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ALTERNATIVE SOURCES OF POWER

FOR

SMALL-SCALE WATER SUPPLIES - A CASE STUDY

Acknowledgements

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Introduction

The difficulty of choosing appropriate technologies for developing countries is a problem which is becoming increasingly obvious. The difference in factor availabilities between developed and less developed countries is growing and the failure of the technologies of one culture to take root in other cultures is apparent in almost any developing country.

The following is an attempt to analyze the technological solutions to one particular problem in one area of one developing country. The most formal expression of what characteristics might be found in an appropriate technology has been made by Schumacher, who has proposed the introduction of Intermediate Technologies and his ideas have been used here as a framework for trying to identify the choices which are available.

To quantify the comparison, the Little and Mirrlees' method has been applied to the alternative solutions as far as possible, while incorporating some modifications which either seem justified in relation to the Intermediate Technology philosophy, or are necessary to allow completion of the analysis.

Summary and Conclusions

Several feasible methods of supplying water to small farms in southern Zambia have been examined. The methods were chosen to encompass a wide range of labor/capital intensity, and were compared using the Little and Mirrlees' method. Each method of supplying water was analyzed for several farm sizes. The methods considered were:

(a) man powered pumps;
(b) animal powered pumps;
(c) methane powered pumps;
(d) wind driven pumps;
(e) diesel powered pumps.

The very location-specific nature of the wind powered solution meant that local wind data had to be collected. Furthermore, the lack of a general method for determining equipment size made it necessary to develop a method of calculating the necessary equipment specifications. This method is rather extraneous to the main analysis, though essential to the process of comparison. It is, therefore, presented in detail in an annex.

The results of the comparison showed that different technologies were appropriate to different farm sizes. For the smallest demand analyzed (a small farm with ten cattle), man power was the most economical solution. For intermediate demand levels, man, animal and wind power are all competitive, the "best" solution varying with assumptions made about the discount rate, the growth of the productivity of labor in agriculture and the inflation rate.

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At higher demand levels (up to 200 cattle), animal power is clearly the best solution, but it is obvious that diesel power rapidly becomes competitive at higher demands and thus for irrigation systems would clearly be the best alternative of those considered.

The results support the Intermediate Technology philosophy, in that for typical needs the best solution is very much an Intermediate Technology--it is more capital intensive than the basic local method, but less so than a "Western" solution would be; it is based on existing local inputs (animal power) and it is <u>not</u> available at the moment to the potential user.

Chapter I

The Area, Its People and the Problem To Be Analyzed

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The Area and Its People

This research was based on two field trips to Zambia in 1973 and 1974. The location visited is on the Tonga plateau in southwest Zambia near Monze. In this area, previously expatriate-owned farms are being resettled by Zambians. The operation is being run by Family Farms Ltd., a largely volunteer organization funded by various aid agencies in Canada and England. Following successful initial work the organization is now receiving Government help, mainly in the form of land for settlement.

Settlement is planned as follows: the availability of land for settlement is advertised, and applications received from interested individuals based on questionnaires. Promising candidates are then visited at their farms and their farming methods, including the implements they own, their storage facilities, etc. are appraised. Those who seem to be good and dedicated farmers are offered holdings, dependent in size upon the number of their cattle herd and assessed farm management ability.

Those offered farms face a demanding few years. Although they gain a secure leasehold farm, they leave their villages and must often live some miles from the nearest village and construct a home, find water and clear land for farming as required. Basic fencing is supplied, but all internal fences and roadways must be built.

The farmer gets access to credit and extension services from the settlement advisor (now mostly expatriates with trainee Zambian assistants).

Farm sizes vary from about 100 to 400 acres, depending on herd size. Seven acres per animal is allowed, and rules to prevent overgrazing are enforced.

Cattle form an intrinsic and problematic part of life in most of Zambia. The Tonga are particularly keen to own cattle, the herd being a symbol of wealth. Ownership is rarely simple--cattle are owned by the family and since they are given and received at weddings, several people can have a claim on any one animal. Thus, although Zambia imports some 50% of its beef, sales of cattle for commercial purposes are limited, and the stock of cattle is very substantial.

The prime agricultural activity is growing maize, the staple diet. Fertilizer and high yielding varieties of seeds are used widely and yields (about 1-1.3 tons/acre) are higher than in most developing countries.

The Problem

Water supplies are needed to open up land for farming, not for irrigation but to provide domestic water and drinking water for the ubiquitous cattle.

