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Power Plant Reject Heat Utilization: An Assessment of the Potential for Wide-Scale Implementation

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FOREWORD

It has been recognized that, because of power cycle operating conditions, nuclear power plants reject more waste heat per unit of electricity produced than comparable fossil stations. Because the waste heat problem is more severe for nuclear power stations, research in the area of beneficial uses of waste heat has been sponsored for a number of years by the Advanced Concepts Evaluation Branch of the Department of Energy — Nuclear Research and Applications Division (formerly in ERDA).

These studies have considered various uses for power plant reject heat and have centered on agricultural uses. Some of this agricultural work has been carried out in a cooperative program with the Tennessee Valley Authority (TVA). This work is continuing with an 0.5 acre greenhouse demonstration at the Browns Ferry Nuclear Station to be constructed this year.

During the course of the beneficial uses investigations, it became evident that an assessment of the potential for implementation of these systems would be helpful in determining which technologies should be emphasized. Therefore, this study was initiated to address this question.

SUMMARY

An assessment of the relative economic and heat utilization merits of waste heat utilization systems was made in an effort to indicate those technologies that show the greatest potential for wide scale use in the power generating industry.

The systems were designed to accommodate the yearly cooling needs of a 1000-MW(e) power plant. Thus, for the purposes of this analysis, it was assumed that these systems replaced the cooling tower as the primary condenser cooling water heat dissipation system. The systems analyzed in this report included greenhouses, undersoil heating, algal ponds, extensive pond aquaculture, intensive raceway aquaculture, and animal rearing facilities.

These systems were evaluated by analyzing implementation potential and user incentive considerations. The implementation analysis included economic, marketing, and power plant performance criteria. The user analysis essentially examined the cost to transport the heat from the power station to the user and the thermal performance of the heat use system when utilized as a power plant cooling system. The overall assessment combined these two perspectives to determine their compatibility and rank the technologies in terms of their potential for implementation.

The user analysis indicated that use of reject heat in these systems was economically attractive. It also indicated that for the climatic conditions used in the study, most systems (greenhouses and animal rearing systems being the exception) could beneficially utilize reject heat throughout the year. To insure a reliable heat source each system design included a fossil fuel heating system as a backup system.

The power plant performance analysis indicated that the power plant generating capability was not adversely affected when these systems were used as the heat rejection system.

Because the extensive pond aquaculture systems appeared to be superior in terms of economic and market considerations, the assessment indicated it had the highest potential for implementation. It appeared that this system should be vigorously pursued in terms of research and development.

Animal rearing systems were rated second with algal ponds and greenhouses being rated third and fourth, respectively. It appears that these systems also have significant potential and should be pursued.

Intensive aquaculture was rated fifth because of marketing constraints. These systems could be beneficial but probably only in selected sites.

Undersoil heating was ranked last because of economic feasibility problems. It appears that this technology should not be pursued in the United States.

POWER PLANT REJECT HEAT UTILIZATION: AN ASSESSMENT OF THE POTENTIAL FOR WIDE-SCALE IMPLEMENTATION

M. Olszewski

ABSTRACT

As assessment of the relative economic and heat utilization merits of plant reject heat utilization systems was made in an effort to indicate those technologies that show the greatest potential for wide-scale implementation in the power generating industry.

The heat utilization systems were designed to accommodate the yearly cooling needs of a 1000-MW(e) power plant. Thus, for the purposes of this study, it was assumed that these systems replaced the cooling tower as the primary condenser cooling water heat dissipation system.

Implementation potential and user incentive considerations were used in assessing the technologies. Assessment of the implementation potential included economic, marketing, and power plant performance criteria. The user incentive assessment essentially viewed the use of reject heat from the user's perspective. Heat costs and performance characteristics of the heat utilization system were the criteria used in this assessment. The two analyses were combined in the overall assessment.

The overall assessment indicated that extensive pond aquaculture offered the greatest potential for wide-scale implementation. This was followed by animal rearing, algal pond, greenhouse, intensive aquaculture and undersoil heating systems.

Based on this assessment, it is recommended that extensive pond aquaculture should receive top research priority. Animal rearing, algal pond and greenhouse research should also be vigorously pursued. It appears that intensive aquaculture can be investigated in certain locations but undersoil heating should not be pursued.

INTRODUCTION

Background

Generation of electricity is one of largest consumers of primary fuel in the United States today. Since the efficiencies for thermal power plants are typically 30 to 40%, it appears that energy conservation efforts in this sector can have a significant impact on national energy consumption.

The thermodynamics of heat engine cycles dictate the use of a heat sink in any power producing cycle. Thus, even if power generating cycle efficiencies could be raised to 50%, significant amounts of energy would still be rejected to the heat sink. Given the present U.S. situation of escalating energy prices and diminishing energy resources, it is desirable to utilize our energy resources to the fullest extent possible before exhausing them to the atmosphere as reject heat. It is, therefore, important to focus attention on the heat rejected from power generating cycles and attempt to utilize this resource in some useful manner. Utility statistics[1] indicate that thermal power plants reject about 11.0×10^9 GJ (11.0 quads*) of heat annually. Utilization of half of this rejected energy represents an energy resource of 5.5×10^9 GJ/year (5.5 quads/year). This energy resource is equivalent to about 2.2×10^8 m^3 (1.4×10^9 bbls) of oil per year. Thus, this reject heat can be viewed as a large and, as yet, untapped source of low temperature thermal energy.

For a typical thermal power station, heat rejected in the condenser raises the temperature of the condenser cooling water. The temperature level of this flow is governed by climatic considerations and the type of cooling system employed. For once-through cooling systems the condenser cooling water effluent temperature is typically in the range of 16 to 32°C (60 to 90°F). If a closed cycle system (e.g., cooling tower, cooling pond etc.) is utilized, the condenser cooling water outlet temperature is raised to 24 to 49°C (75 to 120°F). Since recent environmental legislation has essentially barred the use of once-through systems for new power plants, the available temperature level of power plant reject heat will be rising.

Various techniques have been proposed and studied to utilize the heat contained in power plant condenser cooling water streams. These applications have focused primarily on agricultural (greenhouse and livestock facility heating, open field undersoil heating and spray irrigation) and aquacultural applications. Information available in the literature, especially from the two major waste heat utilization conferences,[2,3] indicate that most reject heat utilization efforts are centered around the development of individual applications. These efforts include modeling

*1 quad = 10^{15} Btu.

efforts to predict the system performance, experimental or pilot systems and demonstrations.

One aspect of waste heat utilization that has apparently not been addressed deals with the potential limitations to the implementation of reject heat utilization. For example, previous research efforts[4] have suggested that large tomato yields can be expected from greenhouses. Therefore, marketing constraints may limit the acreage of greenhouses that can utilize reject heat. Since most of the other reject heat uses deal with crop or animal production, similar constraints may exist for these applications. An examination of these potential limitations would seem desirable to indicate which technologies could find the most wide-scale use in the power industry. Such information could be valuable in determining which technologies should receive the greatest attention.

Purpose

The purpose of this report is to assess the relative economic and heat utilization merits of general system concepts that utilize thermally enriched water from power plants. An assessment of the power plant and heat utilization system performance was also made to determine if beneficial use of reject heat detrimentally affected power plant performance. An analysis from the user's perspective was also performed to determine if the use of reject heat was economically and technically attractive. Essentially, the overall assessment was performed to indicate those technologies that have the greatest potential for wide-scale use in the power generating industry.

Method

This analysis focused on systems that previous investigations at the Oak Ridge National Laboratory (ORNL) and elsewhere identified as technically or economically promising. The reject systems analyzed in this report thus included: (1) greenhouses, (2) undersoil heating, (3) algal ponds, (4) extensive pond aquaculture, (5) intensive raceway aquaculture and (6) animal enclosures for chicken broiler and swine rearing. Intensive aquaculture is used to indicate systems that use manufactured high protein feeds and oxygenation systems in an effort to achieve maximum yield from a body of water. Extensive systems are those that utilize the natural ecosystem food chain and seek to maximize growth by controlling water temperature.

The algal and aquaculture systems included both open and closed system operation. Open systems are those that use the condenser cooling water directly in the heat utilization system. Closed systems employ a heat exchanger to separate the two water streams.

Since this report focused on applications that utilize heat contained in the condenser cooling water, systems that require the use of back-pressure turbines or turbine bleed steam, such as district heating, were excluded. Because of the trend toward closed loop cooling systems, applications with large consumptive uses of water were also excluded. Therefore, warm water field or spray irrigation systems were excluded because they are essentially once-through cooling systems.

These systems were evaluated by analyzing implementation potential and heat user incentive considerations. The implementation analysis essentially sought to identify those technologies that possess the economic and market potential for wide-scale use in the power industry. The heat user analysis sought to determine if reject heat was an economically feasible option for the potential user. The overall analysis examined the results to determine the compatibility of the two perspectives.

The implementation analysis included economic, marketing and power plant performance criteria. Based on research performed at ORNL and the results of other investigators, the costs and land requirements for the alternative heat utilization systems were computed. These systems were designed to provide for the total yearly cooling needs of a 1000-MW(e) power station. Based on the system costs and performance capabilities, appropriate products were chosen and revenues and maximum acreage to supply 100% of the U.S. demand for the selected products were computed. The economic index chosen was the ratio of annual revenue and annual system cost. The marketing index was the number of 1000-MW(e) power plants that would be required to supply 100% of the U.S. consumption of the selected system products. The power plant performance was computed for each of the heat utilization systems. This performance was compared to the performance of a station using an evaporative cooling tower to produce a performance index.

The heat user analysis essentially examined the cost to transport the heat from the power station to the user and the thermal performance of the heat use system. This information was used to determine if the system performance and associated heat cost were economically attractive to the user.

