdown or operation at reduced capacity is significant, and (2) direct utility management of the agricultural system is neither a goal nor outcome regardless of the financial incentives. This viewpoint limits the options to either purchase and leaseback or contractual firm. In purchase and leaseback the utility provides the capital and leases the facility to a single management firm which maintains and operates all subsystems over the lifetime of the power plant. In the contractual agreement a cooperative group of firms agree to construct and operate the agricultural system with the utility assuming the cost for the water transport system.

Table 6 [from 11] shows the net present value (NPV) comparisons for these three options. In purchase and leaseback free, agribusiness gets all the revenue and pays managerial and operating capital costs while the utility bears the capital cost for the subsystems and water transport system. In purchase and leaseback rent, agribusiness pays the managerial costs and costs for operating capital while the utility uses the remaining revenue to defray costs for capital for the subsystems and water transport system. In the contractual firms option, agribusiness bears all initial capital costs for the subsystems and the utility agrees to supply free waste heat and pays the firsm for their dissipation of the waste heat. A payment is necessary because the difference between the utility operation of only the water transport system and the utility operation of the total system is negative; hence, a payment would be set by bargaining between the utility and the firm. The details on the methods used to calculate the values in table 6 are given in Meekhof [11]; they involve an economic breakdown of the terms in equation (1).

POLICY CONSIDERATIONS

The MSU study was limited to heat dissipation, economic, and institutional arrangements. However, other factors affect the desirability of adoption of agricultural usage of waste heat. Some of these are contained in a study on energy parks in Michigan. Others are shown in studies by others on once through cooling to the Great Lakes.

Economic Expansion

Beneficial agricultural uses of waste heat were included as one collocated industry in an energy park study funded by the Federal Energy Administration [13]. Unlike concurrent energy park studies where the park would be located on federal land, the Michigan study assumed the hypothetical park could obtain privately held land near Harbor Beach in Michigan's thumb for the 9510 acre 23125 MWe complex (13 nuclear and 8 fossil fuel units).

This peripheral involvement in the energy park study occurred relatively early in the MSU study. The components suggested and their sizes are shown in tables 7 and 8. The sizes were determined by marketing constraints. The initial capital and annual costs were estimated from costs for enterprises not using waste heat. The heat dissipated was estimated from the optimal temperatures for the subsystems. Three interesting points emerged from the study. First, over seventy-five percent of the waste heat could not be used beneficially either at high temperatures for industrial and urban uses or at low temperatures for agricultural uses. Second, the measures for the benefits are related to economic expansion either as jobs created or as production from energy dependent industry. And third, it was postulated that some environmental groups would say "... (the park) should be accomplished only if the economic and social benefits overwhelm the economic, social,and environmental costs. The arguments must be unquestionably convincing and the documentation must be of unquestionable integrity".

This last point has implications even for the agricultural system, alone. The primary impact in the local economic environment of the agricultural system would be caused by the manner in which the land is acquired. The conversion of of 960 acres of land to purposes other than it has been traditionally used will affect the distribution of wealth and income in the community, the revenue base of the local governmental unit, existing input suppliers growth or decay, the long range planning incentives of the remaining agricultural land holders, and the existing marketing channels for agricultural and aquacultural commodities.

Once Through Cooling

The comparisons in table 1 assume the alternative conventional cooling is limited to cooling towers. If once through cooling were possible several of the results would be changed. The least negative conventional cooling system would be once through cooling. Because the reservoir would be eliminated, the NPV for the integrated agricultural system would improve. However, the discharge water temperature might vary by about fifteen degrees Fahrenheit [14,Fig.5] which would made it more difficult to design the agricultural subsystem to maintain an optimal temperature.

Environmental groups prevented the operation of the 700 MWe Palisades Nuclear Plant in 1971 until a commitment was made to install a mechanical draft cooling tower by 1974 [14]. The setting of agreed on environmental standards is a complex issue. Current concern includes [15,14]:

1. a lack of quantitative estimate of potential effects,
2. an increase of attached filamentous algae along the shoreline,
3. and the need to assure protection and propagation of a balanced indigeneous population of fish and ther aquatic species.

Legislationand court action over the last several years on these issues from a national perspective is outlined in a recent Congressional Research Service review [17]. A lower standard for thermal discharge but not discharge from the agricultural system is permitted if the native ecosystem survives intact [16]. Research to quantify the effects on once through cooling are in progress. An Argonne study found no adverse effects on the migratory behavior of fish tagged at the Point Beach Plant [18]. A continuing MSU Institute of Water Research study has found effects imparted to fish, if any, at the Monroe Plant on Lake Erie were soon dispersed into the lake population and became unidentifiable [19].

