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by

Hartmut Krugmann

Instituto de Física, Universidade de São Paulo

C.P. 20516, 01000 São Paulo, Brasil

UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE FÍSICA
Caixa Postal - 20.516
Cidade Universitária
São Paulo - BRASIL

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THE ECONOMICS AND ENERGY INPUT-OUTPUT OF A SOLAR WATER HEATING SYSTEM IN SÃO PAULO, BRAZIL

Hartmut Krugmann*

Instituto de Física, Universidade de São Paulo,

São Paulo, Brazil

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INTRODUCTION AND SUMMARY

Solar energy has been promoted for a number of reasons ranging from its quality as a nearly ubiquitous renewable energy source to its potential for reducing international political instabilities resulting from the competition for localized non-renewable energy sources. Solar energy technologies seem particularly appropriate for developing countries: they do not require large capital investment per project and do not commit to large operating expenses; they involve small construction times and thus less uncertainty; they offer flexibility with respect to scale and kind of end use and can be deployed in small units for decentralized applications such as exist in small villages; they rely on the sun which in general shines lavishly in developing countries; they tend to be technically less sophisticated and more labor-intensive than conventional centralized energy technologies and as such lend themselves to domestic manufacture.

In developed as well as developing countries, however, the prospects for solar energy systems crucially depend on whether they are economical and whether they are net producers of energy, two aspects about which there is a lot of controversy. Opinions differ as to whether or how much fossil fuel prices would have to rise from what they are today in order for solar energy systems to achieve significant energy market penetration. As for the net energy issue, widely diverging results have been published, for example, for solar electric systems[41], with bad news coming from nuclear energy promoters[1,2] and good news from solar energy enthusiasts[3,4].

Solar water heating is generally viewed as one of the most promising solar applications[4,5]. In this article, I examine the economics and energy input-output balance for a flat-plate collector solar water preheating system currently being installed as part of the thermal energy supply system of a hospital of the University of São Paulo which is to commence operation in late 1979. I compare the money and energy capital investment in the solar collectors with the later savings in money and energy, respectively, made possible by the substitution of solar energy for fuel oil. The periods required for money and energy payback serve as measures for economic and "energetic" performance of the solar system, respectively.

I find that the energy payback period is less than 2 years while on the basis of the current very low fuel oil price the money payback period is likely to be longer than 20 years. The latter could be brought below 10 years, however, by quickly raising the fuel oil price to international levels.

Besides the very low fuel oil price, factors responsible for the pronounced difference in energy and money payback period are the fact that only a minor fraction of the money costs of the materials going into the solar collectors are due to energy purchases, and that money is discounted in time while energy is not. Consequently, greater shares of material costs due to fuel purchases as a result of energy price increases and reduced effective discount rates such as in case of availability of low interest loans for solar equipment would lead to reduced money payback periods, approaching the energy payback period.

Description of Solar Collector Hot Water System(6)

The flat-plate solar collectors are arranged on the roof of the hospital (capacity 400 beds) in 6 separate rows, each 60m long and 2m wide, for a total effective collecting area of $720m^2$. The absorber, of aluminum, is blackened on the front side and thermally insulated on the back side. Copper tubes in good thermal contact with the aluminum carry the water, and glass covers reduce convective and radiative heat losses and protect the absorber against external impact. Walls made of concrete serve as support for the collectors which are tilted at an angle of 23^{o} to maximize the thermal energy captured during the course of a year.

The collectors are to be used to preheat water which is to be consumed at a temperature of $40^{o}C$. An average of 50,000 liters of water per hour will be heated by a few degree centigrade (less than $10^{o}C$) while passing the collectors, subsequently flow to heat exchangers where its temperature is brought up to the final $40^{o}C$ through thermal contact with water heated in a separate loop by burning oil, and then go to the consumer. Because of the low operating temperatures of the solar absorbers, their efficiency is high (an estimated 75%). No thermal storage is required, since the thermal energy supplied by the solar collectors is always smaller than thermal energy demand. At an average incident solar flux of 10^6 kcal/m^2 year (130 watt/m^2) in São Paulo, the solar collectors will furnish 5.4×10^8 kcal of thermal energy annually which is about 10% of the heat required at $40^{o}C$ and 4% of the total heat requirement of the hospital.

Several cost reducing features of the solar hot water system are noteworthy:

- the roof of the hospital serves as natural support for the collectors (by using the collectors themselves as the roof it would be possible to further reduce their cost);

- the low collector temperatures allow application of simple technologies, e.g. the use of conventional paint instead of costly electrolytic methods to blacken the surface of the Al absorber, without appreciable loss in collector efficiency;

- the solar absorbers are constructed by inserting thin copper tubes under pressure into aluminum tubes which have two fins attached to them in one plane (Al tube and fins are fabricated in one piece) and by placing the latter side by side; this technique is less costly and provides better thermal contact than welding tubes onto plates;

- no thermal storage is required.

