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ENERGY ANALYSIS OF TWO TECHNOLOGIES: GASOHOL AND SOLAR SATELLITE POWER STATION

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ABSTRACT

A large flurry over net energy analysis in 1975 died down quickly when calculations showed that the energy supply technologies under study were far from the net energy limit (i.e., that according to anyone's interpretation they were not in danger of "requiring more energy than they would produce"). Here I report on two technologies which are close to that limit, the production of ethanol from the fermentation of grain for ethanol/gasoline mixture (gasohol) and the production of electricity by the solar satellite power station (SSPS). Many of the classic methodological problems of net energy analysis exhibit themselves in the analysis; these are discussed in context. The SSPS suffers from uncertainty of input data, since much of the technology is only speculative, but appears to provide positive net energy. Gasohol lies either on the good or bad side of the energy limit depending on assumptions of system boundary and end-use efficiency.

I. INTRODUCTION

The notion of the net energy limit - the point at which an energy supply technology requires more energy than it produces - is a plausible one. Surely some day we shall approach that limit. However, as a criterion for policy, net energy analysis has encountered many objections regarding 1) the methodology for determining (or even defining) the net energy balance (4, 13) and 2) the relative merits of energy analysis and economics as a policy tool (10, 20).

To a large extent this debate has turned out to be moot, since a number of computations on a spectrum of energy technologies have shown that the net energy limit is far away. Glossing over the difficulties of definition, one can say that these computations showed current and near-term future supply technologies to "produce" from 5 to 50 times as much energy as they require (14), and the list included several non-breeding nuclear options. (Note, however, that energy costs of decommissioning were neglected). Further, admitted uncertainties in data and method blurred the distinction between different technologies.

In spite of this I believe that energy analysis of energy supply technologies has a useful role as a provider of one kind of information to the general decision-making process. I feel, however, that only when the technology is near the limit can the energy analysis be useful; far from the limit other criteria will dominate (such as dollars). This paper deals with two disparate technologies which are close to the limit as compared with "conventional" energy supply techniques: "gasohol" and the solar satellite power station (SSPS). Gasohol refers to a mixture of gasoline and ethanol derived by fermentation of grain. The SSPS is an array of photocells in geosynchronous orbit which converts sunlight to electricity, and electricity to microwaves which are beamed to terrestrial receiving antenna, and then converted to electricity for distribution. Both of these schemes are touted as solar technologies, as indeed they are. A comparison of the two is given in Table 1; they differ on many points. Here I will deal only with an energy analysis of both. In the discussion I will touch on many of the "classic" methodological problems of energy analysis, which I will identify in context. These are listed in Table 2, and are discussed in general terms in (11).

Table 1. Comparison of Selected Aspects of SSPS and Gasohol.

	ASPECT	SSPS	GASOHOL
1.	Output	Electricity	Liquid fuel
2.	Solar conversion process	Photovoltaic cells	Biomass
3.	Relative size	Collector and Rectenna of order 100 km^2 (10 GW output)	Typical distillery (of order 10^4 M^2) producing of order 20 x 10^6 gal/yr.
4.	Capital cost	\$10-50 Billion	\$10-20 Million
5.	Potential energy contribution	All U.S. electricity	~2% of present gasoline (crop surplus limitation)
6.	Regional suitability	-	Grain belt states
7.	Vested interests	NASA, aerospace contractors	USDA, agriculture lobby
8.	Time scale to implement	30-50 years	1-2 years
9.	Uncertainties in data	High	Low