CONCLUSIONS FOR THE INTEGRATED SYSTEM

The mathematical variables used contained useful information, although their numerical values are only approximate. Thus, the net present value criterion is a useful way to structure a study of waste heat.

The comparative NPV's do not either clearly prove or disprove the concept of waste heat utilization. Because the net present value for the integrated agricultural system is not more negative than conventional cooling methods, beneficial use of waste heat is not clearly disproved.

Feasible institutional arrangements can be made, but the negative NPV implies the electric utility must indirectly pay the agricultural complex to dissipate heat.

Because water transport NPV dominates the analysis, the primary technical problem is the system for water transport. The water from the power plant to the 160 acres of fish ponds is carried by a concrete pipe 600 feet long and 10 feet in diameter.

NPV is not a totally acceptable criterion. The NPV certainly represents waste heat dependent economic expansion in a new industry (catfish culture in a cold climate), or in retaining an existing industry (heated greenhouses in the presence of rising natural gas prices and supplies), but in soilwarming can be positive even when no waste heat is utilized.

A small demonstration project would serve to replace the secondary and synthetic data used with more accurate primary data. It would also improve liaison with agribusiness.

SIMULATION DEVELOPMENT

The MSU study manipulated mathematical models rather than executing field experiments. An effort was made to structure the simulation and optimization in a manner familiar to the electric utility industry. Desalination of sea water by nuclear power plants [20] seemed to be a problem analogous to the MSU study on waste heat utilization. This view was expressed by the MSU group several years ago [21]. The analogy proved to be poor. It is worthwhile to outline this formulation of the waste heat problem. Although the computer code developed for it was not effective for optimization, the code is quite useful as a matrix generator for a linear (separable) programming formulation of the problem.

Initial Formulation

As an optimization problem the goal is to maximize the net present value. To accomplish this the four type of variables in the NPV equation (1) are manipulated: R, K, C, and A. The revenue (R) is the price of the product time the quantity produced. The production in each subsystem depends on its temperature: thus, models are needed to predict temperature for a specified quantity of reject heat and to predict biological growth rate at a given temperature. At the time it seemed reasonable to assume that the agricultural waste heat complex would contain as many as eight subsystems: soilwarming, fish culture, greenhouses, waste treatment, algae culture, irrigation, recreational lake, and animal shelters. Thus, the problem was one of allocating the heat between the competing subsystems. It also seemed reasonable to assume the initial capital (K) and combined annual pumping and operating costs (C) could be found after the system was optimized. Also the water transport NPV (Z*) was not assignable to any particular subsystem even based on the quantity of water used.

To develop the methodology or "tool", soilwarming and fish culture were chosen as good candidate subsystems. To satisfy the 1983 zero discharge requirements a cooling reservoir (lake) was included. Thus given a power plant with a known quantity of reject heat at a known temperature, the problem was (1) to allocate the heat to two competing agricultural subsystems on a monthly basis, and (2) to determine the size of each agricultural subsystem. Temperatures for optimal growth were avaiable in the literature. Applying this methodology to all eight candidate subsystems, the optimization would give (1) the best size for each subsystem (including some of size zero), and (2) would determine whether a particular subsystem should be operated at a "non-optimal" temperature in some months in order to make the best total system. Thus, the best uses would be selected and the problem of designing for utilization versus dissipation posed by Shapiro [23] would be solved.

Next an optimization technique was selected. The mathematical optimization technique would need to handle constraints because the sume of the reject heat allocated to the subsystems was limited by the reject heat available from the power plant. Because the equation to be developed for the heat transfer and biological growth had not been decided on a general mathematical programming procedure was selected. The "complex" method [22] met both these requirements. The method handles constrained, multi-variable problems and only requires computation of functional values, not gradients.

Subsystems

The major research effort in small scale waste heat field studies is defining the effect of temperature on growth, while a major economic concern is to have marketable products from the heated enterprises. The same concerns were present during the development of mathematical models for the revenue (R) in equation (1). The variable R is the first of four types of variables to optimize in equation (1). Selecting enterprises for the subsystems was not difficult: for candidate "crops" lists of optimal temperature for growth were developed and lists of comparative economic advantages of production were developed. The crops were the best from the combined list. Catfish was chosen for the fish enterprise because a detailed economic analysis was available [24]. Tomatoes and several other field crop varieties were selected for the soil warming enterprise and the economics developed at MSU. Ornamental flowers were selected for the greenhouse enterprise and the economics also modelled at MSU.

