RESEARCH

Efficiency of Energy Delivery Systems: I. An Economic and Energy Analysis

CHARLES HALL[1]
MITCHELL LAVINE[2]
JOANNA SLOANE[1]

[1]Section of Ecology and Systematics
Langmuir Laboratory
Cornell University
Ithaca, New York 14853

[2]Center for Environmental Research
Cornell University
Ithaca, New York 14853

Abstract / Energy-return-on-investment (ERI) analysis is a variation of more traditional cost–benefit analyses, a variation that is particularly important in times of diminishing fuel resources. We present a simple set of procedures for ERI analysis and apply those procedures to central New York State, where there is a proposal for a new 870 MW_e coal-fired generating station. We compared the energy and dollar costs of building that facility with the costs of an alternative comprehensive regional program of insulation. The analysis showed that regional insulation was more efficient in conserving energy than the plant was in providing it by at least a factor of 4 in economic terms and by a factor of more than 15 when viewed as energy returned on energy invested.

Introduction

Society, through its public and private institutions, invests money and energy into facilities and programs that produce social benefits such as warm houses in winter, industrial process heat, jobs, and so on. However, all facilities and programs do not generate equal social returns per dollar or calorie invested. As our most readily available fossil fuels become depleted, and hence more expensive, and as the scientific and public awareness of the adverse environmental effects of any fuel burning increases, it is appropriate to examine the efficiency with which we as a nation invest money and energy in each major energy facility. A series of papers (e.g., Gibbons et al. 1978; Ross and Williams 1976; Lovins 1976; Ford Foundation 1974) has suggested that conservation may represent a readily available "source" of energy by freeing for other uses energy that is presently being used at a less-than-optimal efficiency. However, there are few studies that compare the effectiveness and efficiency of conservation to other alternatives.

This paper and its two following parts have four objectives, each related to examining the effectiveness and, especially, the efficiency with which energy production facilities and conservation programs provide social benefits. The first is to formalize a straightforward set of procedures to determine *energy return on investment* (ERI) for energy systems. The second is to apply these procedures to a specific case, that of the proposed Cayuga electricity-generating station versus a comprehensive regional program of insulation. The third is to compare methods and conclusions based on economic analysis and on the three available energy-assessment methods. Finally, our study examines the conclusions of our analyses in light of some institutional constraints that are important components of the decision-making process. We have chosen a coal-fired power plant for our analysis, but the methods given here are, in theory, applicable to any proposed energy facility.

Energy-Return-on-Investment Methods

The energy-return-on-*dollar*-investment analysis we use is similar to routine cost–benefit analyses used in economics (e.g., Eckstein 1958; Mishan 1971). The ratio derived here is the quantity of *energy* returned to society from a facility or program divided by the total quantity of money invested. For the power plant construction example, the ratio is the quantity of energy delivered to the user divided by the total quantity of money invested in the electricity-producing system, as determined from the price per unit of electricity.

The energy-return-on-*energy*-investment procedure we use is also similar to routine economic cost–benefit methods: The total energy generated by a project is divided by the total energy invested in the project. In both procedures it is necessary to compare the costs and benefits for the entire energy-production system. Although these methods are not new (see, e.g., Chapman et al. 1974; Gilliland 1975; Pilati and Richard 1975; Odum et al. 1976; Perry et al. 1977), their potential utility has not been sufficiently formalized nor appreciated, nor are they routinely applied to examine specific proposed energy facilities and their alternatives. Finally, methodological arguments (e.g., Huettner 1976) have obscured their general usefulness in situations where different energy-analysis methods still result in similar conclusions, as is the case in the example presented here.

The energy-return-on-energy-investment analysis can be illustrated by comparing the traditional formula for eval-

Environmental Management, Vol. 3, No. 6, pp. 493–504

0364-152X/79/0003-0493 $02.40

uating energy efficiency with what we believe is a more useful formula. The energy efficiency of a coal-fired power plant traditionally is found by dividing the heat equivalent of the electrical energy generated by the heat content of the coal used to fire the boilers:

$$\text{Gross efficiency} = E_g/CB \cong 35\text{–}40\%,$$

where E_g is the electrical energy generated expressed in thermal equivalents (i.e., BTUs or kilocalories), and CB is the total quantity of energy in the coal that is burned to produce E_g.

We have redefined the efficiency of coal-burning plants so as to compare the electrical energy with the total energy investment required to supply that need. We call this the net or *system efficiency* of the plant, which is identical to the energy-return-on-energy-investment mentioned earlier:

System efficiency

$$= \frac{\text{Amount of energy delivered to consumer}}{\text{Total energy used to produce and deliver that amount}}$$

$$= \frac{E_g - E_{pu} - E_{tl}}{CB + E_m + E_p + E_t + E_{pc} + E_{tfc}}$$

$$= \frac{E_g - E_{pu} - E_{tl}}{CB + E_i},$$

where E_g is as before; E_{pu} is the energy utilized internally by the power plant; E_{tl} is electricity lost in transmission (which is a function of the line voltage and the distance transmitted); E_m, E_p, and E_t ($=E_{mpt}$) are the energy required to mine, process, and transport coal; E_{pc} is the energy required to manufacture (and install) the generating station and associated equipment; and E_{tfc} is the energy required to make transmission facilities such as line towers, high voltage lines, transformers, and other substation equipment amortized over the nominal lifespan of the power plant.