II. GASOHOL

Gasohol (10% ethanol, 90% unleaded gasoline) is currently for sale in Illinois in small quantities, at about 10¢ per gallon above pure gasoline. It is usually envisioned as a mixture of anhydrous ethanol (fermented from grain, say) and unleaded gasoline, although strictly speaking the intermediate production of pure ethanol is not necessary. The potential contribution of gasohol depends on the available fermentable material. If it is based on the U.S. grain "surplus" which can amount to 10^9 bushels, the ethanol would amount to several percent of todays gasoline use (volume basis). Already there is considerable media coverage of the energy balance questions for gasohol (3), with strong claims on both sides. My analysis of these claims indicates little disagreement on actual data, but considerable disagreement on interpretation, covering several of the difficulties of energy analysis listed in Table 2. The process is sketched in Fig. 1. Within the solid line boundary of the ethanol production/purification process we find (usually): 1. grinding of grain and mixing with water; 2. cooking of grain and conversion of starch to sugar by enzymatic action; 3. fermentation of sugar to ethanol; 4 distillation of ethanol to 95% purity; 5. further purification to 100% ethanol. (This is then mixed with unleaded gasoline, usually at the filling station); 6. preparation (e.g., drying) of feed by-product.

Table 2. Methodological Problems in Energy Analysis.

		EXAMPLES	
	Problem	SSPS	GASOHOL
1.	Specification of system boundary.	Should research costs be included?	Should agricultural energy be included?
2.	Comparison of different energy types.	Electricity out vs. fossil fuel in.	Should process be evaluated as a petroleum-like fuel producer only?
3.	Consideration of end use.	Will electricity be used in heat pumps?	Does gasohol get better miles-per-gallon than gasoline?
4.	Consideration of joint product.	-	How is energy "content" of feed by-product counted?
5.	Confusion of energy payback with energy ratio.	Complicated by SSPS's expected decrease in output over lifetime.	-
6.	Inclusion of fuel in energy ratio.	{This is not a problem with these solar technologies but it is for competing fossil-based technologies.}	
7.	Dynamic effects (from ambitious building programs)	{Potentially, always a problem}	
8.	Question of negative costs vs. positive benefits. (This does not change balance but does change energy <u>ratio</u>.)	-	Should feed by-product energy be subtracted from input?

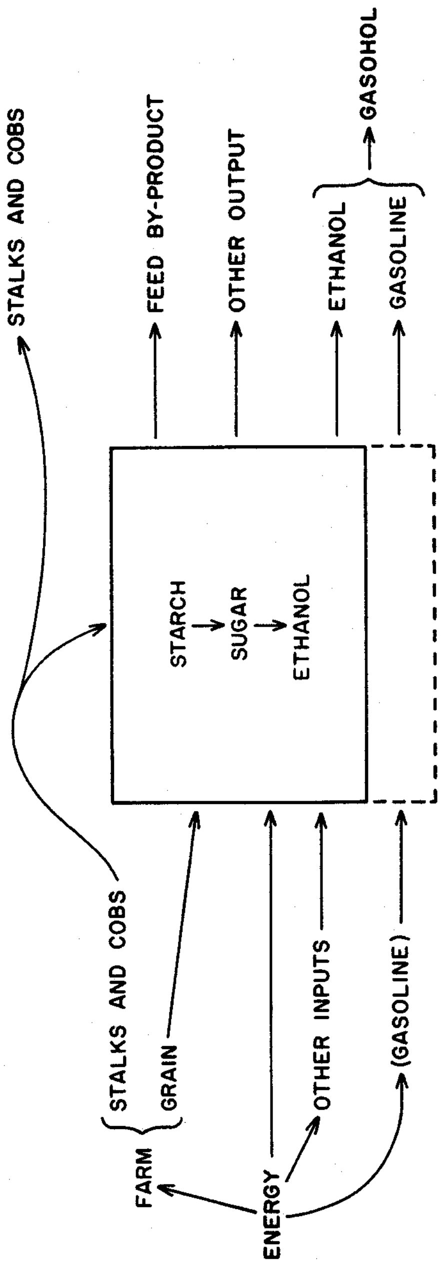

Fig. 1. Schematic diagram of gasohol production. The processes studied here produce anhydrous ethanol which is then mixed with unleaded gasoline, but this is strictly speaking not necessary since the product is 10:90 ethanol:unleaded gasoline.