The price assumptions were: per pound channel catfish $0.30, per bushel tomatoes $5.50, ornamental flower rotation and price; 6-inch Chrysanthemums $2.60, 6-inch Poinsettias $3.25, 6-inch Lilies $2.60, 4-inch Geraniums $0.65.

The heat dissipation was modelled by algebraic energy balance equations. The optimization method assigned a quantity of heat to be dissipated to these equations and the corresponding subsystem temperature computed. For the fish pond and cooling reservoir, the three equations (10,15,17) in Edinger et al. [25] were solved simultaneously to yield the thermal exchange coefficient and equilibrium temperature. Values for Meyer's evaporation term were $C_1=11$ and $f = 0.00682 + 0.000682\ W$, where W is windspeed in mph. For the soilwarming system, the climatic data based Kendrick-and-Havens heating pipe model developed by Dewalle [26] was used. The heat required to maintain greenhouses at specified levels of temperature was computed with the model by Walker [27] with the ventilation rates adjusted for those used in waste heat greenhouses [28].

Having established the temperatures, the quantity of crops from the subsystems could be predicted. The growth of catfish used a model of the form:

$$\frac{d\,W}{d\,t} = \mu \; W \qquad (3)$$

where W is the weight of harvested fish and μ is a parameter modelled by a Lagrangian interpolation polynomial using data from Andrews [29].

The growth of field crops used a model from Paltridge and Denhold [30] of the form:

$$\frac{d\,G}{d\,t} = \alpha\ G\ H(s-t)\ \ -\beta\ G \qquad (\ 4\ )$$

$$\frac{d\,W}{d\,t} = \beta\ G\ H(t-s) \qquad (\ 5\ )$$

where G is vegetative material, W is harvested material (tomatoes), H is a step function, s is a switch time, and β is related to soil temperature. Both equations (3) and (4) are reasonable approximations to experimental data. Conventional production values were used for the greenhouse enterprise. The revenue (R) from each subsystem is simply the quantity of harvested material times its price.

Initial Optimization

The difficulties with the assumptions in the initial formulation became obvious when optimization was tried. These were related to: (1) the definition of a harvestable crop, (2) design of the water transport and (3) institutional limitations on the number of subsystems.

The formulated optimization problem allocates heat to the subsystems on a monthly basis. Only monthly climatic data was readily available. However, the harvestable material is only defined in a particular month for tomatoes and in a particular size interval for fish. This problem was handled by (1) optimizing on a yearly rather than a monthly basis and (2) using a sensitivity study to define input conditions for fish size at harvest. The monthly heat allocation pattern was represented as the sum of certain Walsh functions. Each function is a pattern with either unity or zero in a given month; i. e., to allocate the same unknown heat dissipation to the fish pond in the three months January, February and December the function has the form (1,1,0,0,0,0,0,0,0,0,0,1). The optimization routine found the best amplitudes for these functions. A total of five functions was adequate for the allocation to two systems over twelve months; thus, the number of optimization variables was reduced from 24 to 5. The use of Walsh functions would provide a reasonable approximation to a specific optimal temperature pattern obtained analytically by others for lobster culture [31].

Associated with each monthly heat dissipation is a water flow rate to each subsystem. When these monthly flow rates were used to determine a water transport system, a more serious problem arose. The flow rates are shown in table 9 for three Walsh functions for fish ponds and two for soilwarming.

The water transport system determines the next three optimized variables in the NPV equation: C, K, and Z*. The annual costs (C) are determined by the flow rate and the friction head loss in an established, well-known manner. The flow rates are given and the headloss is computed by assuming the pipe diameter and (1) assigning a roughness length, (2) using a Moody diagram to compute the dimensionless friction factor, and (3) using the Darcy-Weisbach equation to compute the head loss. This procedure was repeated trying different diameters until a satisfactory engineering design was obtained. The wide variation in flow rates shown in table 9 made this design not totally satisfactory. A computer program for the calculations involved was found too late in the project to be used [32]. Although more designs could have been tried using the program, the problem of the variations would have made it difficult to choose correct pipe diameters and pump sizes.