Economics

A simple model, already proposed elsewhere[7], is adopted here for an economic analysis of the performance of the solar system under consideration. This model provides a mathematical relationship between the payback period for the initial investment in the solar equipment (the measure for economic performance adopted in this paper) as a function of the magnitude of the initial investment, the annual savings in fuel oil, the fuel oil price escalation rate, and the money discount rate.

It is assumed that the investment I in the solar system is made in some base year ("year 0") and that the system commences operation in the following year ("year 1"). If p is the price per unit amount of fuel oil in the base year and q the amount of fuel oil saved annually, then the product pq stands for the annual money savings in fuel oil, in an economy without interest payments on money savings and in the absence of fuel oil price escalation. In reality, money earns interest and, therefore, has to be discounted in time. If r is the prevailing interest rate, then the year 0 value of the fuel oil savings in the year i is $pq/(1+r)^i$. Thus the fuel oil savings have to be discounted in time using r as the discount rate. If, in additon, fuel oil prices escalate in time at an annual rate s, then the year 0 value of the fuel oil money savings in the year i is $pq(\frac{1+s}{1+r})^i$. The money payback period T is given as the number of years it takes for the year 0 value of the cumulative fuel oil savings to break even with the initial investment:

$$I = pq \sum_{i=1}^{T} (\frac{1+s}{1+r})^i = pqu \frac{1-u^T}{1-u} , \qquad (1)$$

with

$$u \equiv \frac{1+s}{1+r} . \qquad (2)$$

Solving for T yields

$$T = \begin{cases} \log \left[1 - \frac{I(1-u)}{pqu}\right] (\log u)^{-1} , & r \neq s \qquad (3a) \\ \frac{I}{pq} , & r = s \qquad (3b) \end{cases}$$

In recent years, Brazil has been plagued by high and increasing monetary inflation. Overall inflation is now around 50 percent annually, with different economic sectors inflating at different rates. To simplify the following discussion, the fuel oil price escalation and discount rates will be counted in real terms, i.e. after inflation. The year 1978 will be referred to as the base year ("year 0") for monetary costs and prices.

There is an old law in Brazil, the so-called "lei da usura", prohibiting interest charges higher than 12 percent. However, to correct for inflation charges in addition to basic interest are levied by loan institutions[42]. Viewing high interest rates as one of the prime reasons for galloping inflation, the government moved recently to control and lower them. Commercial and investment banks are now required to tabulate their interest charges and, from September 1979 on, to adjust them in such a way that their mean be only 90 percent of that in August 1979[8]. However, the government move to reduce interest rates will affect only small- and medium-term loans. It will not appreciably change long-term interest charges (on loans having payment terms longer than one year), which should be used to discount savings of solar energy systems having lifetimes of many years. Long-term interest rates net of inflation will continue to be in the range of 3 to 10 percent, typically 6 percent, depending on the extent to which projects to be financed are perceived to meet development needs[43]. The 3-10 percent range will be assumed to apply as range of possible discount rates in the following analysis.

It is hard to predict the future rate of fuel oil price escalation in Brazil. Currently, 80 percent of petroleum consumption is met by imports and Brazil will continue to be dependent on OPEC for most of its supply with crude oil and thus will have to live with uncertain OPEC oil pricing policies. A further element of uncertainty is introduced by the fact that the prices of petroleum derivatives in Brazil, including fuel oil, are subject to changing regulatory rules dictated by the federal government. There is good reason to believe, however, that the price of fuel oil will rise somewhat faster than that of the mostly imported crude oil. The government has shifted from a policy of hefty fuel oil subsidization, which protected domestic industry from "world reality" with the result of ever more increasing fuel oil consumption, to one of fuel oil conservation (along with conservation of other petroleum derivatives) through stimulation of the use of substitute fuels such as domestic coal, imposition of industry-specific fuel oil consumption ceilings, and drastic fuel oil price increases. In just a few months fuel oil prices have risen by more than 50 percent in real terms, outpacing even soaring petroleum prices. It looks as though the current trend of disproportionately rapidly rising fuel oil prices, still below the cost of fuel oil production though, will continue at least until fuel oil ceases to be subsidized.

One way of estimating the future rate of OPEC petroleum price hikes is by extrapolation from the past. Since 1973 the OPEC petroleum price has risen from 12 to an effective average of some 22 US$, a price increase of 80 percent in 6 years corresponding to an annual escalation of 10 percent or about 2 percent in real terms (after U.S. inflation)[9]. That essentialy all of this price increase occurred in 1979 suggests that real petroleum price escalation could be higher than 2 percent annually. However, a good fraction of the recent petroleum price increases in effect only compensated for the drop in purchasing power of the U.S. dollar, the currency in which OPEC oil prices are denominated, between 1974 and 1979. In addition, excessive future petroleum price inflation causes progressive general inflation, as long as the world economy relies on oil as its chief fuel. Therefore, any assumption of future real petroleum price escalation higher than a few percent annually would appear unrealistic. Consequently, the fuel oil price in Brazil is unlikely to escalate in real terms by more than an annual 5 percent between now and the turn of this century.