Table 3 shows energy data for ethanol production from two original sources (16, 19). These sources are almost identical. Implicit in Table 3 is the choice about which inputs or outputs ought to be included in the energy analysis. This is the system boundary problem, number 1 in Table 2.

Table 3. Total Primary Energy Inputs Per 2.5 Gallons Ethanol (Or Per Bushel of Corn) Units = 10^3 Btu

	Reilly, 1977 (Ref. 16)	Scheller & Mohr, 1976 (Ref. 19)	
INPUTS:			
Agricultural energy of which:	-	119(d)	
Drying			
Transport			
Capital			
Cooking/fermentation(f)	354	62	357
Distilling and centrifuging		101	
Purify 95% → 100%		36	
Concentrate feed by-product		109	
Dry feed by-product		49	
Capital(c)	-	-	
OUTPUTS:			
Ethanol (gal)	2.5(a)	2.5(a)	
Feed by-product (bu)	0.3(f)	0.3(e)	
Stalks (lb)		49(b)	

(a) Heat of combustion = 84 kBtu/gal ("high heating value").

(b) Heat of combustion = 6340 Btu/lb ("high heating value"). This represents 75% removal from field. There is a need to know what happens to soil quality if this removal is continued.

(c) Estimated to be of order 5 x 10^3 Btu/2.5 gal. and hence neglected.

(d) Scheller and Mohr attribute this to Ref 15. In subsequent analysis I use a figure of 184 x 10^3 Btu/bushel, from (3). The latter is more recent and comprehensive.

(e) Calorific content of edible portion. Average value of 433 kBtu/bu used in subsequent analysis. Slight variation between sources has been ignored. These more than mask Scheller and Mohr's inclusion of small amounts of fusel oil as an output.

(f) Boiler efficiency for producing steam ≈80%.

In Table 4 I quantify the energy consequences of various analysis options. I choose, for example, to isolate the gasohol as the only output, all other output being instead treated as negative input (problem number 8 in Table 2). I somewhat arbitrarily choose a base case using average corn, including agricultural energy, drying of feed by-product (and crediting it with its calorific energy content). For this base case, 411 kBtu (357 + 184 - 130) is required (total primary energy) to produce 2.5 gallons of ethanol (which has a calorific energy content of 210 kBtu).

Table 4. Quantitative Effect on Total Primary Energy Inputs of Applying Options to Base Case. Normalized to production of 2.5 gallons of ethanol; all by-products credited as inputs (see text). Units = 10^3 Btu.

	INPUT
BASE CASE (uses corn, includes agricultural energy, drying of feed by-product, credit for feed by-product)	411
CHANGES TO BASE CASE	
INPUTS	
1. Ignore agricultural energy	-184
2. Use corn belt corn (better yields)	- 66
3. Use wheat	+ 6
4. Don't dry corn	- 15
5. Use inferior or spoiled crop	0[a]
PRODUCTION PROCESS	
6. Don't dry feed by-product	- 49
7. Burn stalks in process	-248[b]
OUTPUTS	
8. Sell excess stalks for fuel (after use in Option 7)	- 75[b, c]
9. Credit feed by-product only with equivalent agricultural input	+75[d]

[a] The point is always debatable. The energy inputs to a spoiled or failed crop have already been consumed; hence I feel they ought to be counted.

[b] I assume that about 30% of process energy cannot be met by burning stalks.

[c] 75% removal rate of stalks, cobs, etc.

[d] From (3), primary energy inputs to national average corn production amount to 42% of the corn's heat of combustion.

We can see, however, that there is particular sensitivity of the input energy to using stalks and cobs as boiler fuel, and to including agricultural energy inputs. In this context it is interesting to compare the two sources, Reilly, and Scheller and Mohr. From the original papers (16, 19), we find that Reilly did not include the burning of stalks and cobs, while Scheller and Mohr did. In a word, I believe this is the reason for the whole controversy documented in (3). Inclusion of stalks and cobs reduces the (other) energy inputs to 163 kBtu/2.5 gal ethanol, which is below the calorific energy content of 210 kBtu. In this context the stalks and cobs change the energy balance. All is a simple consequence of problem 1 in Table 2, the system boundary question.

