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MATHEMATICAL MODELING OF WASTE HEAT MANAGEMENT ALTERNATIVES FOR THE UNITED STATES

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ABSTRACT

Waste heat resulting from electric power generation can produce serious local environmental problems in water bodies which receive the heat. It is possible through added devices or system modifications to divert some of this waste heat to the atmosphere or to useful purposes for the consumer. This paper examines two alternatives to once-through cooling, where all the waste heat is received by a local natural water body. These are (A) dry cooling towers, and (B) the Modular Integrated Utility System (MIUS). In the first case the waste heat is rejected immediately to the atmosphere, and in the second a substantial fraction of the waste heat is utilized in the local community for hot water, space heat, sewage treatment, etc. prior to its release to the atmosphere. Results are obtained using an equilibrium model for the U.S. energy-environment economic system developed previously by the author.

1. INTRODUCTION

The conversion of thermal energy from the combustion of fuel, or from the nuclear fission process, to electrical energy yields approximately two times as much rejected low grade thermal energy, or waste heat, as electrical energy produced. Since the efficiency of electric power production is increased by reducing the temperature of the exhaust steam as much as possible, large amounts of cooling water from rivers, lakes, or the sea must be used as the temporary receiver of this heat, which eventually is transferred to the atmosphere and then into space. During power plant operation the rate of addition of heat to the water body exceeds the rate of transfer of heat to the atmosphere and therefore the water body becomes warmer than it would normally be under natural conditions. This alteration in temperature causes changes in the local ecology of the water body. Some of these changes are undesirable, and could be considered as environmental damage. The effects of rejected heat on the ecology of the water which receives it are well summarized in Refs. [1], [2], and [3].

To reduce or prevent the environmental damage associated with heated water, alternative schemes have been used or proposed. Among these are wet cooling towers, cooling ponds, dry cooling towers, and various ways in which some of the rejected heat can be utilized prior to its ultimate transfer to the atmosphere. References [1] and [3] contain brief descriptions of such systems. One possible system which utilizes much of the waste heat in the Modular Integrated Utility System (MIUS), discussed in Reference [4]. The waste heat from the electric power plant is utilized for residential and commercial space and water heating, as for sewage treatment. Two obvious benefits of a MIUS are the reduction of environmental damage to the natural water body, and the reduction in fuel energy required for space and water heating. These benefits are not without their costs, however. Construction and operation of a MIUS requires capital, labor and energy, which must be considered in the overall assessment of its effectiveness.

This paper considers two alternative systems for the management of waste heat from electric power plants in the U.S. and compares their behavior with that of a reference system in which it is assumed that all cooling for power plants is of the once-through type. The two alternatives considered are: (A) dry cooling towers for all plants, and (B) the use of MIUS's on all plants. The first alternative has been chosen as the ultimate in prevention of undesirable environmental effects from waste heat. Heat transfer to the atmosphere is direct without loss of water through evaporation, and without associated undesirable atmospheric moisture. The second alternative is chosen for its added benefit of energy conservation.

The analysis for the two alternative systems are made using a simple model of the U.S. energy-economic-environment system developed by the author, Ref. [5]. The reference case (in which once-through cooling of power plants is assumed) is developed from economic data in Ref. [7], using environmental costs and control costs given in Refs. [4] and [8]. The model, shown in Fig. 1, assumes quantitative relationships between the energy flows (F's) the goods flows (GU's) the service flows (SU's), the labor (L's) and the environmental services (WU's). Envrionmental damage is accounted for in unwanted goods (GUc*), unwanted service (SU_C*), and decrease in labor productivity in a polluted surroundings. Control costs are accounted for by the monetary value of the environmental services (WU's). All quantitative relationships are determined from system coefficients which relate various outputs to various inputs. Simple analyses, presented in this paper, yield the modified coefficients for the alternative systems considered. Information other than environmental damage and environmental service costs can be obtained from the computed results. These include fuel energy used in each sector, labor used in each sector, distribution of goods and services, and the material well-being of the consumer. The effectiveness of the considered alternative depends on all of these results.

2. DISCUSSION OF THE MODEL

The model as shown in Fig. 1 in a closed-system equilibrium model. Exports and imports are not included, and each sector is assumed to operate in a steady-state equilibrium for which the output value added by the sector is equal to the values contributed by the inputs. Each alternative which is considered is an instantaneous alternative; no changes over time are considered for the total labor and the total energy resource reserves available. Technology changes required for the particular alternative, and rearrangements of the capital necessary for their accomplishment are assumed to be instantaneous. This approach enables one to answer the question: "What would have occurred if we had done these things instead of what we did do?"

2.1 Notation for the Model

The symbols appearing in Fig. 1, and in the equations describing the system operation are defined below, together with the units for each quantity.