IMPLEMENTATION POTENTIAL

Economic Analysis

The design data used to compute the system costs are presented in Table 1. Since the system heat rejection capability is a function of the ambient weather conditions, all systems were designed for the same location. The Portland, Oregon, area was chosen because heat rejection figures were readily available for this area from Ref. 5.

The heat rejection system capital and annual costs, presented in Table 2, were computed for the system sizes indicated in Table 1. These costs include only costs directly associated with the heat utilization system. This includes capital items, land acquisition (if the system land requirements exceed the normal utility land area purchase), and power costs associated with operation of the complex as a heat dissipation system. Costs for circulating the heated water through the heat utilization complex and returning it to the condenser were computed separately.

The heated water distribution costs, presented in Table 2, were estimated assuming a square layout for the waste heat utilization complex. Other design assumptions included: (1) a maximum water velocity of 2.4 m/sec (8 ft/sec), (2) prefabricated, insulated steel pipe conduit and (3) a maximum pipe diameter of 1524 mm (60 in.).

Greenhouse systems normally use cool water in their evaporative pads for summer cooling. The swine and broiler rearing facilities similarly would not use the reject heat in summer. Therefore, it was assumed that the summer heat rejection needs of the power plant were met using a

Table 1. Design summary

System	Minimum heat rejection (MW/ha)	System size required for 1000 MW(e) station		Additional cooling required (MW)
		Heat rejection system (ha)	Total complex[a] (ha)	
Greenhouse	5.00[b]	400	440	2000[c]
Algal pond — open system	7.00[b]	286	314	0
Algal pond — closed system	7.00[b]	286	314	0
Extensive pond aquaculture — open system	6.75[b]	296	326	0
Extensive pond aquaculture — closed system	6.75[b]	296	320	0
Undersoil heating	0.33[b]	5000	5000	0
Intensive raceway aquaculture — open system	5.00[d]	400	440	0
Intensive raceway aquaculture — closed system	5.00[d]	400	440	0
Animal enclosures				
Broilers	6.25[e]	320	352	2000
Swine	6.25[e]	320	352	2000

[a] Includes 10% for access roads and other auxiliaries.

[b] Adapted from Ref. 5.

[c] From Refs. 5 and 6. Warm water not used in the summer.

[d] Adapted from Refs. 5 and 7.

[e] From Ref. 8.

Table 2. Cost summary for a scale factor of 1.0

System	Heat utilization system costs[a]			Distribution system costs[b]			Additional cooling system[c]			Total unit annual cost [$/MW(e) − year]
	Total capital cost ($10⁶)	Power (kW)	Unit annual[d] cost [$/MW(e) − year]	Total capital cost ($10⁶)	Power (MW)	Unit annual[e] cost [$/MW(e) − year]	Total capital cost ($10⁶)	Power (MW)	Unit annual[f] cost [$/MW(e) − year]	
Greenhouse	289.0[g]	224[h]	64,207	73.4	6.1	12,677	25	23.7	6689	83,573
Algal ponds — open system	11.0[i]	357[j]	2,520	89.0	14.9	17,045	0	0	0	19,565
Algal ponds — closed system	31.4[k]	1,707[l]	7,351	89.0	14.9	17,045	0	0	0	24,396
Extensive pond aquaculture — open system	1.5[m]	0[n]	345	73.0	6.1	12,615	0	0	0	12,960
Extensive pond aquaculture — closed system	20.4[k]	1,350[l]	4,834	73.0	6.1	12,615	0	0	0	17,449
Undersoil heating	480.0[o]	18,000[p]	110,502	237.2	12.3	39,466	0	0	0	149,968
Intensive raceway aquaculture — open system	1430.0[q]	650[r]	317,602	105.0	23.7	21,475	0	0	0	339,077
Intensive raceway aquaculture — closed system	1450.0[k]	2,000[l]	332,338	105.0	23.7	21,475	0	0	0	343,813
Animal enclosures										
Broilers	267.2[s]	976[t]	59,385	58.7	4.9	9,099	25	23.7	6689	75,173
Swine	404.4[s]	976[t]	89,900	58.7	4.9	9,099	25	23.7	6689	105,688

[a] Includes system capital costs, costs for internal pumping, and land acquisition cost for land in excess of that normally purchased by the utility. Land normally purchased is 500 acres (Ref. 9).

[b] Based on square layout, max. velocity 8 fps; conduit cost data from Ref. 10.

[c] Assuming a mechanical draft evaporative cooling tower. Costs based on Refs. 11 and 12.

[d] FCR 22.2% power @ 2.5¢/kWhr.

[e] FRC 15.5% power @ 2.5¢/kWhr.

[f] FCR 15.5% power @ 2.5¢/kWhr and capacity factor of 50%.

[g] Ref. 13.

[h] Ref. 14.

[i] Refs. 5 and 15.

[j] Ref. 16.

[k] Includes heat exchange cost adapted from Ref. 13.

[l] Includes head loss of 10 ft in heat exchanges.

[m] Refs. 15 and 17.

[n] Ref. 17.

[o] System design adapted from Refs. 5 and 18. Cost from Refs. 19 and 20.

[p] Adapted from Ref. 5.

[q] Adapted from Ref. 7. For concrete raceway system.

[r] Adapted from Ref. 7.

[s] Adapted from Ref. 21.

[t] Adapted from Ref. 14.

mechanical draft evaporative cooling tower. The cost for this system is also presented in Table 2.

The system costs presented in Table 2 are updated linear extrapolations of small experimental systems or estimates using typical cost estimating information. As such, they do not account for savings that would be expected due to economies of scale. Since the reject heat utilization complexes consist of a number of identical modules, it was assumed that an economic scale factor of 0.9 was reasonable for these applications. Table 3 presents the heat rejection and water distribution system costs using an economic scale factor of 0.9.

A comparison of Tables 2 and 3 indicates that close to a 50% reduction in capital costs is achieved for most of the systems when a scale factor of 0.9 is used. Because the scale factor plays such an important role in the economic analysis, the results for both a scale factor of 1.0 (linear extrapolation) and 0.9 are included in this report.

The unit annual costs presented in Tables 2 and 3 reflect the yearly cost to provide cooling for each MW(e) of installed capacity. As used in this report, the system unit annual cost includes the heat utilization system cost and the cost associated with the additional cooling system, if required. The total unit annual cost includes the system unit annual cost and the cost associated with the distribution system. In computing the annual costs, capital charges associated with the heat utilization system were annualized using a 22.2% fixed charge rate and the distribution system was annualized using a fixed charge rate of 15.5%. This reflects the assumption that industry financing would pay for the complex and utility financing would be used to pay for the distribution system. A summary of the unit annual costs using a scale factor of 1.0 is presented in Fig. 1. Figure 2 presents similar information for a scale factor of 0.9.

Based on the cost information in Tables 2 and 3, products were selected for each system. These selections are presented in Table 4 with their probable market. The selection of high cash crops (tomatoes, cucumbers, for the fresh market and floral crops) for the greenhouse and undersoil heating systems were necessitated by the high unit system costs. Alternate system outputs with larger potential markets, such as soybeans

Table 3. Cost summary for a scale factor of 0.9

System	Heat utilization system costs			Distribution system costs			Additional cooling system			Total unit annual cost [$/MW(e) – year]
	Total capital cost ($$10^6$)	Power (kW)	Unit annual cost [$/MW(e) – year]	Total capital cost ($$10^6$)	Power (MW)	Unit annual cost [$/MW(e) – year]	Total capital cost ($$10^6$)	Power (MW)	Unit annual cost [$/MW(e) – year]	
Greenhouse	145.0	224	32,249	36.8	6.1	6,854	25	23.7	6,689	45,792
Algal pond – open system	5.7	357	1,378	46.1	14.9	10,183	0	0	0	11,561
Algal pond – closed system	16.3	1,707	3,974	46.1	14.9	10,183	0	0	0	14,157
Extensive pond aquaculture – open system	0.8	0	180	37.7	6.1	6,992	0	0	0	7,172
Extensive pond aquaculture – closed system	10.5	1,350	2,596	37.7	6.1	6,992	0	0	0	9,588
Undersoil heating	186.9	18,000	45,442	92.4	12.3	16,546	0	0	0	61,988
Intensive raceway aquaculture – open system	716.7	650	159,243	52.6	23.7	13,084	0	0	0	72,237
Intensive raceway aquaculture – closed system	726.7	2,000	161,738	52.6	23.7	13,084	0	0	0	174,822
Animal enclosures										
Broilers	136.9	976	30,614	30.1	4.9	5,586	25	23.7	6,689	42,889
Swine	207.3	976	46,045	30.1	4.9	5,586	25	23.7	6,689	58,320