A consideration of the use to which gasohol is put is also important (problem 3 in Table 2). Practically speaking, it is destined for cars. The question then is: what about miles-per-gallon (mpg) for gasohol. If the mpg is different from that expected on a pure calorific basis, should credit or blame for this be allocated wholly to the ethanol, thus treating it as an additive? (This is a variation on the joint products problem, number 4 in Table 2). Here I will assume that the weight should be on the ethanol, in which case the ethanol will have an effective energy value given by

$$(1+x)H_g = p\,H_e + (1-p)H_g,$$

where

H_g = Heating value (per volume) of gasoline = 125 kBtu/gal

H_e = Heating value (per volume) of ethanol = 84 kBtu/gal

x = fractional increase in miles-per-gallon with gasohol (x could be <0)

p = volume fraction of ethanol in gasohol = 0.1

Solving,

$$\alpha = \left(1 + \frac{x}{p}\right)\frac{H_g}{H_e}$$

αH_e is the energy value of the amount of pure gasoline which would have to be burned to produce the same change in miles per gallon caused by the addition of the ethanol.

Actually a further multiplier is appropriate because gasoline carries with it a refining and processing energy penalty. Calling this β, which has a value of 1.208 (8), we want $\alpha\beta$. For the values given above, $\alpha\beta = 1.80\ (1 + 10x)$.

This indicates a strong dependence on x. For no change in mpg, the energy value of the output (as a displacer of gasoline) is multiplied by 1.8. Scheller and Mohr report (18) a 7.2% increase in mpg, i.e., $x = 0.072$ giving $\alpha\beta = 3.09$, which is very large and makes gasohol a net energy producer with any of the inputs assumed here. It seems possible, therefore, that the end-use consideration may actually be the dominant aspect of the energy analysis of gasohol.

It should be noted, as stated at the beginning of this paper, that gasohol is always courting the net energy limit. Even with an $\alpha\beta$ of 3.09, (energy out/energy in), which I define as the energy ratio (ER), is not much larger than 1.5 (without inclusion of stalks, which in my opinion is a relatively untested option). On the other hand, it is possible to analyze the gasohol process only as a producer (and consumer) of petroleum - like products, not of total energy as I have already done. (Problem 2 in Table 2). To do this one merely ignores all non-petroleum inputs and outputs. Since coal is typically used as boiler fuel, the only persistent petroleum input to the process is agricultural energy, and the base case petroleum input is about 120 kBtu/2.5 gal. ethanol (3), which looks quite favorable even before exercising options or using the end use multiplier.

I conclude for gasohol that it is rather unambiguously a net producer of petroleum-like energy, but it is uncomfortably close to the net energy limit for total energy to allow an unambiguous statement without several qualifiers.

III. SOLAR SATELLITE POWER STATION (SSPS)

Unlike gasohol, the SSPS is an untested technology. It has been studied at a low level since its proposal tin 1968 (7) subject of Congressional hearings in April, 1978 (5). It has the obvious advantage of almost completely uninterrupted insolation in its geosynchronous orbit. Design concepts are ambitious: typically one talks of a 5-10 GW capacity, with an array size in space of 100 km^2 and a receiving antenna (rectanna) of 100-200 km^2. It goes without saying that any design data are somewhat uncertain.

I have attempted an energy analysis (9) based on available publications (1, 2, 6, 12). Because of data uncertainties I have used a rather aggregated approach in which the SSPS is characterized by 5 "modules" (for example, transportation to orbit) each requiring 10 materials (for example, silicon for solar cells) and whose overall requirements or performance are governed by 8 parameters (for example, half life of solar cells in space). These are listed in detail in Tables 5 and 6.

Table 5. Modules in SSP Energy Analysis
(From Ref. 9)

1. Ground transportation.
2. Transportation to geosynchronous orbit.
3. Materials in solar array.
4. Materials in conversion and transmission of microwaves to earth.
5. Materials in rectenna.