E = extraction of energy resources

PG = production of goods

PS = production of services

W = waste removal and control

F_E = fuel to extract fuel (QBtu/yr)[a]

F_{PG} = fuel to production of goods sector (QBtu/yr)

F_W = fuel to pollution control secotr (QBtu/yr)

F_{PS} = fuel to service sector (QBtu/yr)

F_C = fuel to cosumer (QBtu/yr)

L_E = labor for extraction of fuel (B pers-hr/yr)[b]

L_W = labor for pollution control (B pers-hr/yr)

L_{PG} = labor for goods production (B pers-hr/yr)

L_{PS} = labor for service production (B pers-hr/yr)

GU_E = goods units[c] required by extraction (B units/yr)[b]

GU_W = goods units required by pollution control (B units/yr)

GU_{PS} = goods units required by the service sector (B units/yr)

GU_C = goods units purchased by the consumer (B units/yr)

GU_C^* ="unwanted" goods purchased by consumer to combat effects of pollution (B units/yr)

SU_{PG} = service units[d] required by goods production sector (B units/yr)

SU_C = service units purchased by the consumer (B units/yr)

SU^*_C = "unwanted" service units purchased by the consumer to combat pollution (B units/yr)

WU_E = pollution control units[c] required by the extraction sector (B units/yr)

WU_{PG} = pollution control units required by the goods production sector (B units/yr)

WU_{PS} = pollution control units required by the service production sector (B units/yr)

ℓ = hourly wage (\$/per-hr)

P_F = fuel price (\$/MBtu)[f]

P_G = goods price (\$/unit)

P_S = service price (\$/unit)

a QBtu = 10^{15} Btu

b B pers-hr = 10^9 pers-hr;
B units = 10^9 units

c Goods units = part of L_{PG} required for goods used

d Service units = part of L_{PS} required for services used

e Pollution control units = part of L_W required for the particular control effort considered

f MBtu = 10^6 Btu

2.2 Basic Equations for the Model

The quantities defined above are assumed to be related as follows:

Fuels used:

The fuels used by each sector are proportional to their outputs. The fuel used by the consumer depends on the consumption rate for goods. That is:

$$F_{PG} = B_{PG} \left(GU_E + GU_{PS} + GU_W + GU_C + GU_C^*\right) \qquad (1)$$

$$F_W = B_W \left(WU_E + WU_{PG} + WU_{PS}\right) \qquad (2)$$

$$F_{PS} = B_{PS} \left(SU_{PG} + SU_C + SU_C^*\right) \qquad (3)$$

$$F_C = B_C \left(GU_C + GU_C^*\right) \qquad (4)$$

In the above, B_{PG}, B_W, B_{PS}, and B_C are constants determined from economic and technical data. See Ref. [7].

The goods (units) and service (units) required by E, PG, PS, and W are proportional to the labor effort expended, and are diminished by a productivity reduction factor dependent upon the level of pollution in the environment. That is:

$$GU_E = \gamma_E L_E (1-\gamma w^2) \qquad (5)$$

$$GU_W = \gamma_W L_W (1-\gamma w^2) \qquad (6)$$

$$GU_{PS} = \gamma_{PS} L_{PS} (1-\gamma w^2) \qquad (7)$$

$$SU_{PG} = \sigma_{PG} L_{PG} (1-\gamma w^2) \qquad (8)$$

In the above, γ is constant determined by loss of performance data given in Ref. [2], and w is the fraction of the total possible effluent from all sources. The other coefficients are determined from economic data.

Outputs:

The output of each sector is assumed to be proportional to the labor invested, diminished by the environmental loss-of-productivity factor just mentioned.

$$F_{PG} + F_W + F_{PS} + F_C = (\beta_E - f_E)\, L_E\, (1-\gamma w^2) \qquad (9)$$

$$GU_E + GU_W + GU_{PS} + GU_C + GU_C^* = L_{PG}\, (1-\gamma w^2) \qquad (10)$$

$$SU_{PG} + SU_C + SU_C^* = L_{PS}\, (1-\gamma w^2) \qquad (11)$$

$$WU_E + WU_{PG} + WU_{PS} = L_W\, (1-\gamma w^2) \qquad (12)$$

In the above, β_E and f_E, are constants determined by the fractions of the various energy resources used and the difficulty of extracting each.

Full employment:

The total labor available is assumed constant. Only the distribution changes. That is:

$$L_E + L_W + L_{PG} + L_{PS} = L_T \qquad (13)$$

Economic equilibrium:

The value of the inputs to each sector is assumed to be equal to the value added by the sector. That is:

$$\frac{p_F}{\ell}(F_{PG} + F_W + F_{PS} + F_C) = L_E + \frac{p_W}{\ell} WU_E + \frac{p_G}{\ell} GU_E \qquad (14)$$

$$\frac{p_G}{\ell} (GU_E + GU_W + GU_{PS} + GU_C + GU_C^*) =$$

$$L_{PG} + \frac{p_W}{\ell} WU_{PG} + \frac{p_S}{\ell} SU_{PG} + \frac{p_F}{\ell} PG \qquad (15)$$

$$\frac{p_W}{\ell} (WU_{PG} + WU_{PS}) = L_W + \frac{p_F}{\ell} F_W + \frac{p_G}{\ell} GU_W \qquad (16)$$

$$\frac{p_S}{\ell}(SU_{PG} + SU_C + SU_C^*) = L_{PS} + \frac{p_F}{\ell}F_{PS} + \frac{p_G}{\ell}GU_{PS} + \frac{p_W}{\ell}WU_{PS}$$

In the above, ℓ = hourly wage.