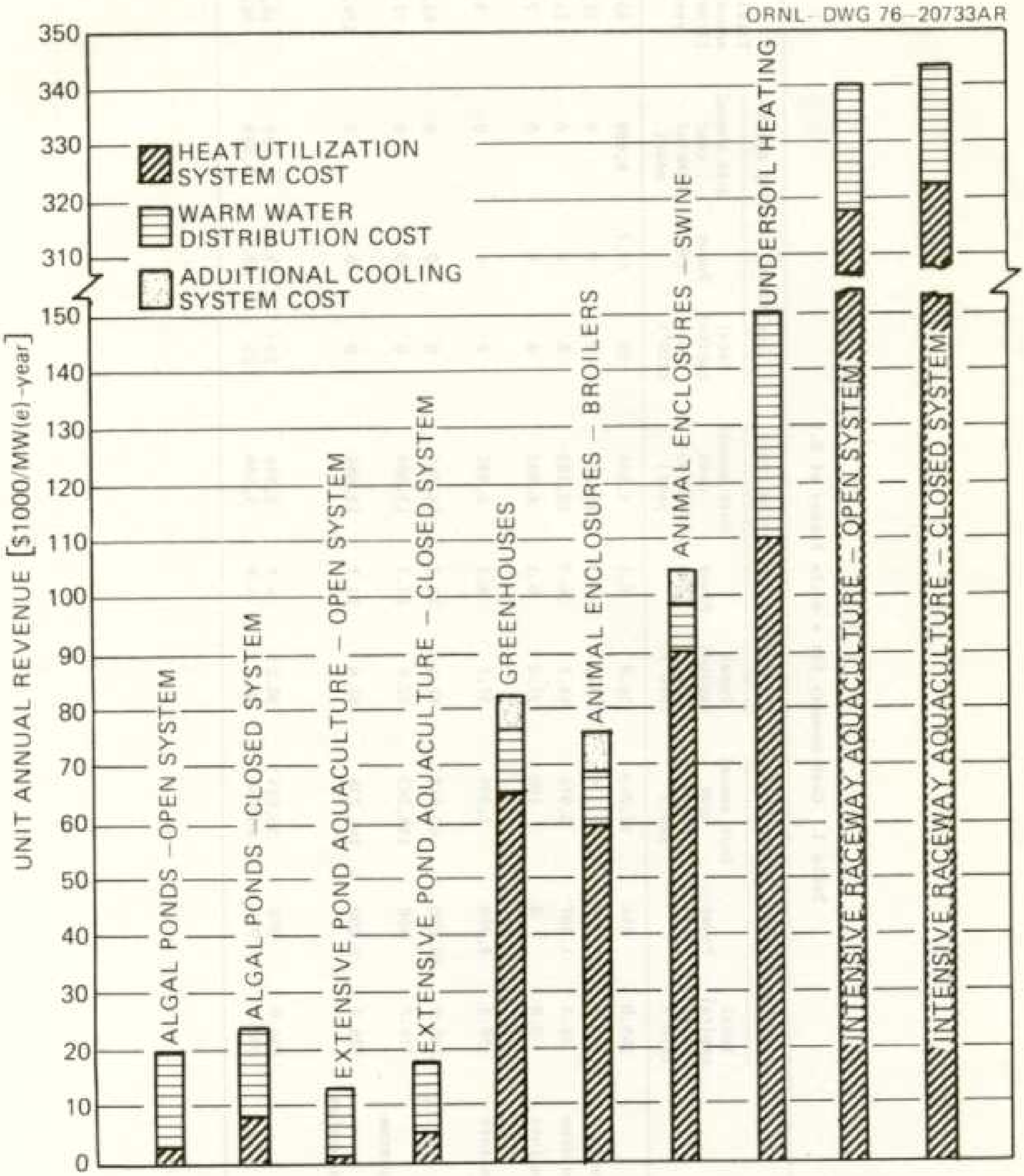

Fig. 1. Cost for utilizing all reject heat from a 1000 MW(e) power plant with a scaling factor of 1.0.

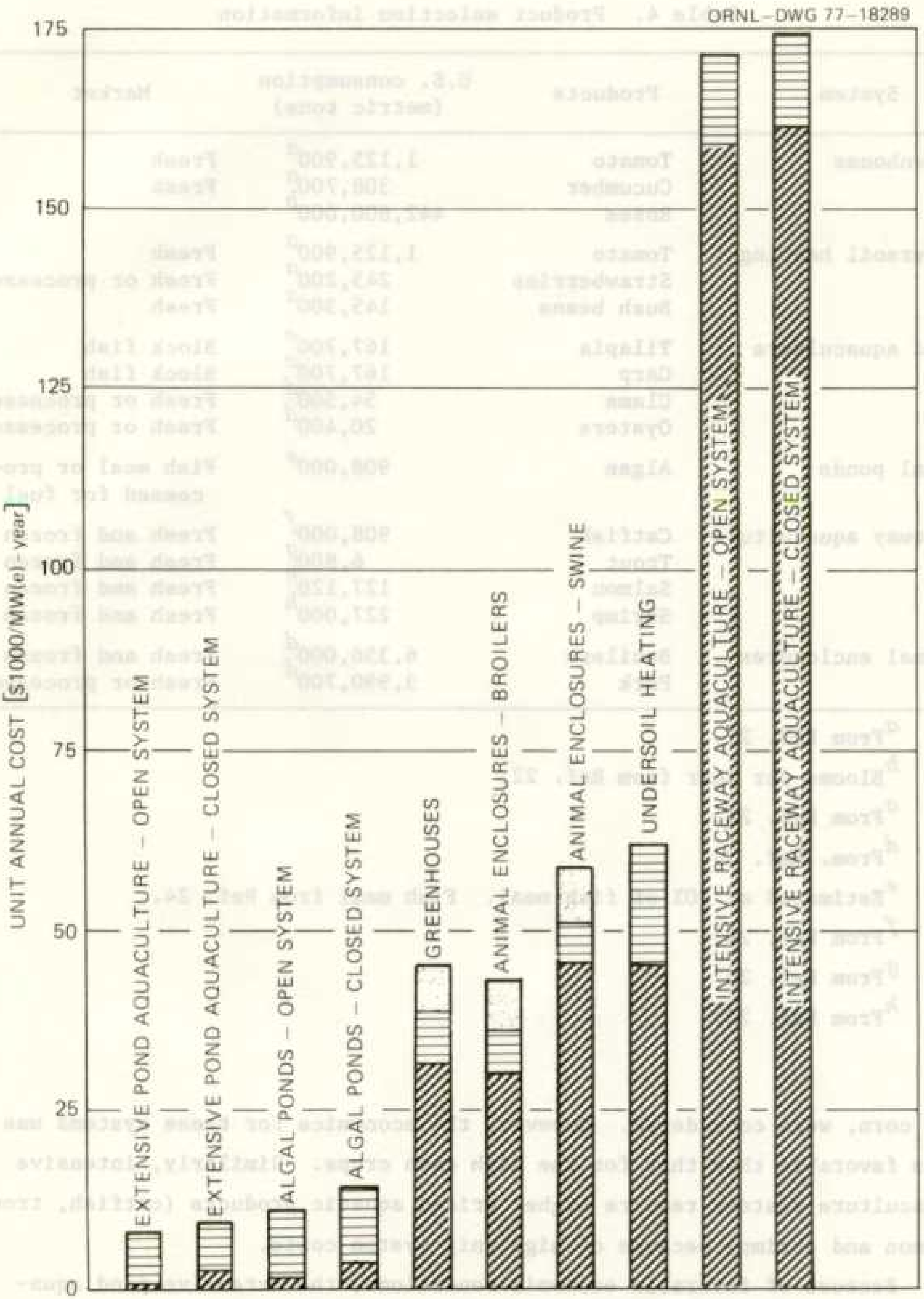

Fig. 2. Cost for utilizing all reject heat from a 1000 MW(e) power plant with a scaling factor of 0.9.

Table 4. Product selection information

System	Products	U.S. consumption (metric tons)	Market
Greenhouse	Tomato	1,125,900[a]	Fresh
	Cucumber	308,700[a]	Fresh
	Roses	442,600,000[b]	
Undersoil heating	Tomato	1,125,900[a]	Fresh
	Strawberries	245,200[a]	Fresh or processed
	Bush beans	145,300[a]	Fresh
Pond aquaculture	Tilapia	167,700[c]	Block fish
	Carp	167,700[c]	Block fish
	Clams	54,500[d]	Fresh or processed
	Oysters	20,400[d]	Fresh or processed
Algal ponds	Algae	908,000[e]	Fish meal or processed for fuel
Raceway aquaculture	Catfish	908,000[f]	Fresh and frozen
	Trout	6,800[g]	Fresh and frozen
	Salmon	127,120[h]	Fresh and frozen
	Shrimp	227,000[h]	Fresh and frozen
Animal enclosures	Broilers	6,356,000[d]	Fresh and frozen
	Pork	3,990,700[d]	Fresh or processed

[a]From Ref. 22.

[b]Blooms per year from Ref. 22.

[c]From Ref. 23.

[d]From. Ref. 24.

[e]Estimated at 20% of fish meal. Fish meal from Ref. 24.

[f]From Ref. 25.

[g]From Ref. 26.

[h]From Ref. 23.

and corn, were considered. However, the economics for these systems was less favorable than that for the high cash crops. Similarly, intensive aquaculture systems require higher priced aquatic products (catfish, trout, salmon and shrimp) because of high unit system costs.

Because of favorable economic conditions, the extensive pond aquaculture system has a wide range of product markets. Carp and tilapia can be raised for the block fish (ground compacted fish blocks used for fish sticks and portions) market or sold on the fresh market. Oysters and clams can similarly be sold fresh or for processing.

Algae can be utilized in animal feeds to replace a portion of the fish meal used. For the purposes of this study it was assumed that algal products replaced about 20% of the fish meal sold in the U.S.

The annual revenue estimates, presented in Table 5, were based on the product selections in Table 4. The unit annual revenue estimates are summarized in Fig. 3.

As an index of economic merit the unit annual revenue, from Fig. 3, was divided by the system unit annual cost from Tables 2 and 3. The economic merit index results for an economic scale factor of 1.0 are presented in Fig. 4. Similar results for an economic scale factor of 0.9 are presented in Fig. 5.

The economic merit index was essentially used to determine which of the systems appeared to be economically feasible. The system unit annual cost was used in this analysis because it represented the basic cost to own the system. If the economic merit index exceeded unity, the system was rated economically feasible.

Since the system unit annual cost does not include operating costs (other than power costs associated with operation of the system as a heat dissipation system), it is not a complete measure of profitability. Obviously, a technology with an economic merit index close to unity can be unprofitable if high operating costs are incurred. In general, however, it is probable that technologies with a large economic merit index would be more profitable than those with a low value.

The inability of some systems to use reject heat in the summer was accounted for in the heat cost paid by the user. This will be discussed in a succeeding section of this report.