Besides fuzzy data for materials requirements, because the project is so far in the future the energy intensities of these materials are also very fuzzy as indicated in Table 6. Given this, the only response is to perform an elementary error analysis, which is included in the statement of results in Table 7. Uncertainty is calculated under two assumptions: 1) a "worst case" (in which it is assumed that uncertainties in the 8 parameters and 10 energy intensities conspire to

Table 6. Input Variables For SSPS Energy Analysis (from Ref. 9).

VARIABLE	RANGE OF VALUES(a)	UNITS	COMMENTS
1. Solar cell half life	30-20	years	Implies SSPS power decreases with time.
2. Solar cell efficiency	15-10	percent	
3. Rectenna area	100-200	Km^2	Dependent on microwave standards
4. Solar cell thickness	0.1-0.25	mm	
5. Duty cycle	95-90	percent	Higher than nuclear or fossil today.
6. Cell attrition	0-10	percent	Depends upon space assembly concept employed.
7. Grid efficiency	100-90	percent	As measured with respect to today; transmission distance longer
8. Transportation energy requirements	1 up to 2	Factor	Both ground and space
9. Energy intensity, aluminum	$6.6\text{-}8.3 \times 10^4$	Kwh/metric ton	
10. Energy intensity, concrete	$3.1\text{-}4.1 \times 10^2$	Kwh/metric ton	
11. Energy intensity, silicon	$1.9\text{-}26. \times 10^6$	Kwh/metric ton	Poorly known, but large and important.
12. Energy intensity, steel	$1.4\text{-}1.9 \times 10^4$	Kwh/metric ton	
13. Energy intensity, rocket propellent 1	$1.4\text{-}1.5 \times 10^4$	Kwh/metric ton	Like kerosene
14. Energy intensity, liquid H_2	$1.4\text{-}2.3 \times 10^3$	Kwh/metric ton	
15. Energy intensity, liquid O_2	$3.3\text{-}4.2 \times 10^3$	Kwh/metric ton	
16. Energy intensity, electronic parts	$5.2\text{-}8.7 \times 10^4$	Kwh/metric ton	

Table 6 (continued)

VARIABLE	RANGE OF VALUES[a]	UNITS	COMMENTS
17. Energy intensity, other	$6.6\text{-}8.3\times10^4$	Kwh/metric ton	
18. Energy intensity, argon	$7.0\text{-}11.0\times10^3$	Kwh/metric ton	

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[a] All energy intensities are in primary terms; Kwh means thermal Kwh.

produce the maximum effect), and 2) a "probable case" (in which it is assumed that the uncertainties vary independently and hence cancel to some extent). To evaluate the latter a Monte Carlo simulation is performed. Discussing Table 7 raises several of the problems of energy analysis.

1. The energy ratio (ER), which is here defined as energy output divided by total fossil energy input, varies according to the weighting given to the electric output of the SSPS (problem 2 in Table 2). For consistency with the gasohol discussion, it most probably should be multiplied by a factor of 3.43 to account for the likely role of the electricity as a displacer of fossil-fuel produced electricity. (In Table 7 the energy ratio is given in both forms.) In this case the net energy balance is positive, with a mean value for ER of 7.5. Even with the calculated uncertainties ER will not be less than 1. This discussion also assumes that SSPS-produced electricity is not a significant fraction of total electricity; if it were, the energy inputs could no longer be calculated using present energy intensities. Ref. 4 discusses this problem

2. The ratio is calculated with solar inputs; these are considered free. On the other hand, in Table 7 I list ER's for several technologies that could compete with the SSPS to produce electricity. I list these both with and without fuel in the denominator. Both definitions have their uses. (Problem 6 in Table 2).

a. ER without fuel corresponds to the usual, marginal, way of approaching an energy supply technology. In this case we envision the technology as borrowing a certain amount of energy from the existing economy as necessary to develop its capital equipment, after which it pays energy back over its lifetime. If the payback energy exceeds that borrowed, the technology is said to be an energy source. This paralle the conventional economic view of considering resources as free except for the costs of developing them.

b. ER with fuel corresponds to a physical measure of conversio efficiency of fossil fuels into useful form. This point of view is associated with assigning inherent value to non-renewable resources. For a fossil fuel-based technology ER with must be less than 1; only for a solar technology can it exceed 1.