The cost per m^2 of installed collector area of the solar water heating system under consideration was 2,500 Cr$ in early 1978, two thirds of which due to materials, or about 150 US early 1978 $ per m^2[10]. For a 75 percent efficiency of heating water by burning fuel oil and a heat content of 9,800 kcal/liter for fuel oil[45], the solar system allows annual savings of approximately 100 liters of fuel oil per m^2 of collector area.

The current price of fuel oil is 2.40 Cr$/kg[46] or about 2.20 Cr$/liter[47]. This price corresponds to approximately 0.08 US mid 1979 $ per liter, or about 0.075 US early 1979 $ per liter. Thus, the fuel oil savings of 100 liter per m^2 and year translate into monetary savings of 7.5 US$ for early 1979. In the special case of the fuel oil escalation rate being equal to the discount rate (s=r), the solar system would pay back its investment in 20 years, according to equation (3b). This case corresponds to conditions for the economics of the solar system which are close to the optimum, since the likely upper bound for fuel oil price escalation (5 percent per year) is only little above the likely lower bound for the discount rate (3 percent per year).

For $r \neq s$ the money payback period T depends on the specific values of r and s. For any given $T \neq I/pq$, the value of the parameter u can be calculated on the basis of equation (3a) and s can be written as a linear function of r alone according to equation (2). Figure 1 shows the r-s lines corresponding to various values of T, as well as a square indicating the domain of likely values of s and r. It appears that the money payback period may be anywhere above 17 years. It is likely to be longer than 20 years and may thus be longer than the lifetime of the solar system.

Inclusion of maintenance costs would lead to still longer payback periods for the solar system[11]. On the other hand, the cost of the solar collectors is not representative of systems to come. Economies of mass production and new technological developments will result in lower collector prices. Furthermore, it is noteworthy that by Brazilian standards São Paulo City does not offer optimal conditions in terms of insolation.

The Northeast shows better features in this respect, with up to 30 percent more annual hours of sunshine[12]. More sunshine, of course, would lead to larger fuel oil savings and thus smaller payback periods[13].

I should finally be pointed out that economic feasibility is dependent not only on quantitative economic perfomance data provided by models such as the one used here, but also on decision criteria utilized by the consumer. There is evidence that in general consumers expect payback times for solar equipment considerably shorter than its probable lifetime[5].

Energy Input-Output

The energy input-output of energy production or conservation systems is commonly discussed in the framework of net energy analysis, whose methods and conventions[14,15], merits[16,17], and shortcomings[18-20] have been pointed out.

Two principal parameters have been used to portray the net energy balance of energy production or conservation systems: the net energy ratio and the energy payback period. The net energy ratio indicates the amount of energy produced or saved by the system during its lifetime per unit lifetime total direct and indirect energy requirements for construction and operation. By contrast, the energy payback period, focusing on energy inputs and outputs in time, tells the period required for the cumulative energy produced or saved by the system (net of energy inputs during operation) to break even with the total direct and indirect energy inputs in its construction. The two net energy measures are not uniquely related[21].

The energy payback period is chosen below as measure for the "energetic" perfomance of the solar system under consideration, for three reasons. First, the solar system has the feature of having energy inputs and outputs nearly strictly separated in time; there are no appreciable energy requirements during operation, aside from the solar input which is considered free[22]. This special time sequence of energy inputs and outputs suggests using an energy perfomance index that is sensitive to time variations in energy input-output. Second, any necessarily uncertain assumption about the lifetime of the system is avoided. Third, direct comparison of economic and energetic perfomance of the solar system becomes possible because of the similarity of the two perfomance indices.

It should be pointed out that it is conceptually important to regard the solar system as an energy (fossil fuel) saving device, not as an energy (heat) producing device. True, the amount of energy the system produces by capturing sunlight is the same as the energy that would be made available from additional oil in its absence (for the assumed equal efficiencies of converting solar energy and oil into heat). Yet low temperature heat is low quality energy, whereas oil is a high quality fuel. It would be questionable to compare low quality heat output with the mostly high quality energy required to make the collector materials. In the fuel saver mode, however, both energy input and output are from high quality fuel.

To assess the energy cost of the solar system a shortcut approach will be taken here. Solar collectors are known to be material intensive products[23] and material industries are energy intensive industries[24]. There is good evidence that for material intensive products, the total energy investiment, i.e. all direct and indirect energy consumed in manufacture, installation, and transportation, is less than twice the energy going into materials[25]. Following this rule, the energy cost of the solar system will be estimated from the materials energy costs.