The objective of this study is to analyze various technologies for providing the required water supplies.

The technologies have been chosen to provide a wide range of labor intensities, and the method of comparison used is the Little and Mirrlees' approach, which allows explicit assumptions about the cost of labor, including allowance for differing values of incremental income to various target groups.

The combination--a choice between more and less labor-intensive technologies, and incorporation of income effects to allow for objectives other than pure economic optimization--provides the basic ingredients for analyzing the Intermediate Technology philosophy.

Chapter 2

Intermediate Technology

1. Choice of Technology

It is a tautology to suggest that developing countries should choose the technologies most suited to their needs. Whether or not they do so is open to debate, and a considerable body of opinion supports the view that often suitable technologies are not chosen. The reason for this could be any or all of the following:

(1) incorrect or incomplete selection methods which do not show the effect of choice of technology properly are used to choose technologies;

(2) technologies enforced by pre-conditions on the giving of aid; and

(3) the "most suitable" technologies may not be available[1].

It is not intended here to analyze the actions of governments when choosing technologies insofar as they are "good" or "bad" in the judgment of an outside observer. Under this heading might fall the investment of large amounts of capital--not least in the form of scarce, highly trained manpower--in prestige projects such as atomic research, the results of which are unlikely to benefit the country as a whole. The selection of capital intensive projects where more labor intensive methods would seem appropriate can sometimes be ascribed to the problems of management. Capital intensive projects will often be more easy to manage--particularly for overseas investors with both experience in capital intense industries and relatively

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[1] A distinction is made throughout between "feasible" technologies, which have been used, or could be developed, and "available" technologies which can be bought "off-the-shelf".

few managers in the developing country.

A situation which is of interest here and could be listed under the first heading, is when a particular set of objectives, which appears rational, works against the best interests of the country. Two factors which will be considered in detail are the trade-off between consumption now and investment for the future, and the related, also often conflicting, objectives of maximizing output and maximizing employment. These types of conflict are also a major issue in the second category of the reasons for choosing inappropriate technology.

Generally, it will be impossible to ascertain whether an inappropriate technology, chosen by correct application of a selection procedure of the wrong type is really caused by a deliberate choice of selection procedure by a government which favors the type of project which shows up well when analyzed in that way, or whether it is just the result of an unwanted deficiency in the selection methods used.

The final cause of using inappropriate technologies is that the appropriate technologies may not be available, and this argument must be presented in some detail, since this has been a major reason for the suggestion and definition of Intermediate Technology.

2. The Range of Available Choices of Technology

In the many years of rather rapid development which the major industrialized nations have experienced, capital has been accumulated on a very large scale. Capital, in this sense, must be taken to mean a vast range of resources--not only financial--including scientific and technical knowledge and the infrastructure for disseminating that knowledge; a work force having the necessary skills and social attitudes to work in extremely productive organizations; the infrastructure of society--roads, telephones, even trade directories[1]--these and many other apparently insignificant details are integral parts of the capital stock of an industrialized country, and are usually totally or partially lacking in less developed countries. The interdependent, reinforcing effect of these capital items is an excellent example of synergy. It often seems to be the case that an apparently "good fit" of a technology into a country fails because some apparently minor factor is lacking in the local infrastructure. Such capital often cannot be transferred in the complete and self-contained way in which a technology can.

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[1] A group of highly trained Spanish engineers with whom the author worked in the UK found that the availability of specialist trade directories and access by telephone to the companies listed a tremendous advantage in comparing alternatives to their normal (Spanish) working environment.

Clearly, engineers and designers working within a given environment will produce designs which use (often, depend on) a variety of readily available inputs. Inasmuch as certain inputs may be very cheap relative to alternative inputs, the design of processes and machinery will tend to reflect this by favoring usage of the cheap input.

Restricting the inputs to two allows graphical representation of the alternative means of producing a fixed quantity of a certain good.