The sum $E_m + E_p + E_t + E_{pc} + E_{tfc}$ is labeled E_i—the *indirect* energy required to generate and deliver electricity. To arrive at a value for E_i, it is necessary to convert such information as economic data and material and labor listings into energy units. This theoretically straightforward procedure has proved to be quite difficult in practice, owing to the scattered, cryptic, unreliable, and nonstandardized nature of the sources on energy requirements for manufacturing (see Part II). In addition, important questions remain pertaining to the choice of analytical method.

Three energy analysis methods are available. Each differs in simplicity of use, comprehensiveness, rigor, appropriateness to the question at hand and even philosophy. The methods are called (1) "process energy," (2) "input–output (I-O) analysis," and (3) "correlation of aggregate national energy use and dollar flow." Briefly, the first method uses national manufacturing economic and energy statistics to derive a relatively aggregated analysis of energy used to produce a good or service. The second uses a similar, but less aggregated method which was derived at the University of Illinois Center for Advanced Computation. The third method, derived from aggregate national statistics, includes an approximate estimate of all energy used to build a facility, including all energy recompense to labor, including "on site" labor. There are advantages and disadvantages to each method, although it is generally agreed that the first method is a minimum estimate of the energy cost and the aggregate national statistics method is a maximum estimate. In some cases their use may be combined to use the most appropriate methodology. We used the aggregate energy-dollar ratio for the energy equivalence of money paid to on site labor, and added this to the I-O derived estimate of capital equipment for our own third estimate, which we call I-O plus labor. Finally we have a fourth estimate for the energy cost of the plant using the aggregate national statistics method for the entire plant cost. Details of the three basic methods are given in Part II (pages 505–510 of this issue) which also includes estimates of the energy costs of various raw and finished materials. This information on energy costs can be combined with a "shopping list" of materials and activities needed for the construction of a power plant (or any other facility or project) to derive the total energy cost of constructing the facility.

Example of Energy Cost–Benefit Assessment: Providing Energy in Central New York State

The New York State Electric and Gas Corporation (NYSEG) service area is a loosely aggregated patchwork of rural counties, suburbs, and small cities encompassing much of central New York state. The region is noted both for its scenic beauty and for its long, harsh winters. As of 1975, the NYSEG service area included 556,000 residential electric customers (or "families") residing in approximately 458,000 houses and apartment buildings (NYSEG 1974). Of these 458,000 dwellings, about 30,000 (or 6.5%) are heated electrically. The mean electricity use per capita is 2154 kWh (or 1.8×10^6 kcal of electrical energy) per year.

Unlike most of the United States, the NYSEG service area is a winter peak load system and is expected to remain so until at least 1990. Furthermore, about half the absolute growth in the winter peak demand over the next 20 years is expected to be due to increased use of electric space heat (NYSEG 1974). Changeovers from cheaper (and more efficient) gas and oil heat are thought likely owing to possible increased prices and especially delivery cutbacks of oil and gas.

NYSEG has attempted to predict its future peak and baseload by using a multiple regression model designed to take into account such factors as population growth, availability and price of alternate fuels, price elasticity of demand, general economic growth, appliance saturation, energy conservation, and weather. The model predicts an average annual consumption growth rate of about 4.8% over the years 1976–1991.

Faced with this expected increase in electricity use, and the New York State Power Pool requirements of an 18% reserve margin, NYSEG has developed plans for a series of new power plants. One such facility is the proposed 870-MW (electric) coal-burning power plant in Tompkins County, New York, the "Cayuga Station" (An alternative site is Somerset, New York, on Late Ontario. While this paper was in press the Somerset site was identified as the preferred site, but our analysis would apply with trivial corrections to that site). The Cayuga plant would be built next to the 270-MW Milliken Station that has been operational since 1955.

Public apprehension over shrinking oil and natural gas supplies for home heating and the consequent anticipated increase in electric heat demand could be alleviated by increasing the amount of insulation in housing. The following sections of this paper examine the effectiveness and efficiency of the power plant and the insulation at meeting local energy needs using energy return on investment methods.

Results

The results of this energy-return-on-investment analysis show that the power plant was less efficient than the insulation program at providing energy to the region by at least a factor of 4 when viewed as energy return per dollar invested, and at least a factor of 10 when viewed as energy returned per calorie invested (Fig. 1).

Energy Return from the Proposed Power Plant

The Cayuga Station is rated at 869.7 $MW_{net\ electric}$ (and 924.7 $MW_{gross\ electric}$), has a nominal efficiency (of net electricity output over coal input, both expressed in thermal units) of 37.78%, and is expected to be operating an estimated 77% of the time over its 30-year nominal life-span (NYSEG 1974). The gross energy output (E_{go}) of the Cayuga Station over 30 years, calculated as mean-output-capacity times operating time, is 187 million MWh, equal to 161×10^{12} kcal.

The *net* output capacity of electricity (E_{no}) is the gross output minus electricity used for internal plant operations. The Cayuga Station is expected to use internally 55 MW_e, or about 6% of gross output. Thus, the net lifetime output is 176 million MWh ($=151 \times 10^{12}$ kcal). The energy output of the Cayuga Station delivered to the consumer (E_d) over 30 years is the net electrical output minus the 3% lost in transmission, or 169 million MWh ($=146 \times 10^{12}$ kcal $= 0.577$ Quad).

Dollar and Energy Costs

The total 1975 dollar investment cost of the energy produced by the Cayuga Station, computed as the energy delivered to the consumer (169×10^6 MWh) times 2.9¢ per kilowatt hour (NYSEG 1977)[1] is $4.9 billion. Alternatively we may choose to use the "incremental cost," that is, the price per kilowatt hour for electricity used for heating once regular service has been established (i.e., requiring no new lines, transformers, billing clerk, etc.) which is estimated as 2.09¢ per kilowatt hour. This number may be especially appropriate for heating comparisons, but is not appropriate for the entire power plant. Thus, the 50% of plant output earmarked for resistance heat would cost $1.77 billion by this accounting. If all output were used (and charged) at 1975 heating-rates the cost would be $3.53 billion.