Table 1 lists the quantities and energy costs of the major basic materials that go into the flat plate solar collector system. A total of 700 Kwh_{th} is required, directly and indirectly, to make the materials.

By far the most important contributor to the total materials energy cost is aluminum. An attempt was made, therefore, to determine the average specific energy cost of aluminum consumed in Brazil most of which is from domestic production. Table 2 presents the details. The 60 Kwh_{th}/kg figure is considerably below figures typically found in the literature for aluminum from primary ore, for two reasons. First, Brazil imports sizable quantities of Al scrap from which to extract aluminum is an order of magnitude less energy costly than from primary ore. Second, the smelting of aluminum, which is extracted from primary ore as bauxite, consumes large amounts of electricity 90 percent of which in Brazil come from hydro installations. While the efficienty of producing electricity from fossil or nuclear fuel is around 30 percent (taking into account also indirect energy costs), that of making electricity from hydro is close to one[32].

The solar system delivers 7.5×10^6 kcal or 870 Kwh_{th} annually per m^2 of collector area, for a materials energy payback period of 10 months which is in basic agreement with the literature[4]. It is concluded that the solar system pays its energy investment back in less than 2 years.

It is interesting to note that in general solar heating systems appear to have energy payback periods anywhere between a few months and 3 years, depending on whether hot water and/or space heat is provided, on the type of active or passive solar system, on whether or to what extent storage is needed, and on the type of conventional backup, if any[33,34].

Economic versus Energetic Perfomance

The solar collector water preheating system will be a clear net energy saver, since its lifetime will be much longer than the energy payback period which is less than 2 years. By constrast, the economics of the system looks much less favorable. The money payback period, which is likely to be longer than 20 years, may well be longer than the system lifetime. Three reasons appear to be responsible for the pronounced difference in economic and energetic perfomance.

First, despite drastic increases in recent months Brazil's fuel oil price, 0.08 $ per liter, is still subsidized and very low by international standards. Indeed, it is approximately one half and one quarter of the home heating oil prices in the U.S.[35] and West Germany[36], respectively. And it is low even among those in developing countries[37]. Figure 2 shows that at a four-fold increased fuel oil price the money payback period of the solar system would be reduced to only approximately 5 to 7 years, while, of course, the energy payback period would remain unchanged[48,49]. Thus, clearly, the fact that cheap fuel oil is saved primarily causes the solar system to be economically not very attractive. If the solar system were used to save electricity instead of fuel oil, its money payback period would be just a few years, since in Brazil a calorie of electricity costs an order of magnitude more than a calorie of fuel oil[38].

Second, while the money savings of the solar system are entirely due to energy (fuel oil) savings, energy purchases account for only a minor fraction of the total capital investment (basically materials)[39]. The difference in length of money and energy payback period would be smaller at an increased fuel cost share of the total solar collector cost, as a result of increased fuel prices relative to prices of other factors of production. The energy payback period may be thought of as a time span that the money period would approach in the limit of fuel prices being very high relative to other factor prices.

However, there is the third reason for the difference in economic and energetic perfomance - the fact that money is discounted in time while energy is not (at least, there seems to be no energy discount rate that makes sense). Because of this difference the energy payback period can never be reached by its money counterpart, as long as the discount rate is greater than the fuel escalation rate. This is likely to be the case in Brazil, unless incentives such as low interest loans for solar equipment are provided, resulting in low effective discount rates.

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6. Based on J.M.V. Martins, O Projeto do Sistema de Aquecimento do Hospital Universitário da USP por Energia Solar, Institute of Physics, University of São Paulo, 1978.

7. P.J. Landsberg, A Simple Model for Solar Energy Economics in the U.K., Energy, Vol. 2, 1977, pp. 149-159.

8. The mean interest rate i_m is to be calculated according to $i_m = \Sigma i_n K_n / \Sigma K_n$ where K_n and i_n are the principal and the interest rate, respectively, associated with the nth of those financial operations either effected in August 1979 or without specific maturity.

9. From the beginning of 1974 to mid 1979 (in 5.5 years) U.S. consumer prices rose by 55 percent. (Conjuntura Econômica: Vol. 29, Nº 8, pp. 144-147, 1975; Vol. 30, Nº 3, pp. 60-64, 1976; Vol. 31, Nº 3, p. 74, 1977; Vol. 32, Nº 7, pp. 79-81, 1978; Vol. 33, Nº 3, pp. 84-85, 1979; and Newsweek (South American Edition), August 6, p. 34, 1979) This corresponds to mean annual inflation of consumer prices during this period of 8 percent.