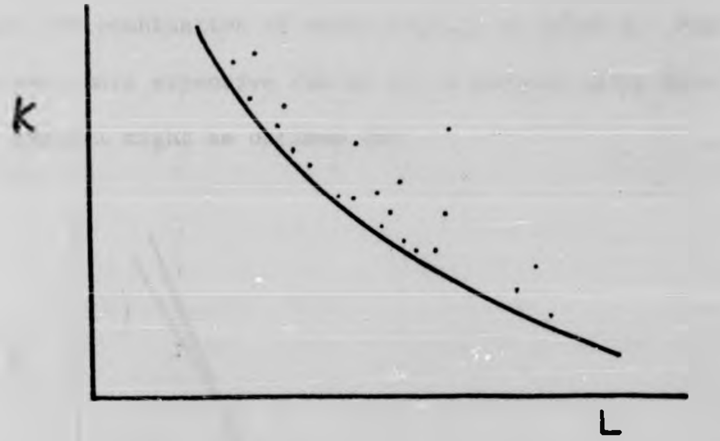

Figure 1: Capital/Labor for Fixed Output

Taking the inputs as capital (K) and labor (L) all the alternative technologies can be represented by points reflecting the inputs of labor and capital required to produce the given output.

Any point which has no other points in the quadrant to the south-west of it will lie on the most efficient technology line--the production function--and this can be drawn in (approximating a continuous curve to what is in fact a series of points joined by straight lines which represent combinations of the technology-points at each end of the line segment).

Now the most appropriate technology for a country, on the basis of minimum cost per unit of output, can be chosen by plotting (Figure 2) the constant cost slope (i.e., the slope of the ratio of the cost of capital to the cost of labor), and noting the point at which this curve is tangential to the production function. For example, a country where the capital:labor cost ratio was low might have a constant cost line such as 1, and would wish to choose a technology (or combination of technologies) at point A. Where capital is relatively more expensive (as in 2), a process using more labor and less capital might be optimum (B).

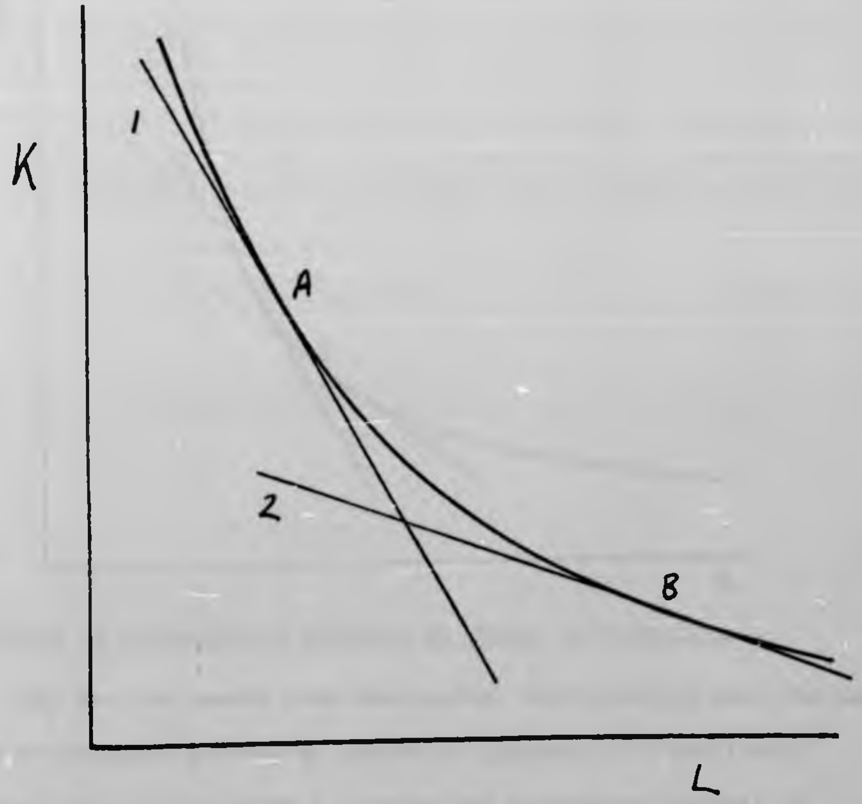

Figure 2: Effect of Relative Capital/Labor Costs on Most Efficient Production Technology

The situation is considerably modified, however, by the fact that designers will produce machines and processes suitable for the environment where they will operate--and since the vast majority of research, development and manufacture is done in and for the industrialized countries, it is to be expected that the technology which is available, as opposed to that which is feasible, will be concentrated (in terms of K:L ratio) around a relatively capital intensive point on the production function, which reflects the availability of production factors in the developed countries. Thus, rather than the gentle curve of figures 1 and 2, a much sharper, shorter curve may be found as in Figure 3.