The coal required (*CB*) to generate 151×10^{12} kcal of electricity can be determined from the mean net output of electricity of the power plant and the efficiency of the plant:

$$CB = 151 \times 10^{12}\ \text{kcal} \times \frac{100}{37.78}$$

$$= 400 \times 10^{12}\ \text{kcal of coal} \div 6.78 \times 10^{6}\ \text{kcal per metric tons of coal (NYSEG 1974)}$$

$$= 59.7 \times 10^{6}\ \text{metric tons of coal required to fuel the plant.}$$

The energy cost of constructing the power plant was derived from an itemized list of components for the construction of the Cayuga plant, obtained from the engineering firm contracted for design (United Engineers 1975). This list, given in Table 1, was combined with our energy-cost-per-unit analysis (Table 1 of Part II, see p. 508) to give energy estimates for each item on the list. The energy costs for

[1] We used the mean price of all electricity sold in 1975 ($0.029/kWh). Residential electricity costs about 11% more than this mean. The price of electricity has been increasing more rapidly than the inflation factors that we have used elsewhere in our analysis; for example, it increased 11% between 1976 and 1977. Thus our prices for the power plant should be considered conservative. Discounted prices are considered in the discussion.

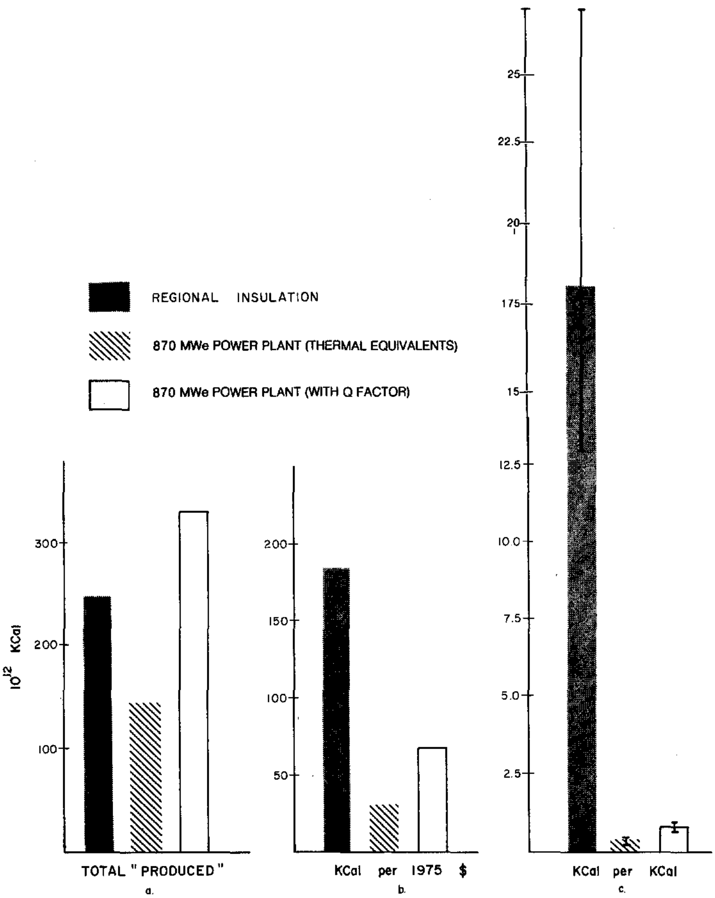

Figure 1. Comparison of a) total energy produced, b) energy produced per dollar invested, and c) energy returned per energy invested.

all items were summed according to each of the three methods of analysis to give a range of the energy required to construct the Cayuga Station (Table 1). The fourth method (use of the aggregate national ratio for total plant cost) was 326 million × 11,816 kcal per dollar, or 3.85×10^{12} kcal. The energy estimate for the *direct* plant dollar costs for the direct process method was from 5 to 15% lower than for the energy input–output (IO) method. The estimates for the IO plus labor and for the aggregate energy–dollar ratio method were considerably higher than for either of the other two methods, reflecting the high energy content of the energy equivalent of recompense to on-site labor. The discrepancies among the methods become more important when indirect costs are included, since there is no apparent way to compute the process energy use associated with taxes, engineering, environmental studies, etc., although such activities certainly use energy. Thus, the range of the energy required to construct the Cayuga Station is between 1 and 3.9×10^{12} kcal, depending upon the method and comprehensiveness of the analysis. Similar analyses done for other components of the power plant are given in Table 3. The importance of the coal energy (for which an unequivocal energy assessment was available and used) with respect to other inputs is clear from this table.