There is no necessary connection between the values of the two ratios. One can envision both an efficient and a very wasteful strip

Table 7. Energy Ratio for SSPS and Several Conventional Electric Technologies.

	ENERGY RATIO[a] Fuel Included, Electricity (1/1)	Fuel Excluded, Electricity (1/1)	Fuel Excluded Electricity (3.43/1)
Coal fired power plant[b]	0.31	7.7	26
Light water nuclear plant[b]	0.24	4.8	16
Combined cycle coal final plant[b]	0.38	14	48
SSPS[c]			
Best	9	9	31
Probable best[g] (+ 1 Standard Deviation)	3.9	3.9	13
Mean[g]	2.2	2.2	7.5
Probable worst[g]	0.7	0.7	2.4
Worst[f]	0.5	0.5	1.7

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[a] $$\text{ER} = \frac{\text{energy delivered over lifetime}}{\text{primary, non-renewable energy required to construct and operate facility}}$$

[b] Source: Ref. 14.

[c] Ref. 9.

[d] Calculated using arithmetical averages of all variables in Table 6.

[e] This factor attempts to account for the role of the SSPS as a displacer of fossil-fuel produced electricity. It is obtained from Ref. 8, Table 4b, but reduced by 9.7% because Ref. 8 includes the effects of transmission losses, whereas here energy is measured before transmission.

[f] Obtained by allowing each variable in Table 6 to assume its best or worst value.

[g] Obtained by Monte Carlo simulation, assuming each variable in Table 6 to be independent. Distribution of each assumed to be Gaussian, with p = 0.90 that variable falls between values in Table 6.

mine (corresponding to high and low values of ER *with fuel*) which have the same ER *without fuel*. In the long run presumably only ER *with fuel* will be useful, and a fossil fuel supply technology will usually appear inferior to a solar based one. With today's economics, it would seem that ER *without* is most useful. In fact, my opening statement about conventional energy technologies being far from the net energy limit was based on ER *without fuel*.

It would be useful if competing *solar* technologies had been subjected to careful energy analysis; to *my knowledge* they have not.

3. I have not used the term "payback" period because it can lead to misunderstanding if the output of the energy technology is not constant over its lifetime. (Problem 5 in Table 2.) The concept is based on the definition of ER *without fuel*, but it is not necessarily an indication of the usefulness of the energy supply. It is possible that by the time the technology has paid back its energy debt, even though it has many years to life it may have little energy left to offer. Special attention is justified with the SSPS since there is significant concern about dimunition of solar cell performance in space. Half-lives of order 20-30 years are mentioned, and we have explicitly included this in our analysis. On the other hand, conventional fossil-fuel power plants better approximate a constant output over their lifetime.

In Fig. 2 I have indicated two simplified but possible power graphs for an energy supply. The first has constant output for 24 years (after a 6 year construction period), which means that payback occurs at 12 years. The second is arranged to share several aspects with the first, including the same payback time, but its output dies off linearly over its lifetime. The first has an ER (*without fuel*) of 4.0; the second, of 2.2. Furthermore, after the payback time the first has a bonus after payback (fraction of gross energy output still remaining) of 0.75. For the second case, with its diminishing output, only 0.55 remains; that is at the payback time three-fifths of its lifetime remains, but only 55% of its output.

Actually, neither ER, payback time, nor bonus after payback is adequate for all purposes. The power curve, such as shown in Fig. 2, contains all the information, and for detailed work this is necessary to avoid misstatement.