A comparison of Figs. 4 and 5 reveals that the economic scale factor does not significantly affect the economic index results. Although the magnitude of the index increases for a scale factor of 0.9, the relative rankings of the applications remain the same. The only significant difference between Figs. 4 and 5 is the fact that the closed algal pond system becomes economically feasible (economic index >1) when the scale factor decreases from 1 to 0.9.

Table 5. System revenue estimates

System	Product	Yield (metric ton/ha)	Price ($/metric ton)	Unit revenue [$/MW(e)-year]
Greenhouse	Tomato	243.0[a]	381[b]	37,022
	Cucumber	88.5[a]	229[b]	8,112
	Roses	1,667,500.0[c]	450,000[c]	180,000
Undersoil heating	Tomato	22.9[d]	381[b]	43,600
	Bush bean	13.6[d]	405[b]	27,700
	Strawberries	4.9[d]	629[b]	15,600
Extensive pond aquaculture	Tilapia or carp	7.4[e]	770[f]	1,680
	Clam	113.5[g]	1,672[h]	56,240
	Oyster	113.5[i]	1,672[h]	56,240
Intensive raceway aquaculture	Catfish	2,270.0[j]	1,100[k]	1,000,000
	Trout	72.6[l]	2,640[m]	76,800
	Shrimp	34.1[n]	4,400[m]	60,000
Algal ponds	Algae	113.5[o]	169[p]	5,500
Animal enclosures	Broilers	329.1[q]	473[r]	50,514
	Pork	1,130.5[q]	752[r]	272,200

[a] From Ref. 4.

[b] From Ref. 22.

[c] Yield data in blooms/ha-year from Ref. 27. price in $/ha-year from Ref. 28.

[d] Yield increase due to undersoil heating. From Ref. 5.

[e] Carp yield from Ref. 29; tilapia from Ref. 30.

[f] From Ref. 31.

[g] From Ref. 15.

[h] From Ref. 24.

[i] From Ref. 32.

[j] From Ref. 7.

[k] From Ref. 33.

[l] From Ref. 26.

[m] From Ref. 22.

[n] Adapted from Ref. 34.

[o] From Ref. 5.

[p] Estimated using protein cost of fish meal. Fish meal at $40/ton.

[q] From Ref. 8.

[r] From Ref. 22.

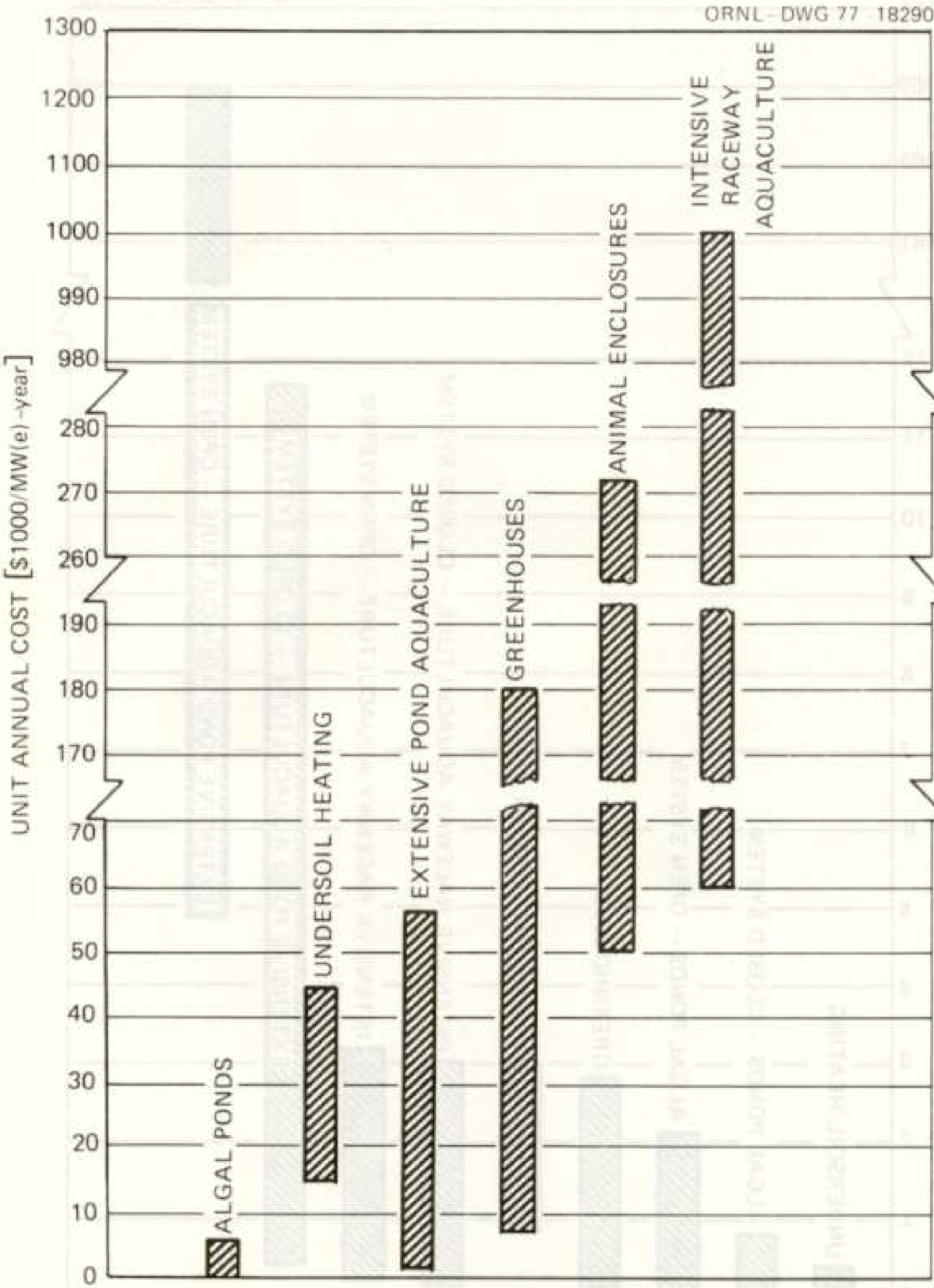

Fig. 3. Unit annual revenue.

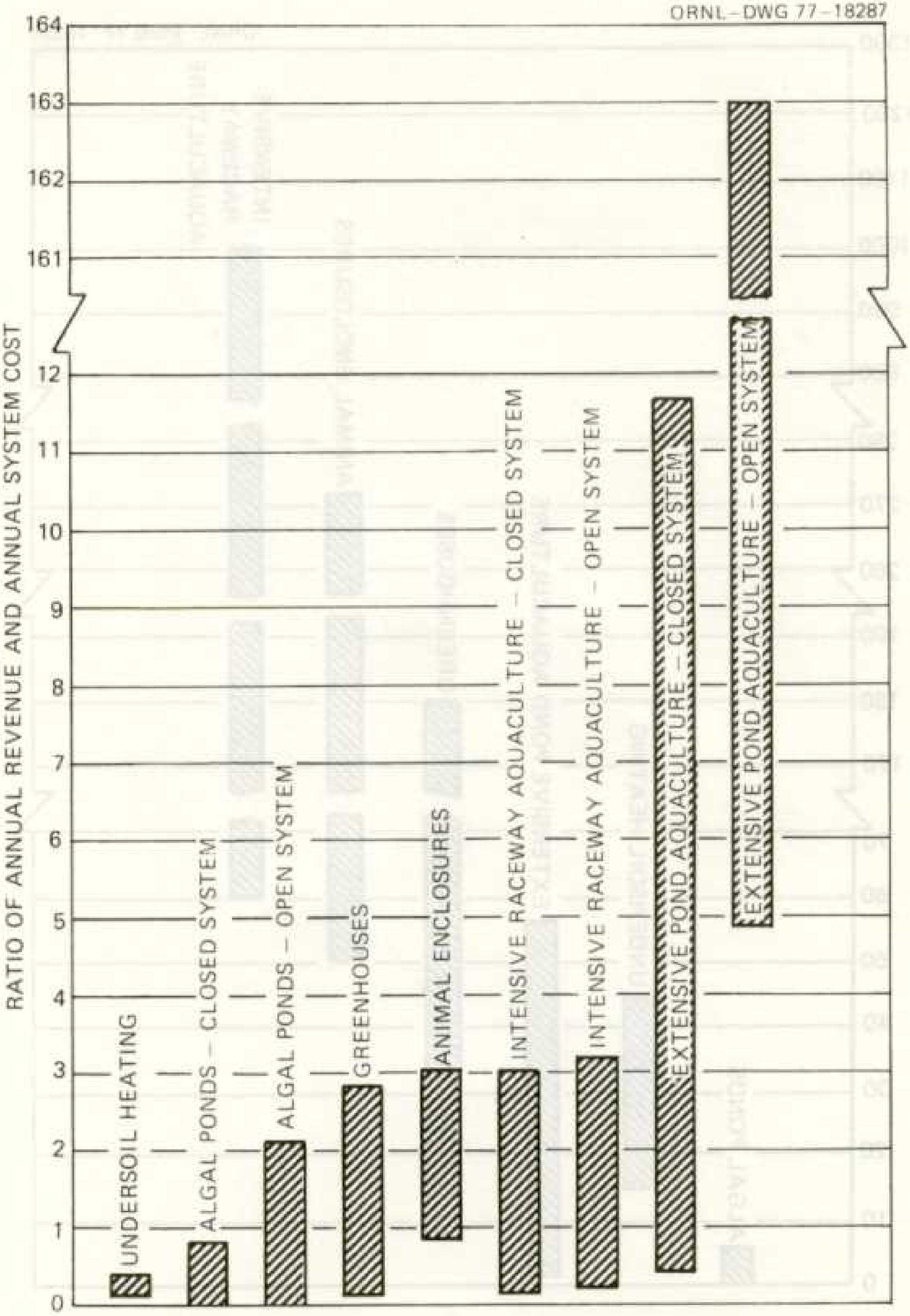

Fig. 4. Economic index for waste heat utilization systems using economic scale factor of 1.0.