Consumer choice:

The amounts of goods, and services, purchased by the consumer are dependent on the consumer income, the prices of fuel, goods, and services, and the perceived benefit or utility from each unit purchased. The following utility function is assumed:

$$R = A\left[1 - \exp\left(-\frac{GU_C}{G_M}\right)\right] + B\left[1 - \exp\left(-\frac{SU_C}{S_M}\right)\right] \tag{18}$$

The quantity R is assumed to be a maximum subject to the income constraint:

$$\left(\frac{p_G}{\ell} + B_C \frac{p_F}{\,}\right)\left(GU_C + GU_C^*\right) + \frac{p_S}{\ell}\left(SU_C + SU_C^*\right) = L_T \tag{19}$$

Environmental effects other than loss of producitvity:

The amounts of environmental improvement services to each sector as given by:

$$WU_E = h(1-w)^2 L_E \tag{20}$$

$$WU_{PG} = h(1-w)^2 L_{PG} \tag{21}$$

$$WU_{PS} = h(1-w)^2 L_{PS} \tag{22}$$

In the above, h is a constant depending on the kinds and amounts of fuels used. The consumer must also purchase certain "unwanted" goods and services to combat undersirable effects of pollution, namely:

$$GU_C^* = kw^2(GU_C) \tag{23}$$

$$SU_C^* = kw^2(SU_C) \tag{24}$$

In the above, k is a constant determined by the kinds, and amounts of fuels used.

3. NUMERICAL VALUES OF COEFFICIENTS

The procedure for determing the numerical values of the coefficients for the reference system, in which once-through cooling is assumed for all electric power plants, is outlined in Ref. [5]. In that reference four assumed mixes of fuel are considered. Here we donsider only one mix, namely that labeled as Case I in Ref. [5]. Values for the reference case (and the two alternatives) are tabulated in Table 1.

The corresponding coefficients for (A) the dry cooling towers alternative and for (B) the MIUS alternative are obtained by accounting for changes in environmental damage, environmental treatment costs, fuel used, equipment used, and labor required when one of the alternatives is substituted for the reference system. In all cases the levels of activity for the 1975 projection given in Ref. [7] are assumed.

3.1 Alternative (A) - Dry Cooling Towers

The use of dry cooling towers eliminate the environmental damage resulting from heated water. This * affects * the total amounts of unwanted goods and services GU_C and SU_C, and consequently affects the coefficient k. For heated water, the consumer-perceived environmental damage is approximately the cost to the consumer of having to pay for extra transportation to obtain the water recreation or esthetic benefit provided only by unheated water. According to Ref. [2], p. 162, 1300 acres of water are required to dissipate 75% of the rejected heat for once-through cooling of a 1000Mw plant under usual operating conditions. Assuming 21 QBtu/yr of fuel energy for the U.S. electrical generation sector in 1975, Ref. [7], and assuming a 33 1/3% thermal efficiency, the amount of waste heat which must be rejected to water is 14 QBtu/yr and the amount of electrical energy produced is 7 QBtu/yr. This is equivalent to an average electrical power output of 2.34 x 10^5 Mw. The amount of water affected by once-through cooling is therefore 3.04 x 10^5 acres. If this is assumed to be allocated to rivers having an average width of 1000 feet, the total river length affected is 1.32 x 10^7 feet. Assuming the total population is distributed in N cities of 100,000 population, we obtain N = 2130 such cities, with a prorated share of river affected equal to 6200 feet. This is approximately one mile of river for each 100,000 population. Assume that 1/4 of the population must drive an extra distance of 2 miles per water recreation trip, and that 25 such trips are made each year.

At 15¢ per mile this yields an environmental cost to the consumer of 0.375 B$/yr. as a result of heated water. This is allocated to GU_c^* and SU_c^* in the same proportions as GU_c^* and SU_c^* occur in the results of the reference case. See Ref.[5]. We get ΔGU_c^* and ΔSU_c^* for heated water to be 0.078 and 0.297 B$/yr respectively. Thus, one could expect approximately a 10% reduction in GU_c^* and SU_c^* for the alternative (A), dry cooling towers. Thus, k for dry cooling towers = 0.9 x k for the reference system.

According to Ref. [8] dry cooling towers require from $20 to $30 per kilowatt for capital equipment, and results in a 1% to 3% increase for the cost of electricity. The capital cost increase is approximately 10% of the plant cost, and increases the goods flow GUw to the environmental service sector. Assuming that 14% of the service in the PS sector is for electrical energy distribution service ($ value of electricity sold rel. to toal service $), it is possible to estimate the increment to GUw thus:

$$\Delta GUw = 2\% \times 10\% \times 14\% \times GU_{PS} \times 1/3 = 0.11 \text{ B units/yr}$$

Here GU_{PS} was assumed to equal 26 B units/yr. See Ref. [5].