4. The "dynamic net energy problem" refers to a program of constructing many similar facilities. Even though ER may exceed 1, sufficiently aggressive construction programs can, in total, require more energy than they return for long periods, well exceeding the single facility payback time (Problem 7 in Table 2.) This is discussed at length by Chapman (4). Without going into detail, I merely note that the problem is more likely to arise if ER is closer to 1 (which does not seem too serious a problem with the SSPS if the output is assumed to displace fossil-fuel electricity), and if the power curve drops off in later years (which probably does occur with the SSPS). As for building schedule, one SSPS deployment scenario (2) calls for the construction of 112 - 10 GW units; it is claimed that the economics of scale are needed to make SSPS electricity competitive.

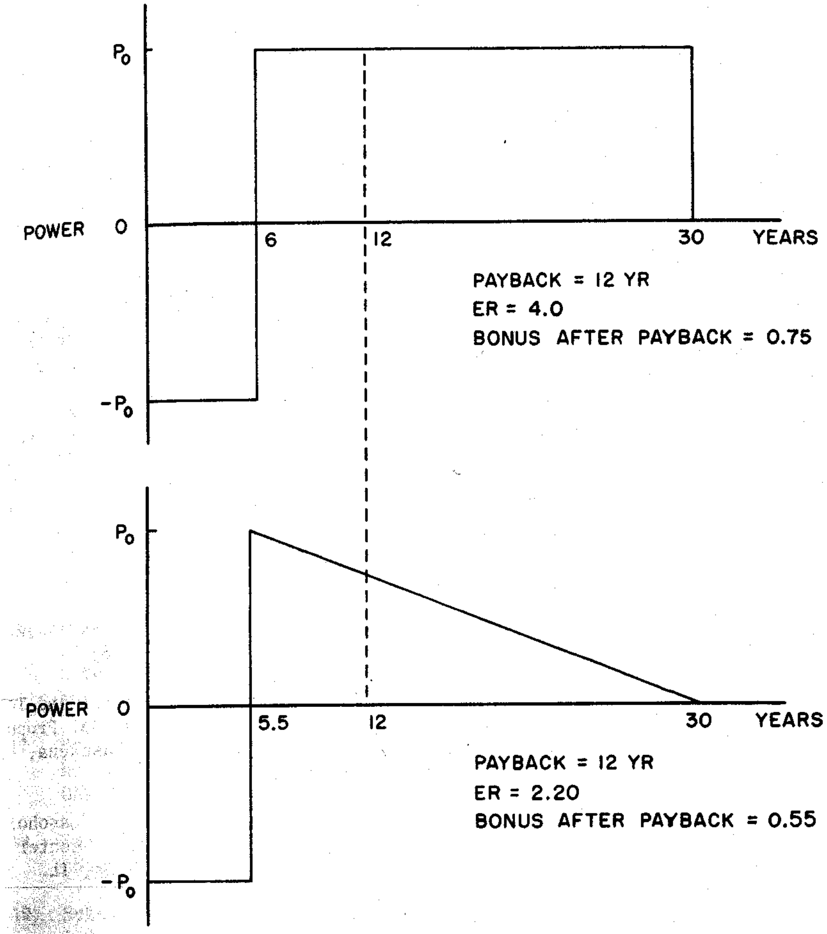

Fig. 2. Two hypothetical power curves to demonstrate that knowledge of "payback time" does not specify energy ratio. Bonus after payback is defined as (energy delivered after payback time is reached) divided by (gross energy output). The latter is energy output between end of construction and the closing down of the facility.

IV. CONCLUSIONS

For gasohol the existing data seem consistent, and whether gasohol pays energetically is dependent on 1) the use of stalks and cobs as fuel, 2) the miles-per-gallon rating. The SSPS issue is clouded by great data uncertainty but it appears that the energy ratio is positive. For reasons related to the suspected decrease of power output over its lifetime, and to a proposed rapid deployment of many SSPS's, more study is probably appropriate.

In closing, I again stress that energy analysis provides only one input to the decision regarding desirability of these technologies. But because they are demonstrably close to a net energy limit, I believe the energy analysis is particularly useful.

V. ACKNOWLEDGEMENT

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