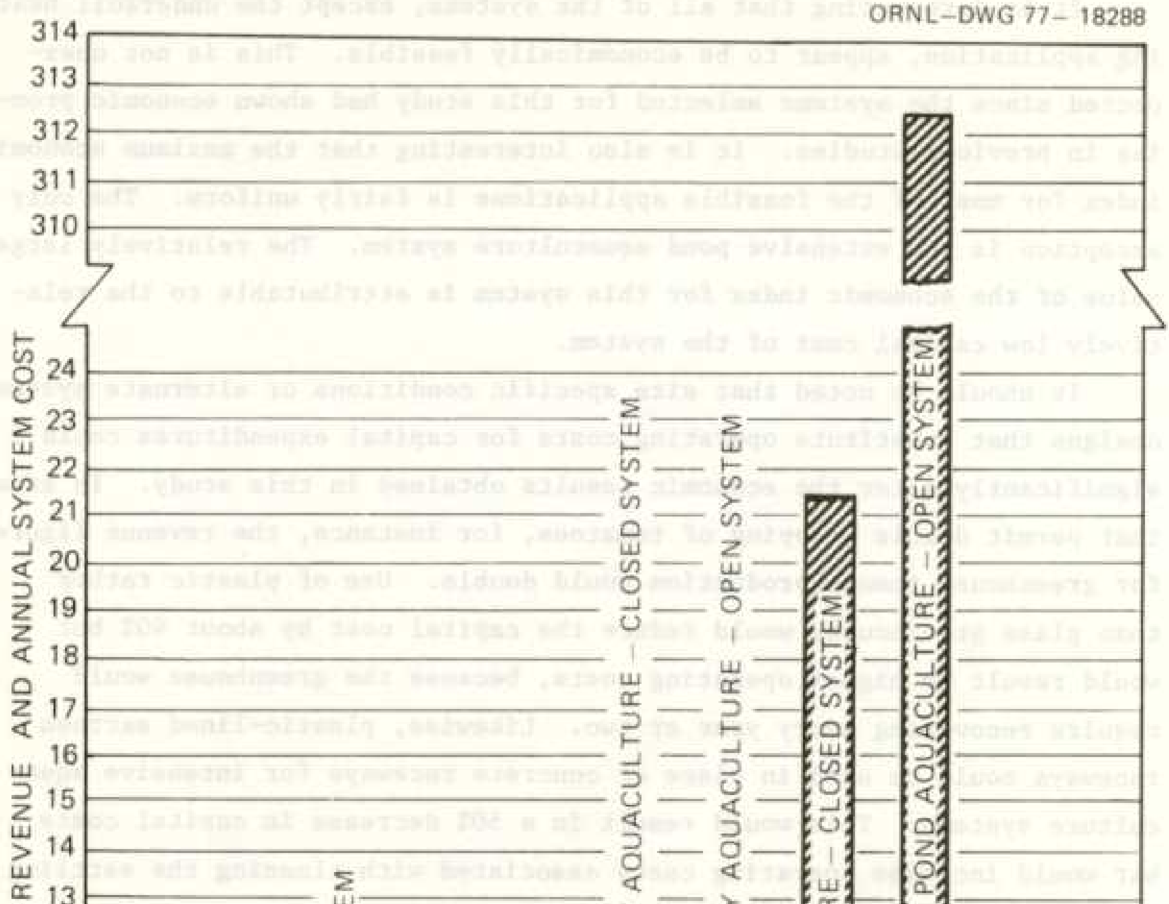

Fig. 5. Economic index for waste heat utilization systems using economic scale factor of 0.9.

It is interesting that all of the systems, except the undersoil heating application, appear to be economically feasible. This is not unexpected since the systems selected for this study had shown economic promise in previous studies. It is also interesting that the maximum economic index for most of the feasible applications is fairly uniform. The only exception is the extensive pond aquaculture system. The relatively large value of the economic index for this system is attributable to the relatively low capital cost of the system.

It should be noted that site specific conditions or alternate system designs that substitute operating costs for capital expenditures could significantly alter the economic results obtained in this study. In areas that permit double cropping of tomatoes, for instance, the revenue figures for greenhouse tomato production would double. Use of plastic rather than glass greenhouses would reduce the capital cost by about 40% but would result in higher operating costs, because the greenhouse would require recovering every year or two. Likewise, plastic-lined earthen raceways could be used in place of concrete raceways for intensive aquaculture systems. This would result in a 50% decrease in capital costs but would increase operating costs associated with cleaning the settling basin required in such systems.

Marketing Analysis

As stated previously, all of the systems considered, with the exception of the greenhouse complex and animal enclosures, are capable of satisfying the yearly heat rejection needs of a 1000-MW(e) power plant. However, constraints associated with marketing the system products may limit widespread use of these systems.

Based on the U.S. consumption figures presented in Table 4 and the yield data from Table 5, the area required to satisfy 50 to 100% of the U.S. demand for the system products was computed. The minimum and maximum areas are presented in Table 6.

The marketing index, presented in Fig. 6, was computed by dividing the area required to satisfy 100% of the U.S. demand by the area required to satisfy the heat dissipation needs of a 1000-MW(e) power plant. This

It is interesting that all of the systems, except the undersoil heating application, appear to be economically feasible. This is not unexpected since the systems selected for this study had shown economic promise in previous studies. It is also interesting that the maximum economic index for most of the feasible applications is fairly uniform. The only exception is the extensive pond aquaculture system. The relatively large value of the economic index for this system is attributable to the relatively low capital cost of the system.

It should be noted that site specific conditions or alternate system designs that substitute operating costs for capital expenditures could significantly alter the economic results obtained in this study. In areas that permit double cropping of tomatoes, for instance, the revenue figures for greenhouse tomato production would double. Use of plastic rather than glass greenhouses would reduce the capital cost by about 40% but would result in higher operating costs, because the greenhouse would require recovering every year or two. Likewise, plastic-lined earthen raceways could be used in place of concrete raceways for intensive aquaculture systems. This would result in a 50% decrease in capital costs but would increase operating costs associated with cleaning the settling basin required in such systems.

Marketing Analysis

As stated previously, all of the systems considered, with the exception of the greenhouse complex and animal enclosures, are capable of satisfying the yearly heat rejection needs of a 1000-MW(e) power plant. However, constraints associated with marketing the system products may limit widespread use of these systems.

Based on the U.S. consumption figures presented in Table 4 and the yield data from Table 5, the area required to satisfy 50 to 100% of the U.S. demand for the system products was computed. The minimum and maximum areas are presented in Table 6.

The marketing index, presented in Fig. 6, was computed by dividing the area required to satisfy 100% of the U.S. demand by the area required to satisfy the heat dissipation needs of a 1000-MW(e) power plant. This

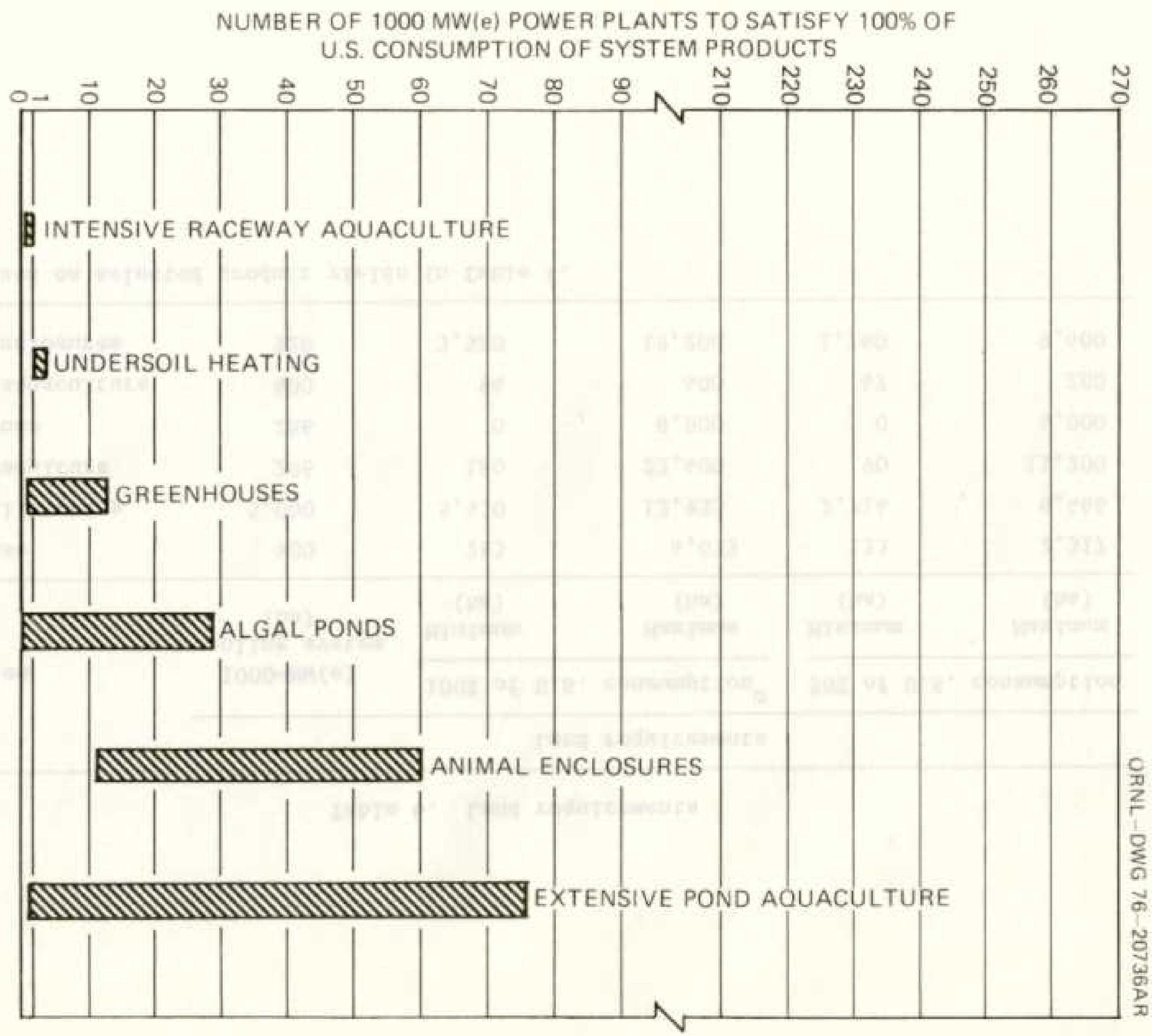

Fig. 6. Marketing index for waste heat utilization systems.

index indicates the number of power plants required to satisfy the total U.S. demand for products from the heat utilization system. Essentially it is an indicator of the potential impact the system could have in the power generating industry.