10. Dr. J.M.V. Martins (Instituto de Física, Universidade de São Paulo), private communication, March 1979.

11. Reference 5 assumes a fraction of 1.5 percent of the installed cost for maintenance costs. For the solar system under study, this would correspond to 2.25 $ per year, leading to net annual fuel oil savings of only 5.25 $ and increasing the money payback period from 20 to 28.5 years, under the assumption of s=r.

12. A.V. de Carvalho Jr., A. de F. Orlando and D. Magnoli, Solar Energy for Steam Generation in Brazil, Interciência, Vol. 4, Nº 3, 1979, pp. 140-147, Figure 1.

13. 30 percent larger annual fuel oil savings, 10 $ instead of 7.5 $, associated with an increase in the average incident solar flux of 30 percent, would result in a decrease in the money payback period from 20 to 15 years, assuming s=r.

14. C.W. Bullard, P.S. Penner and D.A. Pilati, Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis, Center for Advanced Computation, CAC Document Nº 214, University of Illinois, Urbana - Champaign, 1976.

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18. M. Webb and D. Pearce, The Economics of Energy Analysis, Energy Policy, December 1975, pp. 318-331.

19. G. Leach, Net Energy Analysis - Is it any Use, Energy Policy, December 1975, pp. 332-344.

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21. Consider the following two energy supply systems: System A with energy requirements for construction and operation of 10 and 0.5 units, respectively, an annual energy output of

2.5 units and a lifetime of 20 years; System B with the same energy requirement for construction and the same lifetime, but no energy requirement for operation and an annual energy output of 2 units. While the two systems have equal payback periods (2.5 years), they differ markedly in their energy ratios (System A: 3.3; System B: 8).

22. Energy analysts usually count only fossil fuel energy as energy requirement.

23. A high material intensity is characteristic for "soft" solar technologies (see H. Inhaber, Risk with Energy from Conventional and Non-Conventional Sources, Science, Vol. 203, 23 February 1979, pp. 718-723).

24. For example, in the U.K. in 1968 the materials industries contributed 7% to the GNP but consumed 30% of all fuels indicating that they were 4 times more energy intensive than the U.K. average (see P.F. Chapman, The Energy Costs of Materials, Energy Policy, March 1975, pp. 47-57).

25. For the manufacture of automobiles which are material intensive, a U.S. ratio of 1.36 for the total energy cost to the energy expended in making the materials has been calculated (M.F. Fels, Comparative Energy Costs of Urban Transportation Systems, Transportation Research, Vol. 9, pp. 297-308, 1975). Corresponding U.S. ratios for highway construction and airplane manufacture of 1.6 and 1.7 have been determined (see above reference for highway construction and see M.F. Fels, Appendix to Suburb to Suburb Travel: Energy, Time and Dollar Expenditures, report to NASA Ames Research Center, August 1975, for airplane manufacture).

26. P.F. Chapman, The Energy Costs of Producing Copper and Aluminium from Primary Sources, Metals and Materials, Vol. 8, Nº 2, February 1974, pp. 107-111.

27. P.F. Chapman, Energy Conservation and Recycling of Copper and Aluminium, Metals and Materials, Vol. 8, Nº 6, June 1974, pp. 311-319.

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29. B. Hannon, R.G. Stein, B.Z. Segal and D. Serber, Energy and Labor in the Construction Sector, Science, Vol. 202, 24 November 1978, pp. 837-847.

30. Alumínio: Queixas das Indústrias Contra Produtores, O Estado de São Paulo, September 11, 1979, p. 34.

31. F.M. de Vasconcellos, A Energia Elétrica e os Recursos Minerais do Brasil, Revista Brasileira de Energia Elétrica, Nº 14, September-December 1970, pp. 44-49.

32. Some energy analysts do not consider hydraulic energy utilized in hydropower plants to be equivalent to the heat produced in fossil fuel and nuclear power plants, but prefer to count the primary energy requirements of hydro electricity as if it came from thermal power stations. In this case, the average specific energy costs of aluminum consumed in Brazil would be more like 80 Kwh_{th}/Kg and the total material energy cost per m^2 of collector area 860 instead of 700 Kwh_{th}, with no effect on overall conclusions however.

33. L. Sherwood, Total Energy Use of Home Heating Systems, ASHRAE Transactions, Vol. 85, Part I, 1979.

34. H.J. Wagner, Der Energieaufwand zum Bau and Betrieb Ausgewählter Energie-versorgungstechnologien, Jül - 1561, Kernforschungsanlage Jülich, West Germany, December 1978, and Energieökonomie Gewährleistet, Heizung und Klima, October 1978.