The last factor (1/3) is a result of assuming that the electrical energy sold to consumers in their homes is approximately 1/3 of the total. The increase in ΣWU, the environmental service is 2% x electricity cost to all users converted to units of environmental service. This yields ΔWU = 0.16 B units/yr, or about 8% of the total ΣWU provided in the reference case. Thus, h with dry cooling towers = 1.08 in the reference case.

The values of the coefficients β_w and γ_w are also changed by the introduction of cooling towers. The values for these coefficients are obtained by requiring economic equilibrium for the W sector of Fig. 1 with the previously obtained values of ΔGUw and Δ(ΣWU) added to the reference values obtained from Ref. [5]. The corresponding increase in labor is assumed to be found from

$$\frac{\Delta Lw}{(Lw)} \text{ ref.} = \frac{1}{3} \frac{(\Delta GU_w)}{(GU_w)_{ref}}$$

where the factor 1/3 expresses approximately the relation between added capital and added labor for a capital intensive industry (Barry Commoner, Ref. [9]). Balancing the dollar flow results in $\Delta F_w = 0.22$ QBtu/yr for the case, w = 0, maximum environmental controls. Therefore:

$$B_w = \frac{(Fw)\ \text{ref} + \Delta Fw}{(\Sigma WU)\ \text{ref} + \Delta(\Sigma WU)} = 0.5566\ \frac{\text{MBtu}}{\text{W-unit}}$$

$$\gamma_w = \frac{(GUw)\ \text{ref} + \Delta GUw}{(Lw)\ \text{ref} + \Delta Lw} = 0.4419\ \frac{\text{goods unit}}{\text{pers - hr}}$$

Using the previous arguments concerning k and h, we get

$$k = 0.9\ (k)_{\text{ref}} = 0.0374$$
$$h = 1.08\ (h)_{\text{ref}} = 0.0130$$

All other system coefficients are assumed unchanged. All system parameters for the dry cooling tower case are tabulated in Table 1.

3.2 Alternative (B) - MIUS

A description of the MIUS system is given in Ref. [4]. It is a system which recycles waste heat, liquid and solid wastes. The waste heat is utilized to provide hot water and space heating to the residential and commercial buildings in the community which also receives the electric power generated. Waste water from these customers is treated and re-used as make-up water for power plant cooling and for the operation of cooling towers. Solid wastes are incinerated to provide added heat to the power plant.

According to the authors of Ref. [4], slightly more than 1/4 of the rejected heat from the power plant cannot be utilized and must be handled by cooling towers. A conservative estimate, for the purposes of the analysis in this paper, is that 2/3 of the power plant waste heat is utilized for space and water heating. It is assumed that the total fuel energy required for residential and commercial use is reduced by an amount equal to the waste heat energy utilized. Also according to Ref. [4], a MIUS having an electric power output of 2500KW will serve 720 units in the residential sector, plus the required commercial enterprises which accompany this community. For a 2500Kw plant the waste heat generation rate, assuming a thermal efficiency of 33 1/3%, is 1667 KW, of which 2/3 is utilized. Thus, the utilized waste heat rate is 1111Kw or 3.79×10^6 Btu/hr. Assuming that the utilized heat is shared equally by residential and commercial users, each residential unit utilizes 2630 Btu/hr. Although it is not likely that all households in the U.S. could participate in MIUS's, it is assumed for purposes of simple analysis that such is possible.

Therefore, for the entire U.S, with approximately 65.4 million units, the annual utilized waste heat energy in the residential sector is 1.51 QBtu/yr. An equal amount is assumed to be utilized in the service sector.

Consider first the revisions for MIUS in the environmental services sector W. Let $w = 0$, which means that all wastes are treated. For MIUS less effort, fuel and capital are required to completely treat all effluents of the system because only 1/3 of the heated water from power plants must be handled by cooling towers. In the previous analysis for cooling towers it was shown that h, the system parameter which relates the needed environmental service WU to the labor effort invested, had to be increased by 8% over the reference case in which once-through cooling is assumed. For MIUS, we wimply reduce the 8% to 1/3 of 8% or 2.6%. Therefore, $h_{MIUS} = 1.026\ h_{ref}$. For dry cooling towers it was shown that the increment in environmental service units was 0.16 B units/yr. For MIUS we assume that this increase is 1/3 as great, or 0.053 B units/yr. Therefore, $(\Sigma WU)_{MIUS} = 2.105$ B units/hr.