Analysis of Fig. 6 indicates that extensive pond aquaculture systems would be least constrained by market conditions. Animal enclosures also did not face serious marketing constraints. The systems that relied on intensive production (i.e., greenhouses and intensive aquaculture) were constrained to a relatively small number of power stations due to market limitations. The undersoil heating system was limited to a small number of power stations because of the large acreage requirements for a single power station.

Power Plant Performance Analysis

The goal of this analysis was to determine the effect utilization of reject heat would have on power plant performance. If the waste heat utilization system dissipates heat less effectively than a cooling tower, the turbine back pressure will rise thus reducing the power output of the turbine. If a reduction in power output is the result of utilization of reject heat, then an economic penalty, associated with the lost power production, must be assessed against the heat utilization system.

The power plant performance was estimated using a previously developed computer code.[14] This code was written to accept conventional (i.e., once through, cooling towers, spray ponds) heat rejection and heat utilization systems in the design of the heat rejection system. Utilizing ambient weather data, the code is capable of predicting power plant performance and the thermal performance of the heat rejection system.

For the purposes of this analysis the computer code was used to predict the power plant performance when the reject heat use systems under study were used as the heat rejection system. The performance of these systems was then compared to the power station performance when a wet cooling tower was used. The tower used in the analysis had a design approach of 10.0°C (18°F), a range of 16.7°C (30°F) and a design wet bulb of 24.4°C (76°F).

The power plant performance was computed for a typical summer and winter day. The appropriate ambient weather data is presented in Table 7. The relative performance of the systems is presented in Table 8. For this analysis the power production using a wet tower was used as the base. All other systems were compared to this base. Thus, a value less than 1 in Table 7 indicates a power production less than that for the wet tower. Alternatively, a value greater than 1 indicates a power production greater than that for the wet tower cooling system.

Table 7. Environmental data used in power plant performance calculations

Time	Winter		Summer	
	Dry bulb (°C)	Wet bulb (°C)	Dry bulb (°C)	Wet bulb (°C)
0100	3.9	3.3	16.7	11.7
0200	3.9	3.3	15.6	11.1
0300	3.3	3.8	14.4	11.1
0400	3.3	2.8	14.4	11.1
0500	2.8	2.2	15.6	11.1
0600	2.8	2.2	16.7	11.7
0700	2.8	2.2	17.8	11.7
0800	3.3	2.8	18.9	11.7
0900	3.9	2.8	20.0	12.2
1000	4.4	2.8	21.1	12.2
1100	5.0	2.8	22.2	12.2
1200	5/6	3.3	23.3	12.2
1300	6.1	3.3	24.4	12.8
1400	6.7	3.3	25.0	12.8
1500	7.2	3.3	25.5	12.8
1600	7.8	3.3	25.5	12.8
1700	7.2	3.3	25.0	12.2
1800	6.7	3.3	24.4	12.2
1900	6.1	3.3	23.9	12.2
2000	6.1	3.3	22.8	12.2
2100	5.6	3.3	21.7	11.7
2200	5.6	3.3	20.6	11.7
2300	5.0	3.3	18.9	11.7
2400	4.4	3.3	17.8	11.7

Table 8. Ratio of power plant performance for utilization systems and cooling tower

System	Summer	Winter
Cooling tower	1.00	1.00
Greenhouse	1.00[a]	0.98
Animal enclosures	1.00[a]	0.98
Extensive pond aquaculture	0.98	1.00
Intensive pond aquaculture	0.98	1.00
Undersoil heating	0.98	1.00

[a]Cooling tower used in summer operation.

As indicated in Table 8, it was assumed that a cooling tower was used in summer in place of the greenhouse and animal enclosure systems. This insured consistency with earlier assumptions concerning these systems.

An examination of Table 8 indicates that none of the systems differs significantly from the power production using a cooling tower. This is not surprising since the heat utilization systems were sized to meet the critical summer heat rejection needs of the power station. The results shown in Table 8 indicate that there is essentially no penalty, in terms of reduced power production, associated with the use of the reject heat utilization systems. Therefore, no penalties were assessed to any technology.

The results in Table 8 are significant in terms of implementation potential since they indicate that power production will not be adversely affected when reject heat is used beneficially. This is important to the power company because their charter task is the production of electricity. They would, therefore, be reluctant to implement technologies that would adversely affect their ability to generate power. The indication that power production does not suffer when reject heat is used could lessen utility reluctance to implement such systems.

Implementation Assessment

The purpose of this assessment was to determine which technologies appeared to have a high potential for implementation. Consideration of the previously presented economic, marketing and power plant performance criteria were used for this assessment. The applications were then ranked in descending order according to their implementation potential.

The power plant performance analysis indicated that all systems were of about equal merit. Therefore, for the purposes of this assessment, power plant performance considerations did not play a role in ranking the applications.

The economic analysis (Figs. 4 and 5) indicated that extensive pond aquaculture systems were economically superior to the other systems. From Fig. 6 it was also apparent that it was least constrained by marketing considerations. Therefore, extensive pond aquaculture systems appeared to have the highest potential for implementation.

The economic index results from Figs. 4 and 5 indicated that intensive raceway aquaculture, greenhouses and animal enclosures were of about equal merit. The marketing index, however, greatly favored the animal enclosure systems. Therefore, animal enclosures were ranked second.

Although algal ponds rated slightly below greenhouse and intensive aquaculture, its superior market index resulted in its ranking in third place.

As stated previously the economic index for greenhouses and intensive aquaculture systems were about equal. However, the market index indicated that greenhouses should be ranked above the intensive aquaculture applications.

Since the undersoil heating system did not appear to be economically feasible, it was ranked last.

A summary of these rankings is presented in Table 9. It is interesting to note that technologies that achieve a favorable economic index due to intensive production techniques for high valued products (i.e., greenhouses, and intensive aquaculture) generally have marketing problems. The highest rated system uses extensive culture techniques and a low

Table 9. Ranking of waste heat utilization technologies

Ranking	System
1	Extensive pond aquaculture
2	Animal enclosures
3	Algal ponds
4	Greenhouses
5	Intensive raceway aquaculture
6	Undersoil heating

capital cost production system. Therefore, the low capital cost leads to a favorable economic index and the lower production rate yields a high market index.

INCENTIVES FOR USE OF REJECT HEAT

The implementation assessment rankings essentially indicate which systems possess the potential to play a prominent role in reject heat utilization in the U.S. and which systems probably do not have the potential for significant national impact. However, the assessment essentially examined the applications only as reject heat dissipation systems. To determine if the projected potential can be realized, the systems should be analyzed as agricultural or aquacultural operations. The assessment in this section focuses on this aspect by examining a potential user's incentives for utilizing the reject heat. Specifically, heat cost and system thermal performance considerations are examined. Obviously if heat cannot be supplied to the user at an economically competitive price, there will be no incentive to use it. Thus, applications that appear to have a high potential for implementation may be limited by heat cost or system thermal performance considerations.

Heat Cost Using Reject Heat

For the implementation analysis it was assumed that the utility would finance the warm water distribution system. From Tables 2 and 3 it is evident that the distribution system annual cost exceeds that for a cooling tower. For the purposes of this analysis it was assumed that the utility would recover this added expense in the form of a user heat charge. Since it is doubtful that the utility would allow itself to be dependent on a reject heat utilization system which it did not own, it is probable that cooling towers would be constructed as backup. Therefore, the heat cost analysis was performed for the situation where credit is taken for replacement of cooling tower and for the case where no such credit is taken. As previously mentioned, the greenhouse and animal enclosure systems require a cooling tower for summer operation. Therefore, no cooling tower replacement credit was taken for these applications.

Since the economic scale factor appears to be an important consideration, the heat cost analysis was performed for a scale factor of 1.0 and 0.9. The total annual cost to deliver the warm water is presented in Table 10 for an economic scale factor of 1.0 and in Table 11 for a scale factor of 0.9. The total cost includes the fixed charges for the pipeline and power costs for pumping. Maintenance costs were assumed to be negligible in this analysis.

Table 12 presents the annual heat delivery capacity of the distribution system at various capacity factors. A capacity factor of 0.8 was used as the maximum since this is the expected power plant capacity factor.

The unit heat costs for the case where no credit is taken for cooling tower replacement, shown in Tables 13 and 14, were computed by dividing the total annual costs from Tables 10 and 11 by the annual heat delivery capacity from Table 12.