35. Inside the Big Oil Game, Time (South American Edition), May 7, 1979, p. 43.

36. Europe's Prices go up and up, Newsweek (South American Edition), August 27, 1979, p. 24.

37. In May 1979 (i.e. before the OPEC oil price hike at the end of June 1979), the fuel oil prices in Turkey and Chile, for example, were 4.6 and 2.4 times higher, respectively, than that in Brazil. (M.F. Thompson Motta, Intervenção Estatal nas Atividades Econômicas, O Estado de São Paulo, June 17, 1979, p. 57) Meanwhile Brazil's price has risen by more than 50 percent (in real terms) but Turkey's and Chile's prices presumably have gone up too.

38. See reference in note 37.

39. Direct and indirect energy purchases of the basic materials sectors of the Brazilian economy accounted for 17 percent of the total output of these sectors in the year 1970. (Matriz de Relações Inter-industriais Brasil 1970, Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, 1979).

40. F.R.A. Smith, Aluminum Reduction and Refining, Metals and Materials, Vol. 8, Nº 3, March 1974, pp. 182-186.

41. "Conventional" solar electric systems such as the solar tower concept or photovoltaic cells are referred to in this connection. A net energy analysis of the solar power satellite, an "unconventional" solar electric system, has recently been done, reporting a rather poor energy input-output balance for this system. (R.A. Herendeen, T. Kary and J. Rebitzer, Energy Analysis of the Solar Power Satellite, Science, Vol. 205, 3 August, 1979, pp. 451-454).

42. For small- and medium-term loans (payment terms up to one year) a so called prefixed monetary correction is added to the interest charge, based on expected inflation. Interest charges on long-term loans (payment terms longer than one year) include a correction for changes in exchange rates (in the case of foreign loans) or a monetary correction (for domestic loans by the National Economic Development Bank (BNDE) or by the National Housing Bank (BNH)), typically calculated on a quaterly basis.

43. Dr. Ruy Leme (Faculdade de Economia e Administração, Universidade de São Paulo), private communication, September 24, 1979.

44. BNDE Pode Controlar o Cobre, O Estado de São Paulo, September 29, 1979, p. 26.

45. This is the heat content of light fuel oil (see Balanço Energético Nacional, 1978, Ministério das Minas e Energia, Brasília, Brazil, p. 100).

46. Portaria (federal regulation) Nº 06/79, September 3, 1979. The 2.40 Cr$/Kg price is valid for heavy and light fuel oil (types BPF and APF). Fuel oil having a low content of sulphur

(type BTE) costs 3.00 Cr$/Kg but is used only for special applications. The above fuel oil prices are those to final consumers.

47. Based on density for light fuel oil of 0.903 Kg/liter (see reference in note 45).

48. In the case of the fuel oil price escalation rate being equal to the discount rate, doubling and quadrupling the actual fuel oil price would mean halving and quartering the money payback period from 20 to 10 and 5 years, respectively, according to equation (3b).

49. Actually, reductions in the money payback period as a result of fuel oil price increases would be less than indicated because fuel oil is used in making collector materials and, therefore, the solar collectors would become more expensive (assuming technology does not change). However, their cost would increase only by a small fraction relative to the increase in money savings, due to the second reason responsible for the difference in length of money and energy payback period outlined in the following paragraph.

TABLE 1 - Quantities and Energy Costs of Major Materials in Flat Plate Collectors

Material	Quantity[(a)] (Kg/m^2 of collector)	Specific Energy Cost (Kwh_{th}/Kg)	Energy Cost (Kwh_{th})
Aluminum	7.0[(b)]	60[(d)]	420
Copper	3.2	25[(e)]	80
Glass	15.0	8[(f)]	120
Concrete	82.5dm^3/m^2[(c)]	1 Kwh_{th}/dm^3[(g)]	83
TOTAL (rounded)			700

(a) José M.V. Martins, private communication.

(b) Thereof 5 Kg for absorber and 2 Kg for glass support.

(c) For walls that support the collectors on the roof on the hospital.

(d) Most of the aluminum in Brazil is from domestic production. For details of how the energy cost figure listed is arrived at see Table 2.

(e) Most of the copper in Brazil is imported, some is from scrap (see reference 44). The energy cost of primary Cu is very sensitive to ore grade. In 1973 the world average grade of Cu ore mined was about 1.5%, giving an average energy cost of 19 Kwh_{th}/Kg. By constrast, the U.S. average grade of copper ore mined was 0.6%,giving an energy cost of 35 Kwh_{th}/Kg (see reference 26). Recycle of Cu from scrap reduces energy costs by an order of magnitude to approximately 3 Kwh_{th}/Kg (see reference 27).

(f) Values of 7.9 Kwh_{th}/Kg and 6.9 Kwh_{th}/Kg are given for plate glass for the U.S. in reference 28 and for the U.K. in the reference in note 24, respectively.

(g) Reference 29 gives a value of 0.85 Kwh_{th}/dm^3 for ready-mix concrete in the U.S.