The increment in goods units to W, ΔGU_w, relative to the reference system, is taken to be 1/3 of the ΔGU_w for dry cooling towers. Thus, ΔGU_w for MIUS is approximately 0.04 B units/yr, and $(GUw)_{MIUS} = 0.87$ B units/yr for $w = 0$, whereas in the reference case (GU_w) ref. $= 0.84$ B units/yr. Assuming that the percent increase in fuel for W is equal to the percent increase in GU , we get $(F_w)_{MIUS} = 1.056$ QBtu/yr. The relative increment in labor is smaller than that for fuel and capital since we are dealing with a capital intensive and energy intensive device. We take $(L_w)_{MIUS} = \Sigma WU = 2.105$ B pers-hr/yr. From these values, we can obtain $(B_w)_{MIUS}$ and $(\gamma_w)_{MIUS}$ as follows:

$$(B_w)_{MIUS} = \frac{F_w}{\Sigma WU} = 0.5017 \text{ M Btu/unit}$$

$$(\gamma_w)_{MIUS} = \frac{GU_w}{L_w} = 0.4152 \text{ goods unit/pers-hr}$$

Next, consider the consumption sector C. The total fuel for C in the MIUS alternative is (F_C) ref $- \Delta F = 22.28 - 1.51 = 21.27$ QBtu/yr. Assuming the same prices as in the reference case, (See Table 2) and assuming that dollars saved on fuel are spent for the added service which MIUS provides, it can be shown that $(SUc)_{MIUS} = 75.42$ B serv. units/yr. The value of $(GU_C)_{MIUS}$ is assumed equal to that for the reference case, for the purposes of computing the system parameter B_C. We get

$$(Bc)_{MIUS} = \frac{F_c}{GU_c} = 1.0757 \text{ MBtu/goods unit}$$

Consider next the service (PS) sector. The fuel saved for PS is assumed to be equal to that saved for C. Thus, $(F_{ps})_{MIUS} = 22.80 - 1.51 = 21.29$ QBtu/yr. Assuming ΔSu produced is equal numerically to the labor L_{ps}, and that the only increment is service units for MIUS is that mentioned above, we get $(\Delta SUc)_{MIUS} = 0.20$ B serv.units/yr. Therefore, $(SUc)_{MIUS} = 75.40$ B serv.units/yr. Assuming that $(GU_{ps})_{MIUS}$ and $(SU_{pg})_{MIUS}$ are equal to the corresponding values for the reference system, a dollar balance for PS yeilds $(L_{ps}) = 114.52$ B pers-hr/yr. This is not equal to $(\Sigma SU)_{MIUS}$, as required by the model. Therefore, we average L_{ps} and ΣSU to compute the system parameters γ_{ps} and B_{ps} for MIUS. We get

$$(\gamma_{ps})_{MIUS} = \frac{(GU_{ps})_{MIUS}}{\frac{1}{2}(L_{ps} + \Sigma SU)_{MIUS}} = 0.2388 \ \frac{\text{goods unit}}{\text{pers-hr}}$$

$$(B_{ps})_{MIUS} = \frac{(F_{ps})_{MIUS}}{\frac{1}{2}(L_{ps} + \Sigma SU)_{MIUS}} = 0.1870 \ \frac{\text{MBtu}}{\text{serv.unit}}$$

One final comment should be made about the values of the system parameters γ, h, and k obtained above. These are determined by the amount of effluent contributed to the environment by the total system. They were computed for $w = 0$ relative to the reference case for $w = 0$. Now to accomplish $w = 0$ for MIUS requires less effort since for MIUS the total fuel consumed is less and therefore the total effort to clean up the energy-related effluents is less. Since effort to clean up pollution is assumed in the model to be proportional to the square of the effluent removed, it seems appropriate to reduce all parameters computed above by the ratio $(F_{MIUS}/F_{ref})^2 = 0.9239$. Thus, we get corrected values for γ, h, and k as follows

$$(\gamma)_{MIUS} = 0.03696$$

$$(h)_{MIUS} = 0.01138$$

$$(k)_{MIUS} = (0.9239)\left[(k) \text{ dry towers}\right] = 0.03459$$

The entire set of system parameters for MIUS is presented in Table 1.

4. COMPUTED RESULTS AND CONCLUSIONS

The set of equations (1) through (24) are solved using the pattern of solution presented in Ref. [5] for (A) the dry cooling towers and for (B) the MIUS. Results are listed in Tables 3 and 4 respectively. An added variable is labeled E.S.C./Income(%). E.S.C. = the "Environmental Social Cost", E.S.C. $= p_G(GU_c^*) + p_S(SU_c^*) + p_W(\Sigma WU) + \gamma w^2$ (Income). The first two terms are the direct cost to the consumer for "unwanted" goods and services required because the environment is bad. The third term is the cost of improving the environment through environmental services, and the last term is the cost in lost production due to reduced worker performance in a polluted environment. Since income is the product of the hourly wage 1 and the total work force L_T, it is possible to use the price ratios $p_{F/\ell}$, $p_{G/\ell}$, $p_{S/\ell}$ and $p_{W/\ell}$ found by solving the system equations of Ref. [5], one gets

$$\frac{\text{E.S.C.}}{\text{Income}}(\%) = \frac{\frac{p_G}{\ell}(GU_c^*) + \frac{p_S}{\ell}(SU_c^*) + \frac{p_W}{\ell}(\Sigma WU) + \gamma w^2 L_T}{L_T} \times 100$$

Examination of the results for the environmental social cost as a percent of income indicate that a minimum for each system occurs near w = 0.2. It is seen that the alternative (A) Dry Cooling Towers requires approximately a 9% greater share of income for optimum environmental control than for once-through cooling, whereas the alternative (B) MIUS requires a 6% smaller share of income for optimum environmental control.