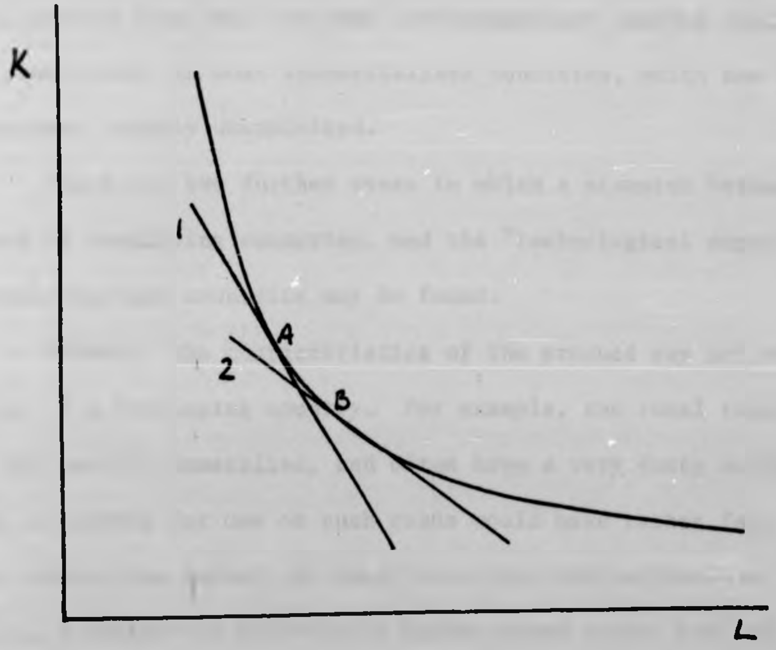

Figure 3: Effect of Concentrated Research on Choice of Technology

This has the result that the capital short country nevertheless is obliged to choose a technology (which is apparently optimal) very close to that chosen by country 1. Given the shortage of capital in country 2, use of capital in capital intensive projects is very likely to result in unemployment or underemployment elsewhere.

This phenomenon is widely recognized in economics, and referred to as the factor proportions problem: i.e., the factor availabilities in many developing countries do not match the requirements of the available technologies, resulting in a labor suprlus even when capital is fully utilized.

In the more general sense of capital, the use of imported technologies may result in under-utilization of various potentially valuable resources, of which labor is only the most obvious. Solar energy, for example, is often abundant in less developed countries, and can provide free fuel for many low-temperature heating requirements--a rare possibility in most industrialized countries, which has therefore remained largely unexploited.

There are two further areas in which a mismatch between the needs of developing countries, and the "technological supply" from industrialized countries may be found.

Firstly, the characteristics of the product may not suit the needs of a developing country. For example, the rural roads in Africa are usually unmetalled, and often have a very dusty surface. Ideally, a bicycle for use on such roads would have rather fat, wide tyres to reduce the amount the wheel cuts into the surface--yet typically, bicycles are fitted with narrow tyres suited for use on metalled roads.

Secondly, the scale of production of a "standard" industrialized country-sized factory may be completely out of line with the demands of markets in developing countries. Marsden (1), amongst other examples, cites the case of a battery plant which satisfied a month's demand every five days when installed in a particular developing country.

3. Towards Appropriate Technologies

Observation of the apparent inappropriateness of technologies imported into less developed countries has resulted in a considerable amount of literature on the subject of choice of technology and the factor proportions problem. Particularly, Eckaus (2) produced an extremely clear analysis of the factor proportions problem, and Kindelberger (3) devotes a chapter to the choice between capital intensive and labor intensive techniques--and raises almost all of the issues still being debated 20 years later.

Although it is agreed that the relatively capital intensive technologies will not utilize all the resources of a developing country--particularly labor--it is not agreed that these technologies are therefore undesirable.

"There is no question from every point of view of the superiority of the latest and more capitalistic technologies" (4).

Discussion of the merits of different types of technology is not the immediate purpose; that will follow in part 6 of this chapter. Here it is proposed first to produce an outline of what sort of technology <u>might</u> be the "most suitable"--an outline firstly in terms of objectives.

It is necessary at this stage to make some assumptions--though these are not of a very controversial nature:

(1) Whatever attitude is taken to the relative importance of either output or investment compared to employment (if these are conflicting objectives), nevertheless employment is a desirable objective.

(2) The "dual" economy, that is, an economy where one part is operating at a high level--typically with employment in imported technologies at high wage rates--while the other part is still at, or close to the subsistence farming level, is undesirable. Particularly undesirable is the destabilizing effect on the rural communities, resulting from a drift of people to the industrial centers with only a small chance of employment, which result in the shanty towns and slums around these centers[1/].