For the case where credit was taken for replacement of the cooling tower, $\$6.7 \times 10^6$/year was subtracted from the total annual costs. The heat cost was then computed as described above. Since the heat utilization system has now replaced the cooling tower, it is not independent of the power station. Therefore, the capacity factor of the distribution

Table 10. Annual cost for warm water distribution system using economic scaling factor of 1.0

System	Fixed cost (10^6 \$/year)	Operating cost at capacity factor = 1 (10^6 \$/year)	Total annual cost (10^6 \$/year)					
			Capacity factor					
			0.8	0.6	0.4	0.3	0.2	0.1
Greenhouse	11.4	1.3	12.4	12.6	11.9	11.8	11.7	11.5
Algal ponds	13.8	3.2	16.4	15.7	15.1	14.8	14.4	14.1
Extensive pond aquaculture	11.3	1.3	12.3	12.1	11.8	11.7	11.6	11.4
Intensive raceway aquaculture	16.3	5.1	20.4	19.4	18.3	17.8	17.3	16.8
Animal enclosures	9.1	1.0	9.9	9.7	9.5	9.4	9.3	9.2
Undersoil heating	36.8	2.6	38.9	38.4	37.8	37.6	37.3	37.1

Table 11. Annual cost for warm water distribution system using economic scaling factor of 0.9

System	Fixed cost (10^6\$/year)	Operating cost at capacity factor = 1 (10^6\$/year)	Total annual cost (10^6 \$/year)					
			Capacity factor					
			0.8	0.6	0.4	0.3	0.2	0.1
Greenhouse	5.7	1.3	6.7	6.5	6.2	6.1	6.0	5.8
Algal ponds	7.1	3.2	9.7	9.0	8.4	8.1	7.7	7.4
Extensive pond aquaculture	5.8	1.3	6.8	6.6	6.3	6.2	6.1	5.9
Intensive raceway aquaculture	8.2	5.1	12.3	11.3	10.2	9.7	9.2	8.7
Animal enclosures	4.7	1.0	5.5	5.3	5.1	5.0	4.9	4.8
Undersoil heating	14.3	2.6	16.4	15.9	15.3	15.1	14.8	14.6

Table 12. Annual heat delivery of warm water distribution system

Capacity factor	Quantity of heat (10^7 GJ/year)
0.8	4.71
0.6	3.59
0.4	2.39
0.3	1.80
0.2	1.20
0.1	0.60

Table 13. Unit heat cost for delivered warm water with no cooling tower replacement credit using an economic scale factor of 0.9

System	Heat cost (¢/GJ)					
	Capacity factor					
	0.8	0.6	0.4	0.3	0.2	0.1
Greenhouse	14	18	26	34	50	97
Algal ponds	21	25	35	45	64	123
Extensive pond aquaculture	14	18	26	34	51	98
Intensive raceway aquaculture	26	31	43	51	77	145
Animal enclosures	12	15	21	27	38	80
Undersoil heating	35	44	64	84	123	243

Table 14. Unit heat cost for delivered warm water with no cooling tower replacement credit using an economic scale factor of 1.0

System	Heat cost (¢/GJ)					
	Capacity factor					
	0.8	0.6	0.4	0.3	0.2	0.1
Greenhouse	26	34	50	66	98	192
Algal ponds	35	44	63	82	120	235
Extensive pond aquaculture	26	34	49	65	97	190
Intensive raceway aquaculture	43	54	74	99	144	280
Animal enclosures	21	27	40	52	78	153
Undersoil heating	83	107	158	209	311	618

system must match that of the power station. As stated previously, this capacity factor is 0.8. The results of this analysis are shown in Table 15. As previously indicated, cooling towers would not be replaced for the greenhouse and animal enclosure applications. They were, therefore, not included in the analysis.

Table 15. Heat cost for delivered warm water with cooling tower replacement credit and a capacity factor of 0.8

System	Heat cost (¢/GJ)	
	Scale factor	
	1.0	0.9
Algal ponds	21	7
Extensive pond aquaculture	12	0
Intensive raceway aquaculture	29	13
Undersoil heating	69	36

It is obvious from Tables 13 and 14 that the unit heat cost decreases as the capacity factor increases. This is expected since the major cost factor is the cost for the piping system. With a low capacity factor the pipeline is idle much of the time and the annual cost is borne by a relatively low annual heat delivery rate. As the capacity factor rises the total annual cost rises slowly because the pipeline capital cost portion of the annual cost dominates the increased pumping cost. However, the total heat delivered increases rapidly. Thus, the total annual cost is distributed over a larger amount of delivered heat resulting in a decrease in the unit heat cost.

A comparison of Tables 13 and 14 indicates that the user heat charge is generally halved when the economic scale factor is reduced from 1.0 to 0.9. Thus, the user heat cost analysis will be strongly influenced by the economies of scale in constructing the water distribution system. The results for an economic scale factor of 0.9, presented in Table 13, indicate that for most of the cases considered, the heat cost appears to be economically attractive. However, the assumption of a scale factor of 0.9 is probably an overoptimistic assumption considering the nature of the construction. Since these results do not appear to have a significant impact and are based on an optimistic assumption, it was decided to concentrate on the results for a scale factor of 1.0 for the user economic feasibility analysis. Assuming a scale factor of 1.0 then, essentially represents a conservative analysis assumption.

For applications (such as greenhouses and animal enclosures) where fossil fuels are typically used for winter heating, the economic feasibility of using reject heat depends upon the heat cost using alternative fossil fuels. Systems, such as aquaculture, that normally close production during the winter, rather than burn fossil fuels, would require a more detailed analysis. This analysis would balance the cost of operating during the winter against the revenue from the additional crop or crops. Since an analysis of this detail was beyond the scope of this report, it was assumed that the economic feasibility criteria for the systems that normally shut down in winter were the same as that for the systems that use fossil fuels.

For the purposes of this analysis it was assumed that the waste heat user would install a backup heating system to insure his heat supply in the event of an unscheduled power plant outage. In this situation, reject heat would be used to displace fossil fuel that would normally be burned in the heating system. Therefore, reject heat use was considered economically viable if the heat cost was below the fossil fuel heat cost attributable to the fuel.

It was assumed that fossil fuel heat costs were bounded by natural gas at the lower end and oil at the upper end. Fuel prices of \$1.75/GJ (\$1.75/10^6 Btu)* and \$2.20/GJ (\$2.20/10^6 Btu) were used for natural gas and oil respectively. A burner efficiency of 75% was also assumed. Therefore, the fossil fuel heat cost was in the range of \$2.33 to 2.93/GJ (\$2.33 to 2.93/10^6 Btu). Thus, heat costs for the reject heat system were required to be below \$2.33/GJ (\$2.33/10^6 Btu) to be economically desirable. If they were within the range of \$2.33 to 2.93/GJ (\$2.33 to 2.93/10^6 Btu), they were considered economically viable.

An examination of Table 14 indicates that the heat cost is a function of the capacity factor. Therefore, before an analysis of economic feasibility can be made, probable capacity factors for the systems must be determined. The results of a previous greenhouse study[35] suggest that the capacity factor for greenhouses is about 0.2 or less depending upon local climatic conditions. For the Portland, Oregon area a capacity factor of 0.1 was used. Because the animal enclosure system operates very much like the greenhouse system, a capacity factor of 0.1 was also used for this system. Since the other systems were designed to accommodate the yearly cooling needs of the power station, a capacity factor of 0.8 was assumed.

Using the assumed system capacity factors the user heat cost for reject heat appears to be an economically attractive alternative for all of the potential users considered in this study. Therefore, the cost of using reject heat does not appear to be a limiting factor for implementation of any of the systems.

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*For the purposes of this report, 1×10^6 Btu will be equated to 1.0 GJ. The actual conversion is 1.055 GJ.

It should be noted that this conclusion could change if a significant decrease in capacity factor occurred for any of the technologies. Table 14 indicates that reject heat would not be an economic choice for some of the applications if the capacity factor were to drop low enough. For instance the capacity factor for greenhouses in some areas (e.g., Knoxville, Tennessee) can fall to as low as 0.05. This would raise the heat cost to about \$4.00/GJ (\$4.00/10^6 Btu) and result in reject heat being at an economic disadvantage. Thus, the economic viability of using reject heat is highly dependent on the capacity factor of the distribution system.

A comparison of Table 15 and the fossil fuel price range indicates that, if a credit can be taken for cooling tower replacement, reject heat is an economically attractive alternative for all systems.

System Performance Analysis

The power plant performance analysis indicated that the systems performed acceptably when viewed as heat rejection systems. However, that analysis did not indicate if the thermal performance of the systems was beneficial when viewed as an agricultural or aquacultural system.

The system performance analysis examined the thermal performance of the reject heat utilization systems to determine if it provided a reasonable growing environment. If, for example, the pond temperature rises too far above the optimal fish growth range, mortality may occur. Thus, the potential user would have no incentive to use reject heat in the summer. This would decrease the warm water distribution system capacity factor and raise the heat cost. The rise in heat cost may in turn result in reject heat no longer being an economically attractive alternative. Therefore, the system performance analysis was performed to indicate if the thermal performance of the system is advantageous to the potential user when compared to ambient systems. It was also used to verify if the capacity factors assumed in the heat cost analysis were reasonable.

It was expected that use of reject heat would be beneficial for all systems for winter operation. This expectation was confirmed by the computer code simulation of the reject heat system thermal performance. The greenhouse and animal raising systems were maintained at temperatures of 21°C (70°F) or higher while the ambient temperature dipped to a low of 2.8°C (37°F). The aquaculture systems were also capable of maintaining water temperatures of 21°C (70°F) under this ambient condition. Since undersoil heating essentially lengthens the growing season in the fall and spring, there is no benefit in terms of added crop production during the winter months. It was clear from these results that the critical period, in terms of system performance, would be in the summer.

Two factors contribute to summer operation being the critical period for the thermal performance of the reject heat system. The first is the fact that ambient air and water temperatures are elevated (in comparison to winter conditions). Therefore, heating requirements are reduced or eliminated depending upon ambient temperatures. Secondly, power plant efficiencies are generally lower in the summer because of increased condenser cooling water inlet temperatures. This results in an increased amount of heat being rejected. Therefore, a larger amount of reject heat must be handled by the heat utilization system at a time when the system heating requirements have been reduced because of ambient weather conditions.