Table 1 Dollar and energy cost for construction of Cayuga Station

Component	Quantity & units		Dollar cost (thousands of 1975 dollars)	Energy cost (10^9 kcal) Process energy method[a,b,c]	Energy input–output method[c]	Input–output plus labor method
Land and land rights			660	ND[d]	1.57	1.57
Structures and improvements						
Clearing and grubbing	50	AC	25	0.10	0.14	0.28
Soil testing			50	ND	0.28	0.57
Site grading						
Earth	700000	Yd3	1400	2.37	7.97	15.88
Rock	1250000	Yd3	10000	9.19	56.93	113.41
Landscaping			250	ND	1.42	2.84
Roads and paving	50000	Yd2	350	3.06	16.01	17.99
Fence and gates	15000	Ft	135	0.75	0.95	1.72
Drains and sanitary lines	10000	Ft	500	0.19	3.92	6.75
Lighting	100	Fixt	160	0.75	0.82	1.73
Railroads + 18 turn outs	35000	Ft	1575	6.18	9.23	18.12
Fire protection and potable water	11000	Ft	630	0.21	4.95	8.50
Subtotal			15735.00	22.80	104.20	189.35
Main building-exc rock	10000	Yd3	250	3.19	1.77	3.18
Backfill concrete	15000	Yd3	525	7.81	3.71	6.67
Earth	10000	Yd3	100	0.03	0.71	1.27
Sub. concrete	17000	Yd3	2443	8.85	17.25	31.05
Sup. concrete	2000	Yd3	400	1.04	2.83	5.08
Structural steel	8500	Tons	8500	57.71	60.03	108.04
Misc. steel	450	Tons	675	3.06	4.77	8.58
Siding	300000	Yd2	1500	8.78	10.59	19.07
Roof, doors, partitions			1260	7.38	8.90	16.02
Painting	8500	Tons	510	3.21	3.60	6.48
Services			3360	13.18	23.73	42.71
Subtotal			19523.00	114.25	137.88	248.15
Administration	10000	Yd2	700	6.36	3.99	7.94
Other buildings	20000	Yd2	800	12.73	4.55	9.07
Subtotal			1500.00	19.09	8.54	17.01
Boiler plant equipment						
Steam generator & equipment			37200	209.80	218.55	428.66
Feedwater system			7600	43.87	35.09	78.01
FD and ID Fans			3400	13.26	15.70	34.90
Air and gas ducts	3500	Tons	6800	23.76	31.39	69.80
Precipitators			5900	23.14	27.24	60.56
Ash and dust handling			5100	20.01	26.12	54.93
Chimney and foundation	650	Ft	3200	60.45	18.22	36.29
Coal handling structures and equipment			16200	96.50	82.98	174.48
Pulverizer motors and foundations			300	1.58	1.38	3.08
Bunkers and equipment			1400	8.20	9.89	17.79
Fuel oil equipment			3500	16.18	17.93	37.70
Misc. equipment			500	1.96	2.24	5.07
Boiler plant piping			10700	61.76	83.99	144.43
Insulation, paint, etc.			1300	11.51	9.70	17.04
Instruments and controls			3200	10.01	15.21	33.28
Process waste system			1800	7.06	15.69	25.85
Subtotal			108100.00	609.05	611.32	1221.88

Table 1 Continued

Component	Quantity & units		Dollar cost (thousands of 1975 dollars)	Energy cost (10^9 kcal) Process energy method[a,b,c]	Energy input–output method[c]	Input–output plus labor method
Turbine generator units						
Turbine pedestal	6500	Yd3	1450	3.39	8.25	16.44
Turbine mat	5000	Yd3	350	2.18	1.99	3.97
Turbine generator and equipment			37400	210.92	219.73	430.97
Condenser and auxiliaries			5300	46.82	41.60	71.54
Intake structure (including equipment)			2000	ND	11.39	22.68
Circ water pipe			7000	40.41	54.95	94.49
Instrumentation			1500	4.69	7.13	15.60
Paint and insulate			100	0.89	0.57	1.13
Subtotal			55100.00	309.28	345.61	656.82
Accessory electric equipment			9300	40.23	44.20	96.73
Misc. power plant equipment			2300	9.02	10.32	23.31
Station equipment-transmission			3800	14.12	19.53	40.99
Subtotal			15400.00	63.37	74.05	161.03
Subtotal-all direct components			**215358.00**	**1137.84**	**1281.61**	**2494.24**
Indirect components			20600	ND	117.27	233.62
Sales tax			4400	ND	69.98	69.98
Environmental studies			7600	ND	35.09	35.09
Engineering, A.E. costs, owners cost, land, etc.			38040	ND	132.99	132.99
Training, startup, tools, etc.			7000	ND	32.32	32.32
Contingency			34000	ND	193.56	385.59
Interest during construction			100000	ND	349.60	349.60
Subtotal			211640.00	0.00	930.81	1239.19
Grand totals			**426,998.00**	**1137.84**	**2212.42**	**3733.43**

[a] Process energy per kilogram were derived from the following references: Barnes and Rankin, 1975; Berry and Fels, 1973; Brevard et al., 1972; Chapman, 1974, 1975; Chapman et al., 1974; Ford Foundation, 1974; Goudarzi et al., 1976; Kline et al., 1977; Lenchek, 1976; Makhijani and Lichtenberg, 1972; Wright, 1974.

[b] Derived from energy per unit mass, where possible, or

[c] Derived from energy per dollar.

[d] Not determined.

Energy Benefits and Dollar and Energy Costs of a Regional Insulation Program

We analyzed the potential energy savings of a comprehensive regional housing-insulation program by combining local demographic, housing-type, fuel use, and level-of-insulation information with a heat-loss-from-houses model in a computer program of regional heating-energy use. Details are given in Part III of this series (page 511 of this issue).