In the initial formulation it was assumed that the water transport design would not be a problem. In reality the flow rates shown in table 9 vary by a factor of 2 for soilwarming and by a factor of 5 to 15 for fish pond depending on whether the system operates in winter or not. Thus, the water transport costs need to be related to the optimized heat dissipation patterns in order to properly optimize equatinn (1). The best way to optimize might be to use LP to select from a set of discrete designs.

The value of the NPV given in equation (1) depends on the sizes specified for the subsystems (A) which is the last optimized variable. Heat dissipation considerations only place an upper bound on each subsystem size. The determination of the mix of sizes that optimize the NPV is determined largely by institutional factors. The terms in the NPV equation are basically a subsystem size times revenue generated (or indirectly heat dissipated). Some subsystems generate large revenues but dissipate heat poorly, others generate small revenues but dissipate heat effectively. Thus while revenue and heat dissipation considerations could indicate the best mix is all greenhouses or all fish culture doing so would possibly mean excessively large amounts of land and/or capital, or large seasonal excess capacity in operating capital, labor, or managerial skill. Also it could create an inability of the marketing structure in the region to handle all the agricultural and aquacultural commodies.

Thus, optimizing the NPV equation is not a problem of finding the best heat dissipation pattern and compatible size mix, but one of finding sizes that are feasible for the institutional arrangement. Table 10 is a list of possible institutional arrangements. As indicated previously the best cptions are: purchase and leaseback and contractual rent.

SIMULATION STUDY

The results presented in this paper were obtained using the following procedure. The problem of selecting optimal uses was considered more as a sensitivity problem than as an optimization problem. An LP program was used for the major analysis with technical coefficients set from the "complex" program used as a matrix generator. The constraint section of the "complex" program was used to set pairs of subsystem size and temperature levels. The constraints on heat and flow rates were checked with the subsystem models. Associated with the temperature levels are crop growth rates and hence revenue. Enterprise costs were calculated in detail at a few sizes and separable programming was used to interpolate between these values.

Separable Programming

Several related procedures are called separable programming. The MSU study used the procedure introduced by Charnes and Lemke [33]. The separable technique was used to (1) handle the nonlinearity in the cost coefficients and (2) to determine whether subsystems should be operated at non-optimal temperature. Other aspects of the LP technique were (3) selecting a reservoir size from the twelve monthly values, and (4) combining capital and net revenue internally to obtain the net present value.

The form of the tableau is illustrated in table 11 for a simple set of conditions. The system represents three components: a fish enterprise operated at the optimal temperature, a fish enterprise operates at a non-optimal temperature, and a cooling lake. The year has two time periods: summer and winter. The fish enterprises only operate in summer. The variables in the tableau are:

d = Discount factor obtained by summing the opportunity cost over the planning horizon, with (R-C) outside the summation,
H = Heat dissipated for a size S in the agricultural subsyste, million BTU per hour,
Q = The quantity of reject heat, million BTU per hour,
N = The positive net revenue (R-C) from equation (1)
K = Initial capital from equation (1),
S = Size of the subsystem that detailed costs were compiled, it can be zero,
S* = Size at a level 2 design temperature,
h = Heat dissipated by the reservoir per acre, million BTU per hour per acre.

The way the four computational features are achieved can be understood by studying the tableau.

Several aspects of the tableau and programming method are of interest. The heat dissipation rates, H, are non-negative; that is, heat is transferred from the subsystems to the environment,not vice versa. Hence the maximum size of each subsystem is limited by heat dissipation considerations since the quantity of heat rejected from the power plant is limited. More importantly the agricultural subsystems only contribute to the net present value if they also dissipate heat.

The size of the agricultural subsystem is limited to be between sizes S_1 and S_2 by the separable constraint; thus, S_1 should be set to zero if the subsystem if not necessarily in the integrated system. Unlike the "complex" program where the subsystem costs could not be related to the water transport costs and design, different discrete water transport designs can be specified as level 1 and level 2 subsystems in the LP program. The "complex" program has some features that can be used to set technical coefficients: given a quantity of heat to be dissipated it will check the implicit constraints on power plant temperature and on designed pumping rates and obtain a feasible subsystem operating temperature for heat transfer considerations.

Program Notes

The mathematical methods developed by the MSU group and those developed by the Price group at Cornell[34] have helped to isolate the key variables in the waste heat problem.

Several aspect and potentials of the LP programming method beyond the goals of the MSU study should be noted.