Noting these assumptions, the following outline of desirable attributes of a technology to be used in a developing country can be drawn up--but as will be shown, these are not the only desirable attributes, and conflicts may arise with other worthwhile aims.

[1/] This can have two further reinforcing effects on the destabilizing of the rural areas: firstly, the people most often attracted away are the young, ambitious people--the very people who are of central importance to development of the rural areas--and secondly, it may be that scarce resources are expended on the shanty towns, to improve conditions there, thus reducing the resources available for use in the country areas and making migration more attractive.

(1) Technologies should utilize readily available resources: if labor is in excessive supply, then technologies should tend to be labor intensive; if wood and leather are substitutable for metals and plastics, and are indigenously relatively plentiful, then technologies should utilize these resources in preference to metals and plastics.

(2) Technologies should reflect market size: if the market is small, then it may be better to import on a small scale if the only alternative is importation of a large scale production unit.

(3) The products of a technology should reflect market needs[1/]: there is no point in making bricks strong enough to support multi-storied buildings if land is plentiful, and single-storied buildings are more economical.

(4) Technologies should not cause social disruption[2/]: if the vast majority of a population are rural, subsistence farmers, then technologies imported from industrialized countries, which may employ few people at very high wage rates, will disrupt the social structure by creating an elite minority, and may discourage

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[1/] See especially Muller (8), who advocates "functional specification" of the product, i.e., specification of the task to be performed by the product (e.g., a comfortable, cheap sandal) rather than specifications which pre-determine the solution (e.g., plastic shoes), even though in the developed world the specifications are essentially interchangeable.

[2/] It could be argued that the selection of technologies in China has deliberately been made to help reinforce drastic social change. In this case, this was part of a very comprehensive strategy of change, and the social effects of technology were one tool in this strategy. Often, social impact is unexpected and detrimental to the planned social development.

individual attempts at progress by highlighting the backwardness of rural groups, and emphasizing the disparity between what they can achieve and what others have achieved.

4. Intermediate Technology

The phrase "Intermediate Technology" was first used by E.F. Schumacher, whilst working as a consultant to the Indian Government in 1963.

Whilst other authors, notably Marsden (1,6), Stewart (5,7) and Muller (8) have added substantially to the definition of appropriate technologies, Schumacher's conception is the most thoroughly presented, and has been used in some of the other works as a basis.

The initial framework of Schumacher's argument is similar to that presented above--the factor proportions problem, the potentially bad effects of imported technologies and the apparent unavailability of more appropriate technologies. The focal point, however, is the effect of the movement to the cities of rural people seeking employment:

"The fact remains, however, that great numbers of people in the rural areas do not work, or work only intermittently, and that they are therefore poor and helpless and often desperate enough to leave the village to search for some kind of existence in the big city. Rural unemployment produces mass migration into cities, leading to a rate of urban growth which would tax the resources of even the richest societies. Rural unemployment becomes urban unemployment.

"I shall not attempt to describe the misery and degradation suffered by untold millions of people today in the monster cities of the so-called developing countries. Statistical projections have been made of the growth of cities in S.E. Asia, South America and elsewhere over the next 20 or 30 years which presage the "immiseration" of people on a scale never before known in the history of mankind a sub-human existence without adequate nourishment for body or soul, without roots of any kind, without hope, but with the ever-present propensity to political revolt. These matters may not normally enter the calculations of economists and they certainly do not show up in national income statistics, but a consideration of development policies without reference to them would seem to be utterly pointless" (9).

Thus the main thrust of Schumacher's argument is firstly that the type of development which generates the "dual economy" phenomenon is wrong, and for social and political reasons must be changed. This change will be enabled by the adoption of technologies which can be successfully used in the villages and rural areas, thus generating economic activity on a broad base, and stabilizing the society.

"... the primary need is workplaces, literally millions of workplaces." (ibid)

Schumacher's definition of Intermediate Technology (ibid p.6) is fairly unspecific--the technology must be suited to the financial, educational and organizational characteristics of the district in question--he advocates a symbolic "£100 per work place" technology--far more productive than current subsistence technologies ("£lper work place") and yet cheap enough to be "within reach" of local people, which many technologies from the industrialized countries clearly are not ("£1,000 per work place" technologies).