In 1977, about half the houses in this region were reasonably well insulated, one-quarter were moderately insulated, and one-quarter were poorly insulated, including 12% that had no insulation at all. Virtually none were insulated to the highest standards we could find—those suggested by the Edison Electric Institute (1977) and HUD (1975). Our computer analysis investigated the dollar and energy costs of raising the insulation levels of the majority of houses in the region to meet these standards (5% were left uninsulated on the assumption that even minimal insulation would be impossible for some houses) and the energy that would be saved by that program. The analysis showed that, for example, a single-family, two-story house would use 116 million kcal each year if uninsulated, 41 million kcal if reasonably insulated, and 28 million kcal if insulated to the

Table 2 Total and electrical energy used per year for dwellings in the NYSEG service area[a]

Year	Category	With existing insulation	If all at Class VIII	Savings
1975	All houses (10^{12} kcal)	21.27	13.61	7.66
1975	All electrically heated houses (10^3 MWh)	474.9[b]	374.5	100.4
1975	All electrically heated houses (MW peak use)	236.4[b]	191.5	44.9
1990	All *new* houses since 1975 (insulated to class VII)[c] (10^{12} kcal)	2.74	2.27	0.47
1990	All electrically heated houses[d] (10^3 MWh)	2226.0	1842.8	383.2
1990	All electrically heated houses[d] (MW peak use)	1113.6	942.5	171.0

[a] Existing insulation levels used as per paper III if 1975 houses are oil or gas heated, Class VII if electrically heated or built after 1975, when Class VII was required for all houses in New York State.

[b] Our theoretical calculations times 0.75, a factor representing principally the relative concentration of electric-heat users in apartments versus large single houses. This correction factor, applied to all electric-heat numbers, was derived from actual use figures in NYSEG service area versus our computer projections since at this time there are no specific data available on distribution of electric-heat users by house type.

[c] With assumption of present mix of oil or gas versus electric heat.

[d] With NYSEG assumption of 25% of houses being heated electrically.

highest standards. Our model predicts that the present mix of houses and levels of insulation in our region use annually about 21 × 10^{12} kcal. If 95% of these houses were insulated to the highest standards the annual use would be about 13.6 × 10^{12} kcal, for a 30-year savings of 244 × 10^{12} kcal, including savings in new houses (Table 2).

Such an insulation program would cost about $900 million, according to our estimates, plus a net cost of $34 million for installing more expensive furnaces to replace the less expensive electric baseboard heaters. Interest at 8% for 10 years adds another $417,000,000. The energy cost, derived in detail in Part III, would be from 8 to 14 × 10^{12} kcal.

Energy Return on Investment

The Cayuga power plant and associated structures and activities that are required to deliver the electricity would cost $4.9 billion to deliver 146 × 10^{12} kcal of energy to the user. If we assume that about 40% of the electricity continues to be sold to residential users, then the cost of the new plant is about $3000–4000 per present customer.

The system efficiency of the power-plant system in supplying electricity to consumers can be calculated as the energy delivered to the consumer (E_d; i.e., net plant output minus transmission losses) over the energy used to produce it, i.e. the energy content of the coal burned plus the energy required to mine, construct, and deliver the components of the energy system (E_i, from Table 3; all units in 10^{12} kcal):

$$E_t = \frac{E_d}{CB + E_{mpt} + E_{pc} + E_{tfc}}$$

$$= \frac{146}{400 + 20.32 + (2.2 + 13.6) + 0.55}$$

$$= 33\% \text{ (i.e. system efficiency)}$$

We have used the middle (input–output) energy cost estimate for this analysis. Using the high and low energy cost estimates (as discussed in the introduction and given in Table 3) would change the ratio to 32 and 36%, respectively. We see from this analysis that there would be a return of some 146 × 10^{12} kcal of energy to society from 437 × 10^{12} kcal invested in the Cayuga Station.

The insulation program, on the other hand, would cost about $1.3 billion to deliver approximately 244 × 10^{12} kcal (Table 3), although the actual energy "produced" will be larger over time since the houses usually last more than 30 years. The energy cost, as given in the following papers, would be from 8 to 14 × 10^{12} kcal. Thus, if the objective is to provide space heat, or to free fossil fuel and/or electricity for other uses, or (most importantly), heating with less gas and oil, the insulation program is a better investment by approximately a factor of 4 to 6 when viewed as an economic investment and a factor of from 15 to 60 (depending upon methods used) when viewed as energy return on energy investment. The difference in rate of return between economic and energy analysis is due mainly to the low dollar price per kilocalorie of coal. The insulation is a better energy return on energy investment even if the coal is not included in the calculation (Table 3).

It should be noted that the principal requirement for new electric generating capacity is the need to meet peak demand. In this study area, the insulation alternative is likely to reduce significantly the winter-peaking energy demand. This aspect probably is not too important for oil and gas heating except to allow for the installation of smaller and more efficient (on average) furnaces. However, the reduction of peak electrical demand by insulation still can be significant. If the 30,000 dwellings currently heated electrically were insulated to Class VIII as opposed to the presently prescribed Class VII, about 45 MW_e peaking power could be made unnecessary. The savings in energy will increase if the number of properly insulated electrically heated new homes increases although, as we point out elsewhere, such additional electric heating may be unnecessary.

Discussion

Energy Quality Adjustment for Output

It is obvious that electricity has some "value" that can be defined independently from its thermal equivalence (i.e., its ability to heat water). This value has been called "essergy" by Evans (1969) and "energy quality" by Odum et al. (1976). Society has been willing to burn some 3–4 calories of coal or oil to generate 1 calorie of electricity, and as a first approximation we would consider that electricity has about 3.5 times more value per heat unit than coal. Of course, this value is reflected in the price, and it is is manifest only when electricity is used for some "high-quality" function such as the running of electric motors, computers, heat pumps, or appliances. The value is lost when electricity it is used for a low-quality function such as space or water heating. Thus, in several senses, it is cost-ineffective to heat with electricity: It is expensive in terms of dollars, and its gross efficiency of use is lower by a factor of 2–3 compared to fuel burned directly in a housing unit. Since 50% of the projected NYSEG load is expected to be for resistance heat (NYSEG 1977), we can recalculate the efficiency of the proposed Cayuga Station with the quality factor (E_{wqf}) added in:

Table 3 Summary of dollars and energy used and saved for constructing the Cayuga Power Station

DOLLAR COST (thousands of 1975 dollars)		Cayuga Station (and accessories)			Regional insulation	
Total capital cost		351,000			913,000	
Cost of plant/Insulation		(326,000)[b]			(879,000)	
Cost of powerline/additional furnaces		(25,000)[c]			(34,000)	
Cost of coal		1,610,000[d]			—	
Salaries, profits, taxes, interest, repair		2,939,000[e]			417,000[f]	
(If based on "incremental cost")		(1,570,000)				
TOTAL DOLLAR INVESTMENT					***1,330,000***	
Based on mean 1975 price of electricity		***4,900,000***[g]				
Based on "incremental cost"		3,531,000				
ENERGY COST (10⁹ kcal)	Low (direct process)	Med (I–O)	High (IO plus labor)	Low (direct process)	Med (I–O)	High (IO plus labor)
Total capital cost	1,244	2,762	4,153	7,875	8,588	9,305
Plant	(1,138)	(2,212)	(3,850)			
Powerline	(106)	(550)	(303)			
Coal						
As coal	400,000	400,000	400,000			
Mining, etc.	9,000	20,320	19,030			
Electricity used[h]						
Internally[i]	(9,577)	9,577)	(9,577)			
In transmission losses[j]	(4,530)	(4,530)	(4,530)			
SUBTOTAL	**410,244**	**423,082**	**423,183**	**7,875**	**8,588**	**9,305**
Salaries, profits, taxes, interest, repair	—	13,572	34,727	—	1,457	4,927
(If based on "incremental cost")	—	(7,250)	(18,551)			
TOTAL ENERGY COST (10^9 kcal)	**410,244**	**436,654**	**457,910**	**7,875**	**10,045**	**14,232**

Table 3 Continued

DOLLAR COST (thousands of 1975 dollars)	Cayuga Station (and accessories)			Regional insulation		
(Based on "incremental cost")	—	(430,332)	(441,734)			
Total energy less coal	10,244	36,654	57,910	7,875	10,045	14,232
Total energy delivered/saved for 30 years						
Thermal	146,000[k]	146,000	146,000	244,000	244,000	244,000
With quality factor	328,500	328,500	328,500	244,000	244,000	244,000
Return on investment						
kcal/$	**29,790**	29,790	29,790	**183,459**	183,459	183,459
kcal/"incremental $"	41,336	41,336	41,336			
kcal/kcal (thermal)	**0.36**	**0.33**	**0.32**	**23.29**	**18.26**	**12.89**
kcal/kcal (w/qual)	0.80	0.75	0.72	23.29	18.26	12.89
kcal/kcal (less coal; w/qual)	32.00	8.96	5.67	23.29	18.26	12.89

Note: At this time energy costs of insulation is "conservative," that is, high by perhaps 30%, until we receive some additional information on labor costs from the insulation industry.

[a] The total cost of insulating all existing houses to Class VIII was multiplied by 0.75 to represent dollar and energy cost of adding on new insulation to the existing mix of insulation. Dollar and energy cost of insulating all new houses to Class VIII rather than Class VII are $39 million and 340 billion kcal, respectively.

[b] From Table 2.

[c] P. Komar, personal communication.

[d] Computed at $27 per ton, cleaned and delivered.

[e] Obtained by difference between total revenues and capital plus coal costs. Does not count cost of repair to electricity-using devices.

[f] Interest at 8% for 10 years derived from local bank president. Upon the advice of local contractors and bankers we did not include money for repair to insulation, but did use high estimates for original cost to provide for good-quality installation and to avoid the need for repairs.

[g] 169×10^9 kWh delivered to consumer times 2.90¢ per kWh NYSEG 1977.

[h] Not included in total energy cost.

[i] Calculated as 6% of gross plant output.

[j] Calculated a 3% of plant output (S. Linke, personal communication).

[k] Assumes 100% end-use efficiency.

$$E_{wqf} = \frac{(0.5 \times E_d) + (0.5 \times E_d \times 3.5)}{CB + (0.87 \times E_i) + (0.13 \times E_i \times 3.5)},$$

where the energy for construction and transportation is corrected for electricity use according to the mean ratio of electricity use in industry for the United States as a whole (12.5%). The output of the plant over 30 years with and without this quality adjustment is 146×10^{12} kcal and 329×10^{12} kcal (equivalent), respectively.

Application of Discount Rates

An important question is whether our analysis should be weighted according to some discounting procedure. By some accounting procedures, a "1975 dollar" spent "later" has a different value than a "1975 dollar" spent "now," since in the meantime it can be earning interest. The insulation alternative requires the money to be spent "now," whereas a substantial portion of the money spent for the power plant would be spent "later." This would work toward making the power plant a *relatively* more favorable investment than is the case with undiscounted analysis, at least according to some standard economic procedures. The "best" discount rate to use is open to controversy, but is probably about 2% in constant dollars (Mount, pers. comm.). Applying this discount rate to our analysis and assuming 3 years for capital construction for both power plant and insulation, and 30 years of operation of the power plant at $151 million 1975 dollars per year, the cost of the insulation is $1.3 billion in "discounted 1975 dollars," and of the power plant $3.69 billion "discounted 1975 dollars." This would change the "energy-return-on-dollar-investment" figures in Table 3 by a factor of 20%. Even by this procedure, however, the insulation retains considerable economic advantage.