Comparisons of the results for GU_c and SU for the three systems indicate that for the alternative (A) Dry Cooling Towers, the values of both GU_c and SU_c are only slightly less than those for once-through cooling, which means that the added effort for environmental control is not felt by the consumer as lost purchasing power. It is felt primarily as the worth while expense of a less disturbing environment. Note that the argument which is sometimes presented is not true, namely that if it were not for the expense of pollution control, a larger proportion of the consumer's income would be available for desireable goods and service. This "extra" income goes instead for defenses against pollution damage. Dry cooling towers provide almost a zero net benefit. They could possibly be perceived as a system with positive net benefit if the utility function for the consumer were modified to include the environmental quality. The advantages of the MIUS are more evident. The value of GU_c for MIUS is slightly greater than GU_c for once-through cooling, whereas SU_c for MIUS is less. This is an indication that the prices for goods and services in MIUS tend to shift the consumer's demand toward goods. Many consumers would perceive this is a net benefit. The most obvious benefit of MIUS is its energy saving feature. Note that the total fuel energy F for MIUS is 6% less than that for once-through cooling for essentially the same state of well-being for the consumer. Less fuel used means less extraction labor and therefore greater employment in the production sector. MIUS provides the same environmental protection as dry cooling towers at less cost to society for controls, and with less demand for energy resources.

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TABLE 1

SYSTEM COEFFICIENTS

SYSTEM COEFFICIENTS	REF. SYST.	DRY COOLING TOWERS	MIUS
B_{PG} (MBtu/goods unit)	0.5044	0.5044	0.5044
B_{PS} (MBtu/serv.unit)	0.2018	0.2018	0.1870
B_C (MBtu/goods unit)	1.1521	1.1521	1.0759
B_W (MBtu/W-unit)	0.4945	0.5566	0.5017
γ_E (goods unit/pers-hr)	0.4092	0.4092	0.4092
γ_W (goods unit/pers-hr)	0.4092	0.4419	0.4152
γ_{PS} (goods unit/pers-hr)	0.2336	0.2336	0.2388
σ_{PG} (serv.unit/pers-hr)	0.7523	0.7523	0.7523
γ (dimensionless)	0.0400	0.0400	0.03696
β_E (MBtu/pers-hr)	9.9795	9.9795	9.9795
f_E (MBtu/pers-hr)	0.7621	0.7621	0.7621
A (dimensionless)	0.4698	0.4698	0.4698
B (dimensionless)	1.1122	1.1122	1.1122
G_M (B goods units)	20.26	20.26	20.26
S_M (B serv.units)	76.98	76.98	76.98
h (W-units/pers-hr)	0.0120	0.0130	0.01138
k (dimensionless)	0.0416	0.0374	0.03459
L_T (B pers-hr)	173.0	173.0	173.0

TABLE 2
SYSTEM VARIABLES vs. w. REFERENCE CASE (1975)

VARIABLE		w=0	w=0.2	w=0.4	w=0.6	w=0.8
$p_{F/\ell}$	(pers-hr/MBtu)	0.216	0.214	0.214	0.214	0.216
$p_{G/\ell}$	(pers-hr/goods unit)	2.350	2.333	2.329	2.336	2.356
$p_{S/\ell}$	(pers-hr/serv.unit)	1.617	1.606	1.602	1.608	1.621
$p_{W/\ell}$	(pers-hr/W-unit)	2.068	2.062	2.065	2.076	2.097
L_E	(B pers-hr)	7.801	7.801	7.800	7.800	7.800
L_W	(B pers-hr)	2.051	1.321	0.749	0.336	0.085
L_{PG}	(B pers-hr)	50.189	50.227	50.256	50.277	50.289
L_{PS}	(B pers-hr)	112.959	113.652	114.195	114.586	114.825
GU_E	(B units/yr)	3.192	3.187	3.172	3.146	3.110
GU_W	(B units/yr)	0.839	0.540	0.304	0.136	0.034
GU_{PS}	(B units/yr)	26.387	26.507	26.505	26.382	26.137
GU_C	(B units/yr)	19.770	19.880	19.821	19.596	19.210
GU^*_C	(B units/yr)	0.000	0.033	0.132	0.293	0.511
WU_E	(B units/yr)	0.094	0.060	0.034	0.015	0.004
WU_{PG}	(B units/yr)	0.602	0.386	0.217	0.097	0.024
WU_{PS}	(B units/yr)	1.356	0.873	0.493	0.220	0.055
SU_{PG}	(B units/yr)	37.757	37.725	37.566	37.279	36.864
SU	(B units/yr)	75.202	75.620	75.396	74.541	73.076
SU^*_C	(B units/yr)	0.000	0.126	0.502	1.116	1.946
F_{PG}	(OBtu/yr)	25.315	25.294	25.187	24.994	24.717
F_W	(WBtu/yr)	1.014	0.652	0.368	0.164	0.041
F_{PS}	(QBtu/yr)	22.799	22.898	22.897	22.791	22.579
F_C	(QBtu/yr)	22.777	22.942	22.988	22.915	22.721

TABLE 2 (cont'd.)