The technique used for internal discounting has been used in another context to weight monetary and pollution costs [35]. This could be used in waste heat by replacing the variable S with a measure of production of catfish wastes and a weight analogous to the discount put in the objective function in order to find a least cost, least pollution integrated system.

The pumping costs imply that the benefits from the agricultural system is derived at the cost of using limited energy resources to pump the water. This trade-off has been discussed in a nice mathematical way in the context of altering the thermal plume by pumping by others [37]. In the LP analysis the variable S could be replaced by a measure of energy usage and the weighted NPV obtained.

Finally, linear (separable) programming is also a method familiar to the electric utility industry in the context of designing a dry cooling tower [38] and better for the waste heat problem than [20,21].

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ACKNOWLEDGEMENTS

This research was supported by Consumers Power Co. (Jackson, Mi.), the Michigan Agricultural Experiment Station, and Detroit Edison (Detroit, Mi.). The results presented are a product of the eleven member MSU research team, especially material adapted from the doctoral thesis by Ron Meekhof. Advise was provided by J. J. Rochow, R. L. Hall, J. H. Kline, and R. E. Albrecht from the sponsoring electric utilities. Views expressed are those of the main author.

TABLE 1
COMPARISON OF COOLING METHODS
NET PRESENT VALUE (Z)
(IN THOUSANDS OF DOLLARS)

Discount Rate and Planning Horizon	Agricultural Method at Optimum	Wet Mechanical Draft	Wet Natural Draft
10% at 30 years	-43395	-56912	-64344
12% at 30 years	-38783	-52123	-59255
15% at 30 years	-33708	-46923	-53730
10% at 25 years	-42255	-55690	-63046
12% at 25 years	-38092	-51382	-58423
15% at 25 years	-33465	-46568	-53352

TABLE 2
MONTHLY RESERVOIR REQUIRED FOR SUPPLEMENTAL COOLING
(ACRES)

Month	Area	Month	Area
January	151	July	350
February	143	August	357
March	195	September	357
April	200	October	242
May	313	November	218
June	329	December	154

TABLE 3
SHADOW PRICES FOR OPTIMAL SYSTEM
(IN THOUSAND OF DOLLARS PER ACRE)

	10% at 25 years	15% at 25 years	10% at 30 years	15% at 30 years
Fish Pond Activity	96.6	69.2	100.	69.9
Soilwarming Activity	1616.	937.	1713.	952.
Fish Pond Resource	39.3	27.3	40.9	27.7
Soilwarming Resource	17.1	11.1	18.6	11.3
(IN THOUSAND OF DOLLARS PER MILLION BTU)				
September Waste Heat Resource	-0.975	-0.766	-1.01	-0.774

TABLE 4
COMPETITIVE POSITION OF NON-BASIS ACTIVITIES
(IN THOUSANDS OF DOLLARS PER ACRE)

Order	Activity	Cost
5	Tomatoes, 75 Acres at 10 % Below Optimal	282.
6	Tomatoes, 75 Acres at Optimal Temperature	295.
9	Fish Ponds, 160 Acres at 10% Above Optimal	482.
14	Greenhouse, 1.25 Acres at Optimal Temperature	622.

TABLE 5
ECONOMIC COEFFICIENTS IN NPV EQUATION FOR OPTIMAL SYSTEM
(IN THOUSANDS OF DOLLARS PER ACRE)

Subsystem	Initial Capital, K	Annual Costs, C	Annual Revenue, R
Fish Pond	11.9	11.4	16.5
Soilwarming	7.75	2.09	4.18
Greenhouse	260.	239.	
Reservoir	10.5	1.61	ZERO

TABLE 6
MANAGEMENT COMPARISONS NET PRESENT VALUE
(IN THOUSANDS OF DOLLARS)

Rate and Horizon	Total Utility Operation	Purchase Leaseback Free	Purchase Leaseback Rent	Utility Water Transport
10% at 30 years	-43395	-60542	-53146	-39967
12% at 30 years	-38783	-53372	-47052	-34905
15 % at 30 years	-33708	-45623	-40471	-29424
10% at 25 years	-42255	-60738	-53616	-40676
12% at 25 years	-38092	-52293	-46139	-34123
15% at 25 years	-33465	-45090	-40018	-29034

TABLE 7
COLLOCATED INDUSTRY AND AGRICULTURE
HYPOTHETICAL ENERGY PARK AT HARBOR BEACH

Industry	Capacity
Paper Mill	2,000 tons per day
Chemical Complex	$240 million annual sales
Petroleum	250,000 bbls per day
Coal Gasification Plant	250 million cfd of gas (300 Btu/cu ft)
Mini Steel Mill	150,000 tons per year
Biocomplex	**Capacity**
Irrigation	3200 acres outside park
Catfish Culture	500 acres in 20 acre ponds
Greenhouse	300 acres (vegetables and flowers)
Grain Drying, Low Temperature	20 million bushels per year
Waste Treatment	85 acres of algae ponds
Park City	
District Heating	135,000 people in 10 square miles.