TABLE 2 - Energy Cost of Aluminum Consumed in Brazil[a]

Source	Fraction of Al Consumption[b] (percent)	Energy Cost (Kwh_{th}/Kg)
Domestic Al from Ore	60	53[c,d]
Imports of Al from Ore	30	88.5[c,e]
Imports of Al scrap	10	3.5[f]
TOTAL (rounded)	100	60

(a) Does not include the energy required to fabricate Al into special forms which in general is relatively small.

(b) Source: Reference 30. There is a trend toward an increasing fraction of domestic Al production from ore. The figures listed are approximately valid for 1978/79.

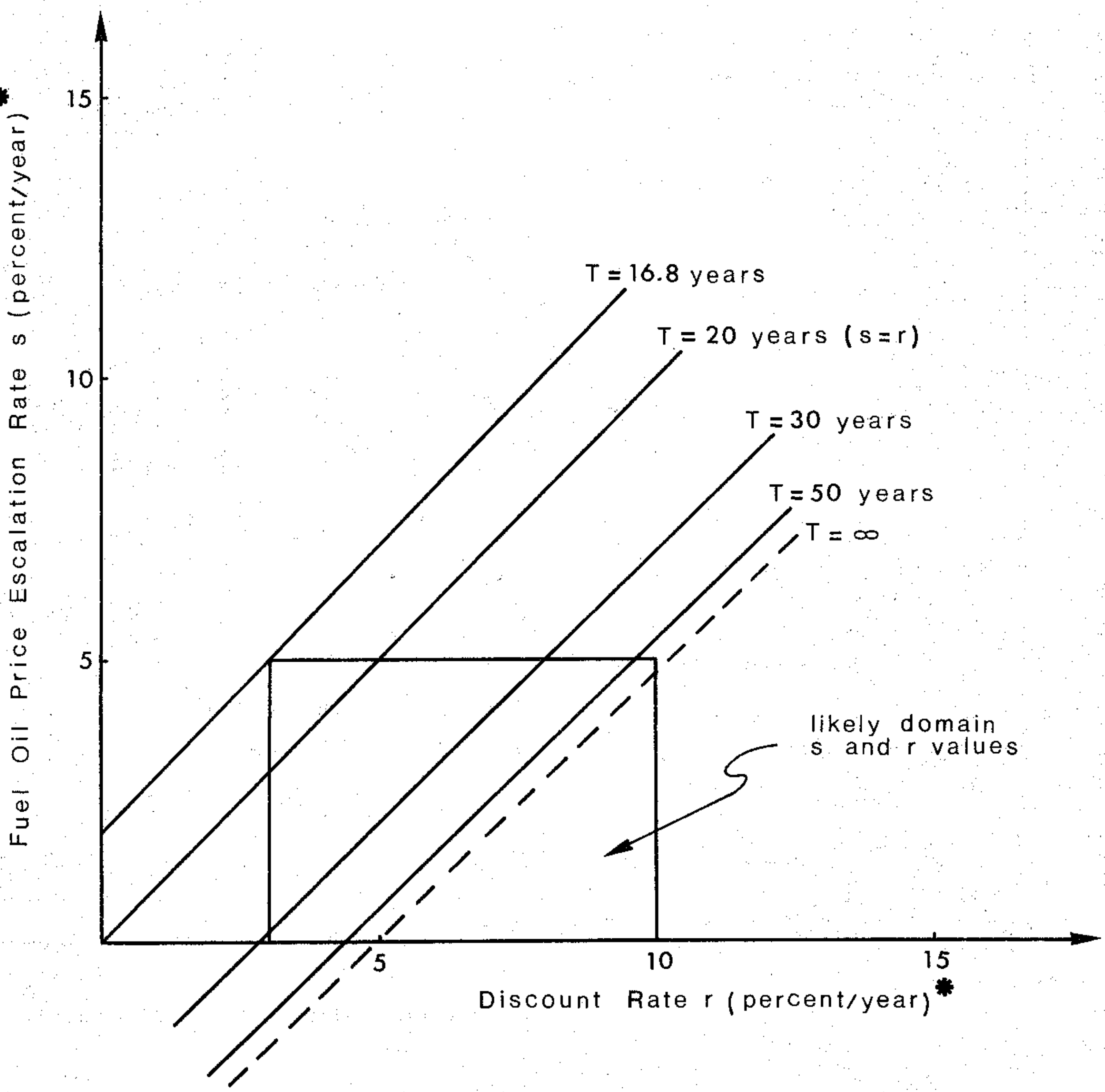
(c) Assuming an energy cost per Kg of Al of 17 Kwh_e plus 29 Kwh_{th} (see references 26, 31 and 40). For the thermal energy requirement, the largest number (ref. 26) is adopted. The electrical energy requirements in the three references are comparable.