VARIABLES	w=0	w=0.2	w=0.4	w=0.6	w=0.8
F_E (QBtu/yr)	5.946	5.935	5.906	5.859	5.791
F (Qbtu/yr)	77.847	77.721	77.346	76.723	75.849
E.S.C./Income, (%)	2.45	1.90	2.18	3.28	5.18

TABLE 3

SYSTEM VARIABLE vs. w. DRY COOLING TOWERS

VARIABLE		w=0	w=0.2	w=0.4	w=0.6	w=0.8
p_F/ℓ	(pers-hr/ MBtu)	0.216	0.214	0.214	0.214	0.216
p_G/ℓ	(pers-hr/goods unit)	2.358	2.338	2.331	2.337	2.356
p_S/ℓ	(pers-hr/serv. unit)	1.623	1.609	1.604	1.608	1.621
p_W/ℓ	(pers-hr/W-unit)	2.162	2.154	2.156	2.167	2.188
L_E	(B pers-hr)	7.814	7.809	7.805	7.803	7.801
L_W	(B pers-hr)	2.220	1.430	0.811	0.364	0.092
L_{PG}	(B pers-hr)	50.223	50.249	50.268	50.282	50.292
L_{PS}	(B pers-hr)	112.743	113.512	114.116	114.551	114.815
GU_E	(B units/yr)	3.197	3.190	3.174	3.147	3.110
GU_W	(B units/yr)	0.981	0.631	0.356	0.159	0.040
GU_{PS}	(B units/yr)	26.340	26.474	26.487	26.374	26.134
GU_C	(B units/yr)	19.707	19.843	19.811	19.615	19.259
GU^*_C	(B units/yr)	0.000	0.030	0.119	0.264	0.461
WU_E	(B units/yr)	0.102	0.065	0.037	0.016	0.004
WU_{PG}	(B units/yr)	0.653	0.418	0.235	0.105	0.026
WU_{PS}	(B units/yr)	1.466	0.944	0.534	0.238	0.060
SU_{PG}	(B units/yr)	37.782	37.742	37.575	37.283	36.866
SU_C	(B units/yr)	74.961	75.476	75.360	74.614	73.257
SU^*_C	(B units/yr)	0.000	0.113	0.451	1.005	1.754
F_{PG}	(QBtu/yr)	25.332	25.305	25.193	24.997	24.718
F_W	(QBtu/yr)	1.236	0.795	0.449	0.200	0.050

TABLE 3 (cont'd.)

VARIABLE		w=0	w=0.2	w=0.4	w=0.6	w=0.8
F_{PS}	(QBtu/yr)	22.752	22.870	22.881	22.784	22.577
F_C	(QBtu/yr)	22.705	22.896	22.961	22.902	22.719
F_E	(QBtu/yr)	5.955	5.942	5.910	5.861	5.793
F	(QBtu/yr)	77.980	77.806	77.396	76.745	75.857
E.S.C./Income, (%)		2.77	2.09	2.23	3.19	4.95

TABLE 4

SYSTEM VARIABLES vs. w. MIUSs FOR ALL ELECTRIC POWER

VARIABLE		w=0	w=0.2	w=0.4	w=0.6	w=0.8
p_F/ℓ	(pers-hr/ MBtu)	0.216	0.214	0.214	0.214	0.216
p_G/ℓ	(pers-hr/goods unit)	2.356	2.340	2.335	2.342	2.360
p_S/ℓ	(pers-hr/serv. unit)	1.627	1.615	1.612	1.617	1.629
p_W/ℓ	(pers-hr/W-unit)	2.087	2.081	2.083	2.093	2.113
L_E	(B pers-hr)	7.488	7.485	7.483	7.481	7.481
L_W	(B pers-hr)	1.947	1.253	0.710	0.319	0.081
L_{PG}	(B pers-hr)	50.685	50.720	50.750	50.771	50.786
L_{PS}	(B pers-hr)	112.881	113.543	114.057	114.430	114.653
GU_E	(B units/yr)	3.086	3.081	3.066	3.043	3.011
GU_W	(B units/yr)	0.802	0.516	0.291	0.130	0.032
GU_{PS}	(B units/yr)	26.956	27.076	27.076	26.962	26.732
GU_C	(B units/yr)	19.840	19.947	19.907	19.715	19.381
GU^*_C	(B units/yr)	0.000	0.028	0.110	0.246	0.429
WU_E	(B units/yr)	0.085	0.055	0.031	0.014	0.003
WU_{PG}	(B units/yr)	0.577	0.369	0.208	0.092	0.023
WU_{PS}	(B units/yr)	1.285	0.827	0.467	0.208	0.052
SU_{PG}	(B units/yr)	38.130	38.100	37.953	37.687	37.303
SU_C	(B units/yr)	74.751	75.171	75.014	74.295	73.022
SU^*_C	(B units/yr)	0.000	0.106	0.415	0.925	1.617
F_{PG}	(QBtu/yr)	25.565	25.545	25.447	25.268	25.011
F_W	(QBtu/yr)	0.977	0.628	0.354	0.158	0.039

TABLE 4 (cont'd.)