From the ideas of Schumacher et al, there have been some attempts to define Intermediate Technology (or Appropriate Technology or Progressive Technology) more in terms of its <u>characteristics</u> rather than its objectives.

Thus Stewart (7) summarizes the characteristics of Intermediate Technology, which have been suggested as "essential aspects". These are:

(1) Low capital cost per workplace
(2) Low capital cost per unit of output
(3) Low capital cost per machine
(4) Simplicity of: (a) manufacture
    (b) operation
    (c) maintenance and repair
    (d) organization
(5) non-modern sector
(6) rural sector
(7) small scale
(8) use of local inputs
(9) self-help

Further, she notes the suggestions which have been made for the capital cost per worker of existing and Intermediate Technologies--Schumacher's figure of £1 per head for subsistence technology is criticized as being "absurdly low" (Schumacher in fact describes this figure as "symbolic") and quotes Marsden (1) as defining the capital cost of Intermediate Technologies as $660.

Of course these characteristics are interesting, and to some extent useful but it should be realized that they only represent illumination of the objectives, not guidance as to possible characteristics: what is appropriate may have some or all of the listed characteristics, but possession of some (or all) of those characteristics does not define or ensure an appropriate technology. It would be ridiculous to discard a solution because the capital cost per worker was $700, not $660--Marsden recognizes a role for capital intensive industry:

"Selected judiciously, (modern technologies) have an important contribution to make in certain areas and circumstances" (1.P2).

Schumacher, too, points to the requirement that any choice of technology must be made in context, and not on a predefined set of criteria (which the list of characteristics or estimates of capital cost could too easily become):

"A considerable number of design studies and costings, made for <u>specific products</u> in <u>specific districts</u>, have universally shown that the products of an <u>intelligently chosen intermediate</u>

technology could actually be cheaper than those of modern factories in the nearest big city" (9) (my underlining).

5. Sources of Intermediate Technologies

There are three distinct sources for the type of technology from which Schumacher's "intelligent choice" can be made--apart from current technology in the industrialized countries.

Firstly, the technologies which were used in the now industrialized countries at a time when their capital availability (again emphasizing the wideness of definition of "capital") corresponded more closely to the current situation in developing countries. Thus wind and water mills may be very appropriate sources of power in some developing countries--the early designs for spinning and weaving machines also might be economical.

It may, of course, be possible to improve on out-dated technologies by using new techniques, to make even more suitable, efficient technologies (see Stewart (5) for a thorough analysis of this).

Appropriate technologies for some countries may also be found in current usage in other countries, especially ones at a similar economic level. The Intermediate Technology Development Group claim as one of their major achievements the transmission of knowledge about donkeys as a means of transport over a distance of 100 miles from where they were already used (see (7) p.5 footnote).

Thirdly, Intermediate Technologies can be invented specially for their purpose. An important part of this process--and a freedom less available when the other sources of technologies are used--is the opportunity to define the product so that it is suited to its working environment.

It should be noted that specific research for and development of labor intensive technologies appropriate to the needs of developing countries can make these technologies very capital-intensive when the full costs are included[1], and the skilled manpower used in development is often substantial.

6. Conflicts of Objectives, and some criticisms of the Intermediate Technology approach

Throughout the preceding sections there has been a continuous basic thread to the argument--the misfit of "imported" technology, and the need for technology applicable in the rural areas to stabilize the society, in developing countries.

This is not of course the only reasonable objective for a government to pursue, and some claims have been made that it is not the most important, nor that most likely to maximize the social good--especially when the Intermediate Technology proposal is reduced from objectives to characteristics (e.g., labor intensive, low capital cost/unit of output, etc.).

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[1] For example, crude, labor intensive methods for road building could be very capital intensive when the rate of destruction of vehicles was allowed for!

The two alternative objectives which, it is argued, most conflict with the characteristics of Intermediate Technology are maximizing output and maximizing growth.

The suggestion that maximizing output may not result from an Intermediate Technology approach stems from the belief that a technology which employs all the latest knowhow and methods must necessarily be more productive than a less sophisticated, labor-intensive technique:

"Any society, if it could rid itself of enough technique and capital could keep every one of its ambulatory members fully employed grubbing for roots and berries" (10).

Lewis (ibid) suggests that the objective should be to maximize output per worker, but emphasizes that "per worker" should include all those available to work, not just those actually employed--the objective is thus to maximize total output. He also makes the point that there may be resistance to use of all factors, stemming from fear of redistribution of ownership. Thus Schumacher on the one hand is pointing to disruption as a result of highly capital intensive industries, whilst Lewis foresees disruption caused by attempts to introduce less capital intensive industries. Often it seems that the redistribution of ownership is an explicit objective of many governments, so some risk of disruption foreseen by Lewis is acceptable.