One might question our decision not to use the discounted price for the final analysis given in Table 3. Our rationale is dependent upon our conclusion that it is necessary to discount *both* dollars and, in a different way, energy. Thus standard discount rates may not apply to energy facilities, and, especially, energy conservation.

Much economic theory, including some important components of the use of discount rates, is based on the concept of a continuously expanding economy, which allows large investment opportunities. Our view is that energy supplies are a fundamental, virtually unsubstituitable component of economic activity, and that economic growth must be accompanied by increases in energy supplies unless energy is used more efficiently. Energy was once extractable rapidly enough to fuel new capital equipment about as rapidly as it was manufactured. In the past decade, however, the situation has changed considerably. Energy is no longer readily and cheaply available; it has become a scarce commodity. The peaking and decline of domestic petroleum production in the early 1970s, and the likelihood of global peaking and decline within about 20 years puts constraints on economic growth and the use of discount rates, since petroleum represents about three-quarters of the energy used in both the United States and the world, and substitutes appear unable to both make up for petroleum shortfalls and maintain growth. Growth of the economy in constant dollars has been relatively slow since 1973, especially when viewed against the sharp expansion of preceding decades. Overall, investments have had less return in the more recent past and may be even less profitable if or as energy supplies diminish further relative to economic demand.

According to standard economic accounting using discount rates, a unit of energy, say a barrel of oil, owned, but in the ground, is worth far less if it is to be sold in 20 years than if it were sold or burned for economic gain now. The profit on a barrel of oil sold now could be invested and return interest for the next 20 years. On the other hand, that barrel of oil may not fit the standard discounting analysis quite so well as routine investment procedures suggest, for two reasons. First, the constant-dollar price of energy may increase more rapidly than returns on investment, so that energy in the "bank" may gain interest more rapidly than money in the bank. Second, the economic pressures of higher energy cost are causing energy to be used more efficiently—in effect each year we get greater economic return per calorie burned (not counting the ever-increasing energy cost of energy extraction) as industrial and other facilities are made more energy-efficient. Thus, the constant-dollar economic worth of a unit of energy owned (or not bought) may, at some point in the future, be as great or greater than its present value plus the potential interest accrual in the interval. The actual discount rate most appropriately applied to energy may be zero or even negative. Money spent now to save energy in the future may be a good investment even with the loss of substantial interest-accrual potential, since it saves the consumer from having to purchase energy at higher future constant-dollar costs.

It is impossible to predict accurately either future energy prices or interest rates for the next 30 years. We have chosen the "conservative" path of using 1975 dollars for our principle analysis although obviously the money will be spent over many years. Perhaps the discounted analysis might be considered a minimum estimate of the advantage of insulating versus building the power plant and the undiscounted rate a possible maximum (but we think more realistic) estimate of the differences in energy return on investment. We believe that standard discounting procedures greatly undervalue the economic return that will accrue from energy conservation measures and lead too frequently to suboptimal economic decisions, especially as we see a future world with energy supplies far less than potential energy demand.

If we assume that an investment in insulation is a much better return on investment than a power plant, why is this not reflected in the marketplace? To some degree it is. Locally, insulation contractors are booming; electrical demand has consistently fallen well below forecasts over the past 4 years. However, a principal reason that insulation is not replacing all new electric demand may be related to consumer habits: The capital outlay for insulation is large and must be paid before the energy savings can take place. Utilities, on the other hand, can borrow or raise the capital needed for the new plant often at lower interest rates than a householder can get. Thus utilities can charge consumers relatively small monthly increments for service. This has predisposed consumers toward the construction of utilities rather than insulation, even though insulation may be far cheaper per unit heat than electricity (or other fuels). This situation no longer exists in New York. In August 1977 the State Legislature passed a bill requiring utilities to provide low-interest loans to consumers for the installation of insulation that would be paid back by small increments on monthly utility bills over a period of up to 7 years. Thus we think that New York state is in a particularly favorable position to "generate" energy through insulation, and that other states should consider the New York plan, although voluntary cooperation with the existing New York Plan has been disappointing so far. Perhaps the centralized leadership of state agencies and utilities that are charged with providing energy supplies could be shifted to comprehensive insulation programs.

Since a comprehensive insulation program could easily cut the need for oil and gas heating fuels by one-third in Central New York this could eliminate the NYSEG-assumed need for new electric space heat, at a considerable savings of consumers' money, with far less use of national energy resources and, presumably, with less pollution. Such a program would lessen the impact of possible future oil embargoes or coal strikes, and a recent analysis indicates that a dollar spent on installing insulation produces many more jobs than a dollar spent on power plant construction (Bullard 1978). However, our analysis indicates that if any insulation is to be installed it is important to do as complete a job as possible the first time around.

As mentioned earlier, heat was only half of the expected increase in electricity demand. But what of the other 50% percent of the projected demand? If there is no need for an 850-MW power plant, is there still need for a 425-MW plant? Lovins (1976) and others argue that the requirements for "high-quality" electric energy in the United States are only about 8% of our present total energy use. Presently, however, some 13% (both in thermal units) of our total energy is supplied as electricity. In other words, we really need only about 62% of our present electricity production for industrial electic motors, home appliances, etc. The rest is used for low-quality functions which, at least in the case of heat, could be provided much more efficiently by using fossil fuels directly. It is interesting to note that at this time New York (but not NYSEG) has a 50% excess peaking capacity of electric generating power, due in part to the recent completion of a series of very large generating units on the Hudson River, Lake Ontario, and a very large hydroelectric facility on the Niagara River, coupled with virtually no increase in electric demand in New York state over the past 4–5 years. Recently NYSEG announced that it would delay for 4 years the initiation of construction of the proposed Jamesport facility, in part because demand had not been growing as rapidly as projected, and the NYSEG demand in 1977 was actually 1% less than the demand in 1976.