The greenhouse and animal enclosure systems utilize a cooling tower for summer heat rejection. Therefore, their summer performance was not analyzed. The undersoil heating system is most beneficial during the cool spring and fall seasons. During summer the heat addition is not really necessary but it apparently does not detrimentally affect growth.[5] Therefore, a detailed analysis of summer performance was not performed for the undersoil heating system.

Analysis of the aquaculture systems indicated that the water temperature was maintained below 35°C (95°F) during the summer. Since the species chosen for the extensive pond system were tropical species, this temperature helped to promote their optimal growth. Species of algae are also available that could benefit from this temperature. Therefore, the extensive pond aquaculture and algal systems could benefit from the addition of reject heat in summer.

The summer water temperature results indicated that intensive aquaculture systems would probably be required to use a dual product system [similar to that used in the Public Service Electric and Gas (PSE&G) Mercer Generating Station system described in Ref. 34] to maximize the use of their facility. In winter they could produce a cold water species (trout) and in summer a warm water species (freshwater prawns). In this way their capacity factor would be maintained at a high level and the heat cost kept to a minimum. If a single species were to be raised throughout the year, reject heat would probably not be required in the summer. This would decrease the capacity factor to about 0.4 and raise the unit heat cost. Although the heat cost was raised it would still be economically competitive with fossil fuels. Therefore, for the purpose of this analysis it was assumed that the system thermal performance presented no serious barrier to reject heat utilization.

Assessment of User Incentives

The purpose of this assessment was to determine if user considerations would affect the implementation potential of any of the reject heat use systems. Consideration of the user heat cost and system thermal performance analysis criteria were used in the evaluation. The user heat cost analysis indicated that reject heat appeared to be an economical source of heat for the potential users when compared to typical fossil fuel prices. Although the heat cost could become uneconomical for some users, if the warm water distribution system capacity factor dropped to exceedingly low levels, it is expected that the capacity factor will remain high enough during normal operation to make reject heat attractive.

The system thermal performance analysis indicated that most of the systems (greenhouse and animal enclosure systems being the exception) could beneficially utilize the reject heat throughout the year. The normal mode of operation would have to be changed for the intensive aquaculture system to a diseasonal system. However, this poses no serious operational problem.

Evaluation of these criteria indicated that user considerations would not pose any limitations to the implementation of these systems.

DISCUSSION OF RESULTS

The relationship between user heat cost and capacity factor indicates that the ambient weather conditions can play an important role in the economic evaluation of waste heat utilization systems. In addition to influencing the warm water distribution system capacity factor, climatic factors will influence the size, hence the market index, of the heat utilization systems. In warmer climates the systems will be larger to compensate for a decrease in heat rejection capability. In cooler climates the systems may be smaller because of enhanced heat rejection capability.

The climatic conditions used in this report did not possess a large annual temperature fluctuation. Thus, systems designed to satisfy summer conditions were able to operate successfully in winter. In areas where the summer and winter temperatures vary greatly this would probably not be the case. It is probable that, in this instance, systems designed to meet the power plant summer cooling needs would be required to shut down part of their operation in winter due to inadequate heat available from the power station. The alternative design approach would be to design the heat utilization system to operate full scale throughout the winter. Then in summer, when the system could not accommodate all of the power plant reject heat, a small cooling tower could be used to augment the system heat rejection. It is, therefore, obvious that climatic considerations play an important part in the analysis. Because of this, it would seem reasonable to perform additional studies for various regions of the United States. These results could then be combined to provide a more comprehensive analysis of the potential for power plant reject heat utilization in the United States.

The user heat cost analysis indicated that power plant reject heat is an economically attractive heat source. The heat cost, however, represents an average value for the entire complex. Thus, users near the power station are subsidizing those far from the station. If the entire heat utilization complex is owned by a single operator, this presents no problem. However, if the complex consists of portions constructed by different owners, the heat cost should be allocated based on the expense to serve the various sections. Thus, those operators near the station would pay a lower heat cost than those further from the station. An analysis could be performed to determine the relationship between user heat cost and distance from the power station. This could be used to determine the distance from the power station within which reject heat would be economically attractive.

The market index indicates that a waste heat complex consisting of several different users (e.g., greenhouses, animal rearing facilities, and aquaculture) could be used to overcome local marketing constraints. Analysis of this alternative could include biological compatibility considerations (e.g., use of swine manure for the aquaculture system) in addition to the obvious heat flow considerations.

The market index results in Fig. 6 indicate that the extensive pond aquaculture system could be implemented at about 75 power stations. If this figure was achieved in practice, extensive pond aquaculture would utilize the reject heat from 75,000 MW(e) of generating capacity. If all the heat utilization systems were implemented to their maximum potential, reject heat from about 175,000 MW(e) of installed capacity would be utilized. This represents a low temperature thermal energy resource of 8.4×10^9 GJ/year (8.4×10^{15} Btu/year) or an oil equivalent of about 2.3×10^8 m^3/year (1.4×10^9 Bbl/year) that could be added to the U.S. energy supply without requiring any additional primary energy. The potential impact in the power industry can be placed in perspective by examining the expected increases in generating capacity. Recent projections[36] indicate that by 1985 the installed nuclear generating capacity in the U.S. will increase by about 168,000 MW(e). During this period fossil fuel-fired generating capacity is expected to increase by about 223,000 MW(e). Thus, if all the reject heat use systems were implemented to the maximum potential indicated above, they could utilize about 45% of the reject heat from these new stations.

It seems doubtful that the heat utilization systems will be implemented to their maximum potential. However, if they are implemented at only 50% of their potential, the amount of wasted energy productively utilized will be about 4.2×10^9 GJ/year (4.2×10^{15} Btu/year). This represents an oil equivalent of 1.2×10^8 m^3/year (7.2×10^8 bbl/year).

The energy savings realized through the use of reject heat depend upon the application considered. Since greenhouses and animal rearing facilities are typically heated by burning fossil fuel, each unit of energy from the reject heat source will replace about 1.3 units of fossil fuel energy (accounting for a 75% burner efficiency). Thus, if greenhouses and animal enclosures are implemented at 50% of the maximum potential, about 5.6×10^8 GJ/year* (5.6×10^{14} Btu/year), or an oil equivalent of 1.5×10^7 m^3/year (9.7×10^7 bbl/year) of U.S. energy consumption will be replaced by the use of reject heat.

For aquaculture applications, the energy savings are not as direct as for the greenhouse case. Since it is generally not economically feasible to use fossil fuels to heat aquaculture systems, most systems are not productive during the colder winter months. Thus, alternative supplies of fish must be found. Generally these supplies are from ocean fishing fleets. Thus, waste heat aquaculture products will be replacing products from ocean fishing fleets and the energy comparison should be made between these alternatives. In general, about 0.91 metric tons (1 ton) of oil is required for 0.91 metric tons (1 ton) of fish.[37] Thus an aquaculture site of 296 ha (740 acres) producing 7150 kg/ha-year (6500 lb/acre-year) will produce about 2.2×10^6 kg/year (4.8×10^6 lb/year) of fish. This would require an expenditure of 1.2×10^5 GJ (1.2×10^{11} Btu/year) if the fish were caught in the ocean. Thus, utilization of reject heat will replace an equivalent fossil fuel expenditure of 400 GJ/ha-year (1.6×10^8 Btu/acre-year). Since it was assumed that algae replaced fish meal, similar savings can be expected for the algal system. Therefore, implementation of aquaculture systems at 50% of the maximum values indicated in Fig. 6 would represent an energy savings of 4.5×10^6 GJ (4.5×10^{12} Btu/year). This is a savings of 0.1×10^6 m^3/year (0.8×10^6 bbl/year) of oil equivalent.

The preceding discussion of energy utilization and savings was based on the market index figures presented in Fig. 6. The market index figures in turn were based on the consumption figures for the chosen products. Because of economic factors, the products chosen for the greenhouse,

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*Assuming an annual capacity factor of 0.2.

animal rearing and intensive aquaculture systems reflect the most probable product selection. Therefore, the market index figures, presented in Fig. 6, reflect a realistic estimate of the implementation potential for these systems.

For the extensive pond aquaculture system, however, the consumption figures presented in Table 4 probably represent lower bounds on the possible product markets. Since these markets are just beginning to develop, it is probable that the final market for these products will be in excess of the figures in Table 4. Thus, it is probable that the ultimate marketing for the extensive pond aquaculture system will be greater than that indicated in Fig. 6.

OVERALL ASSESSMENT AND RECOMMENDATIONS

The overall assessment of the technologies combined the user assessment and the implementation assessment in arriving at the final rankings. As in the implementation assessment, the technologies were ranked in descending order of potential for wide-scale implementation in the power generating industry.

The user assessment indicated that user considerations did not present any factors that conflicted with the implementation assessment. Thus, the rankings obtained in the implementation assessment did not change when user considerations were included in the analysis.

The overall assessment rankings, presented in Table 16, indicate that extensive pond aquaculture appears to have the greatest potential for wide-scale implementation in the power generating industry. It would, therefore, appear that a vigorous research program should be initiated to hasten implementation of the concept.

The systems rated second, third, and fourth (animal enclosures, algal ponds, and greenhouses) should also be pursued in an effort to speed implementation.

Intensive aquaculture systems, rated fifth, could prove attractive for some specialized applications. Development of this technology should be confined to sites where this option looks especially attractive.

Table 16. Overall assessment rankings

Ranking	System
1	Extensive pond aquaculture
2	Animal enclosures
3	Algal ponds
4	Greenhouses
5	Intensive raceway aquaculture
6	Undersoil heating

However, it does not appear that a vigorous large scale program is justifiable.

Undersoil heating was ranked last, and because of economic considerations should probably not be pursued.

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