The argument that less sophisticated techniques are necessarily less productive (in capital per unit of output terms) is open to attack on two grounds:

First, as has been noted already, it is important to take care in defining the product: to use the same example, if the product is defined as plastic sandals, it is unlikely that any technique will be superior to the current industrialized country process in K/O terms, L/O terms or any other terms.

Secondly, the amount of research and development which has been devoted to perfecting the capital intensive industrial technologies in a labor-short environment does not really allow a direct comparison between them and Intermediate Technologies[1/]--Schumacher (9, p.8) points out that mechanization is introduced to improve the worker/output ratio and its effect on the capital/output ratio may as well be negative as positive. Very persuasive arguments are put forward by Bell (11) to explain why research and development in the less developed countries is so often misdirected (apart from the choice of "prestige" projects). He suggests that, because "technology user-supplier" relationships bypass indigenous technical establishments--that is any operational problems are referred to the manufacturer of the equipment, who will often be located outside the user country--or at least the technical services branch will be--so that there is no mechanism whereby <u>local</u> expertise is involved (and hence built up) in the solution of <u>local</u> problems. Bell calls this the "marginalization of science".

[1/] Lewis (op cit P. 59) points out that it is not the application of science and technology which produce capital intensive industries, but rather the high capital environment where the application takes place.

The second objective, which may be difficult to pursue by policies involving Intermediate Technologies, is growth of the economy, and here the conflict seems more certain than is the case above.

Capital intensive technologies typically have a high ratio of fixed to variable costs, as compared to labor intensive technologies. Clearly, in both cases, revenue should exceed costs but in the capital intensive industry, a larger part of this revenue will be allocated to:

(1) Amortizing the capital cost, and

(2) Paying interest and dividends to private investors.

In the case of a labor intensive industry, a relatively large part of revenue will be allocated to wage payments to workers. Now it is argued that growth of economic activity depends on investment, and it is reasonable to suggest that revenue accruing to companies as amortization costs, and money paid to investors, is far more likely to be re-invested than are wages paid to (probably poor) workers. That is, the marginal propensity to consume of wage earners will be high, resulting in increases in consumption at the expense of investment.

Galenson and Liebenstein (12) set out this view, and suggest as an investment criterion that the "marginal per capita re-investment quotient, $\frac{MC\ PQR}{K}$" be maximized. They also favor skewed income distribution as an outcome of investment decisions, being concerned about the effect of increasing low incomes on population growth.

Schumacher (9) strongly disagrees with these lines of argument. Firstly, he suggests that it is erroneous to consider capital as a given quantity in an underemployed economy.

"Employment is the very precondition of everything else. The output of an idle man is nil; whereas the output of even a poorly equipped man can be a positive contribution...to 'capital' as well as 'wages'. Although lacking in economic analysis of the marginal type, in terms of his general line of argument this would seem a valid point.

Thus, he suggests that economic growth may be faster if labor intensive methods are introduced since the "dynamic effects" of widespread economic activity will have an effect:

"their first need is to start work of some kind that brings some reward, however small; it is only when they experience that their time and labor is of value that they can become interested in making it more valuable" (9 p.3).

Marsden (6), carries out a case study of a Puerto Rican Project, demonstrating that a higher growth rate and output is obtained by a labor intensive approach. This, however is on the basis of some assumptions which, as Stewart points out (7) have "little empirical backing".

Marsden raises another important issue in this work; that the number of operations which will be set up given an Intermediate Technology approach will be very large, and management correspondingly more diversified. It seems certain that commercial organizations and others raising money on the open market would be very wary of this, since tight economic control of their projects is required. It is certainly the case that the conventional aid agencies find this sector particularly difficult to work in, mainly for these reasons.

7. Summary and Conclusions

It has been suggested that the importation of technologies from industrialized countries into developing countries may often be not only a sub-optimal choice of technology due to the very different factor availabilities, but also a very harmful action when its consequences are fully worked through. Particular emphasis is placed on the sparing use of labor compared to capital in these imported technologies, and the social effects such as rural depopulation, increasing urban population and rocketing urban unemployment.