Conclusion

Electrical generation facilities have in the past met certain social needs such as the provision of jobs, the increased tax base for local communities, and the obvious social benefits of the energy. They also have supplied certain "disamenities" such as electric bills, air and land pollution, aesthetic changes and (sometimes) the severe disruption of aquatic communities (e.g. Hall 1977; Hall et al. 1978). As each new facility is proposed, the focal point for debate has been an either/or issue of whether or not to build the plant. If the plant is not built, environmental, aesthetic, and development problems are avoided, but the benefits of jobs and energy supplies are lost. If the plant is built, the social benefits are provided but environmental and other amenities are lost, air pollution is increased, *and* consumers must pay for the new facility.

We offer a third alternative: an examination of the efficiency of meeting social objectives by the proposed facility versus the efficiency of meeting the same objectives by alternative facilities or programs. In the case that we have examined in detail, the generating facility was inefficient (in both return on energy invested and return on money invested) by a factor of from 4 to 60, depending upon the base assumptions. We believe that as other large centralized facilities are examined in this light, other inefficiencies will be found. Our remaining fossil fuel resources are far too valuable not to undertake such analyses.

Acknowledgements

We thank H. Boston, T. Butler, L. Herbst, W. Higgens, I. Pessah, C. Tuthill and C. Vorosmarty for help with research and analysis; S. Linke, T. Mount, D. Pimentel and R. Pohl for critical comments; and especially P. Komar of NYSEG for helpful information. However, the analyses and conclusions presented here are solely the responsibility of the authors.

Literature Cited

Bullard, C. W. 1978. Energy and employment impacts of policy alternatives In energy analysis: A new public policy tool. M. Gilliland (Ed.), *AAA Symp. 9.* Westview Press, Colorado.

Chapman, P. F., G. Leach, and M. Slesser. 1974. The energy cost of fuels. *Energy Policy* 2:231–43.

Eckstein, O. 1958. *Water resources development: The economics of project evaluation.* Harvard University Press, Cambridge, Massachusetts.

Edison Electric Institute. 1977. *All weather comfort guideline.* EEI Publ. No. 76-35, New York.

Evans, R. B. 1969. A proof that essergy is the only consistent measure of potential work (for work systems). Ph.D. Thesis. Dartmouth College, Hanover New Hampshire.

Ford Foundation Energy Policy Project. 1974. *A time to choose: America's energy future.* Ballinger, Lexington Massachusetts. 511 pp.

Gibbons, J., R. Carlsmith, M. Whiting, E. Goodson, C. Bullard, D. Chapman, C. Berg, N. Bradburn, P. Craig, J. Darmstadler, S. Rattien, L. Schipper, and R. Uhler. 1978. U. S. energy demand: Some low energy futures. Science 200:142–152.

Gilliland, M. W. 1975. Energy analysis and public policy. *Science* 189:1051–1056.

Hall, C. 1977. Models and the decision making process: The Hudson River power plant case. In C. Hall and J. Day (eds.) Ecosystem modelling in theory and practice. Wiley (Interscience), New York.

Hall, C., R. Howarth, B. Moore, and C. Vorosmarty. 1978. Environmental impacts of industrial energy systems in the coastal zone. *Annual Review of Energy* 3:395–475.

Huettner, D. A. 1976. Net energy analysis: An economic assessment. *Science* 192:101–104.

Lovins, A. 1976. Energy strategy: The road not taken? *Foreign Affairs* 55:65–96.

Mishan, E. J. 1971. *Cost-benefit analysis: an introduction.* Praeger, New York.

NYSEG. 1974. Cayuga Station application to the New York State Board on electric generation siting and the environment for a certificate of environmental compatability and public need. Volume 1. Including exhibit A, need for a facility and testimony of B. M. Rider.

NYSEG. 1977. *1977 Annual Report*, Dryden, New York.

Odum, H. T., C. Kylstra, J. Alexander, N. Sipe, T. Lem, M. Brown, S. Brown, M. Kemp, M. Sell, W. Mitsch, E. DeBellevue, T. Ballentine, T. Fontain, S. Bayley, J. Zuccetto, M. Costanza, G. Gardner, T. Dolan, A. March, W. Boynton, M. Gilliland, and D. Young. 1976. "Net energy analysis of alternatives for the United States." Hearing before the Subcommittee on Energy and Power of the Committee on Interstate and Foreign Commerce, House of Representatives, 94th Congress. *In* Part I, Middle- and Long-Term Energy Policies and Alternatives, U.S. Government Printing Office, Washington, D.C. pp. 253–302.

Perry, A. M., W. D. Devine, Jr., A. E. Cameron, G. Marland, H. Plaza, D. B. Reister, N. L. Treat, and C. E. Whittle. 1977. Net energy analysis of five energy systems. Institute for energy analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee.

Pilati, D. A., and R. P. Richard. 1975. *Total energy requirements for nine electricity-generating systems.* Center for Advanced Computation. University of Illinois, Urbana.

Ross, M. H., and R. H. Williams. 1976. Energy efficiency: Our most underrated energy resource. *Bulletin of At. Sci.* 32(9):30–38.

United Engineers. 1975. Cayuga Station, preliminary cost estimate. Boston, Massachusetts (xerox—3 pp.).

U.S. Department of Housing and Urban Development, Community Services Administration. 1975. *A community planning guide to weatherization,* CSA pamphlet no. 614306. U. S. Government Printing Office, Washington, D.C.