(d) Based on a requirement of 1.4 Kwh_{th} per Kwh_e. 90 percent of domestic electricity is from hydro installations. For this fraction, hydraulic energy is considered to be the heat equivalent and a conversion efficiency of 90 percent is assumed; for the other 10 percent of electricity which is from fossil fuels, a conversion efficiency of 28.6 percent is assumed, corresponding to a requirement of 3.5 Kwh_{th} per Kwh_e.

(e) Assuming a requirement of 3.5 Kwh_{th} per Kwh_e , since most of electricity is from fossil fuels.

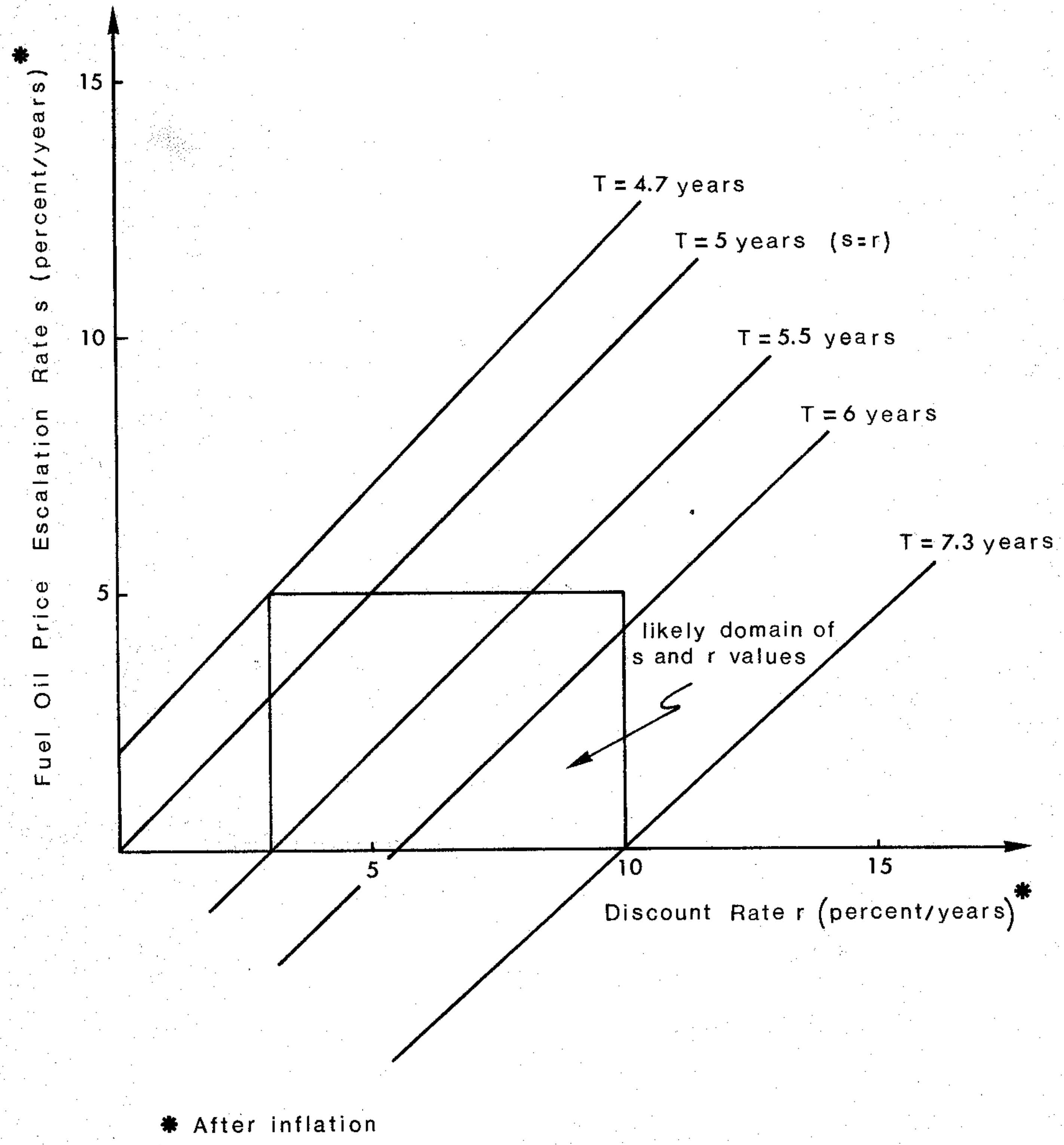
(f) Source: Reference 27.

Figure 1 Relationship between Money Payback Time T, Fuel Oil Price Escalation Rate s and Discount Rate r on the Basis of Current Price of Fuel Oil



* After inflation

Figure 2 Relationship between Money Payback Time T, Fuel Oil Price Escalation Rate s and Discount Rate r on the Basis of Four-fold Increased Price of Fuel Oil



* After inflation