TABLE 8
PARK REQUIREMENTS
HYPOTHETICAL ENERGY PARK AT HARBOR BEACH

Measure	POWER PLANT	INDUSTRIAL PARK	BIO-COMPLEX	PARK CITY	TOTAL
Land (acres)	9510	3000	960	6400	19870
Capital (million dollars, 1975)	10490	1000	59	. .	11549
Operating Labor (man equivalent)	1600	6400	300	. .	8300
Water Usage (million gpd)	170	52	27	. .	249
Heat Dissipated (million BTU/hr)	117800	14000	19200	2850	153850

Source: [13] volume 1, tables 1 and 24.

TABLE 9
MONTHLY FLOW RATES FOR OPTIMAL SYSTEM
(IN THOUSANDS OF GALLONS PER MINUTE)

Month	Fish Pond	Soilwarming	Cooling Reservoir
January	463.6	...	86.4
February	342.1	...	207.9
March	130.0	...	420.0
April	128.9	...	421.1
May	29.9	10.9	509.2
June	31.1	6.2	512.7
July	32.6	6.3	511.1
August	33.2	...	516.8
September	33.9	...	516.1
October	271.6	...	278.4
November	170.9	...	379.1
December	527.8	...	22.2

TABLE 10
SITE ACQUISITION AND MANAGEMENT OPTIONS

Fee Simple Acquisition
  Purchase and Manage
  Purchase and Leaseback
  Purchase and Resale on Condition

Less than Fee Simple Acquisition
  Purchase Easements

Contractural Agreements - For Rent Property Interest
  Waste Heat Water Cooperative
  Contractual Arrangement

Public Authority

TABLE 11
SCHEMATIC REPRESENTATION OF THE SIMPLEX TABLEAU

	Slack Winter Reject Heat	Slack Summer Reject Heat	Area Fish Level 1	Area Fish Level 2	Capital Both Fish and Lake	Net Revenue Fish Discounted	Cooling Lake Costs Discounted	Lake Heat Dissipated Winter	Lake Heat Dissipated Summer	Cooling Lake Size Annual	Fish Size 1 Level 1	Fish Size 2 Level 1	Fish Size 1 Level 2	Fish Size 2 Level 2		Constraint
Objective Function	0	0	0	0	-1	d	-d	0	0	0	0	0	0	0	.=.	Z**
Winter Reject Heat	0	0	0	0	0	0	0	1	0	0	0	0	0	0	.=.	Q
Summer Reject Heat	0	0	0	0	0	0	0	0	1	0	H_1	H_2	H_1^*	H_2^*	.=.	Q
Winter Lake Heat	1	0	0	0	0	0	0	1	0	$-h_1$	0	0	0	0	.=.	0
Summer Lake Heat	0	1	0	0	0	0	0	0	1	$-h_2$	0	0	0	0	.=.	0
Capital Transfer	0	0	0	0	-1	0	0	0	0	k_2	K_1	K_2	K_1^*	K_2^*	.=.	0
Revenue Transfer	0	0	0	0	0	-1	0	0	0	0	N_1	N_2	N_1^*	N_2^*	.=.	0
Lake Cost Transfer	0	0	0	0	0	0	-1	0	0	C	0	0	0	0	.=.	0
Level 1 Separable	0	0	0	0	0	0	0	0	0	0	1	1	0	0	.=.	1
Size Transfer	0	0	-1	0	0	0	0	0	0	0	S_1	S_2	0	0	.=.	0
Level 2 Separable	0	0	0	0	0	0	0	0	0	0	0	0	1	1	.=.	1
Size Transfer	0	0	0	-1	0	0	0	0	0	0	0	0	S_1^*	S_2^*	.=.	0
Separable Mix	0	0	0	0	0	0	0	0	0	0	1	1	1	1	.=.	2