VARIABLE	w=0	w=0.2	w=0.4	w=0.6	w=0.8
F_{PS} (QBtu/yr)	21.109	21.201	21.203	21.114	20.933
F_C (QBtu/yr)	20.852	20.881	20.968	21.112	21.314
F_E (QBtu/yr)	5.706	5.696	5.669	5.625	5.566
F (QBtu/yr)	74.722	74.581	74.230	73.663	72.887
E.S.C./Income, (%)	2.35	1.79	1.98	2.91	4.57

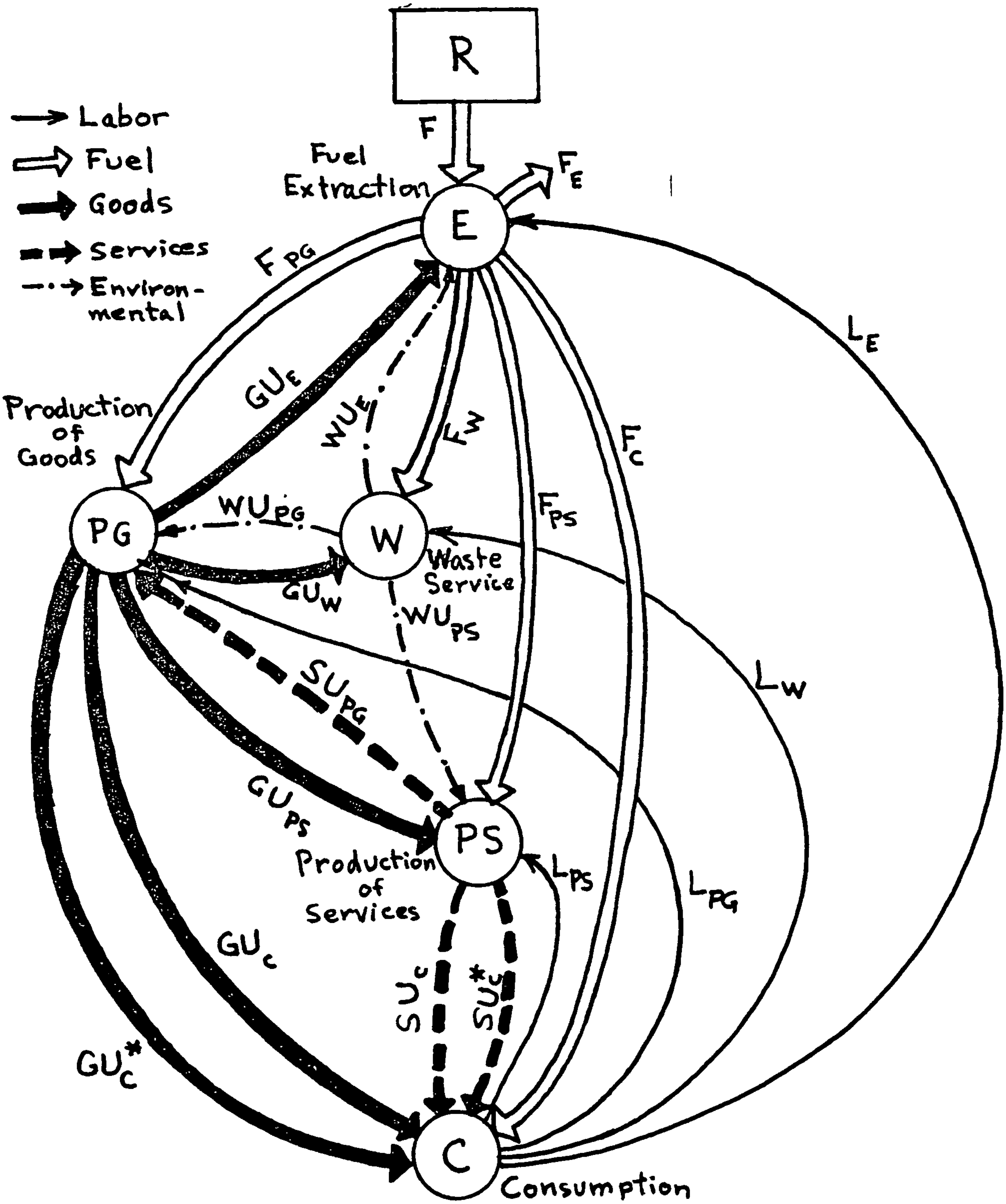

Fig. 1 Equilibrium Model of the U.S. Energy-Environmental-Economic System