Against this, it is argued that the productivity of scarce capital should be maximized, so that the consumption benefits to the population and/or the growth of consumption over time are maximized. It is often the case that the technologies from industrialized countries are the most efficient in these terms, so these should be used.

The conflict, however, is far more concerned with means than ends. Both sides no doubt would wish to see today's less developed countries become prosperous, stable communities in the future. The debate is about the best route to that end, and could be summarized in two points:

(1) Does investment in high technology industries produce the fastest progress to the agreed end?

(2) If so, to what extent are penalties in respect of unemployment, rural decay and urban squalor acceptable in exchange for this rapid growth?

At this point, the central issue becomes not the type of technology, but the evaluation method: if a method could be agreed upon such that both the advocates of high technology and the advocates of Intermediate Technology felt that fair values were being placed on the advantages and disadvantages of any investment, the conflict would disappear. Advocates of Intermediate Technology would still wish for a full analysis of alternative feasible techniques (which may not be available "off the shelf"), but this is a less demanding exercise than the fundamental resolution of the conflict between alternative objectives.

In the following section, the Little and Mirlees' method of project selection is described. This methodology, because it is very disaggregated, allows for the introduction of specific assumptions about the key variables in choosing technology. The value of this lies in the "openess" of the assumptions and the ease with which different assumptions can be tested. The most commonly used project appraisal technique--discounted cash flow--inevitably includes assumptions which are not readily obvious, e.g., are the wages of skilled workers correctly valued compared to non-skilled workers? Are machinery costs correctly valued compared to labor, etc? While financial analysis is concerned only with money costs and incomes, economic analysis involves a closer look at the determinants of the money values and other factors may require adjustments to these values.

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Chapter 3

Comparison Methodology

Comparison of Alternatives

The method used for economic comparison of the technical alternatives is that developed by Little and Mirrlees (LM) (1,2). Their method (or close approximations to it) is now fairly widely used in development institutions (World Bank, Asian Development Bank, Ministry of Overseas Development (UK), etc) and some developing countries including India and Malaysia. Detailed aspects of the methodology are discussed later in this chapter, but some general comments on the underlying philosophy and justification for using the technique in this case are in order at this stage.

Cost-benefit analysis is in general justified by a recognition that financial profit, as a measure of project viability, fails to capture important effects of an investment. This is particularly obvious in investments in roads and other infrastructural sectors where financial benefits (or profits) may not accrue to the implementing agency, but are manifested by (say) increased trade, reduced transport costs, increased land values, etc. On the cost side, to take the same example, pollution and other social costs of the project may also not enter into a financial appraisal. The first stage, therefore, is a recognition and incorporation into the analysis of broader effects than direct financial aspects.

The second stage centres on the values or prices to be used in making the analysis, and it is here that LM have made their major contribution. Their proposals begin with an emphasis on consistency between analyses, and go on to suggest a framework for establishing the appropriate prices. Consistency would be achieved by instituting a Central Office responsible for determining the prices and values to be used by all planning and appraising organizations.

Their proposals for establishing the appropriate prices contain three key proposals:

a) The use of uncommitted social income - income freely available to the government to spend as it chooses - as numeraire, and discrimination between the value of social income (the numeraire) and private income/consumption;

b) discrimination within private income/consumption between income to more and less wealthy recipients;

c) the use of border prices for traded goods, and adjusted-to-border prices for non-traded goods.

The use of government income as numeraire differs from the approach suggested by UNIDO(3), where consumption is chosen as numeraire, but is uncontroversial except in its application with regard to differentiating between public and private income. LM suggest that private consumption will generally be less valuable than income to the government. This can be criticised on several grounds: Bauer (4) suggests that government involvement in the economy should be kept to an absolute minimum, that government activities generally limit freedom of choice and hence, presumably, that government income should be at a discount. He nevertheless recognises the role of the government in providing basic services which the private sector would not provide unaided. Hence, even if Bauer's ideas are fully embraced, the relative value of government versus private income would depend on the level of development. In Zambia, for example, most public services are in need of extension and improvement, and government investment is needed to provide this. At rudimentary levels of development government activity often serves to increase the choices and opportunities available to the consumer by providing basic infrastructural services.

Related criticisms involve the efficiency with which the government uses funds at its disposal, including the desirability of the investments it makes and the bureaucratic costs (including corruption) of government as a channel for investment. LM do not ignore these issues, and recommend their inclusion in assessing the relative value of public and private income - indeed the separation of these items in the LM methodology specifically allows judgements of this kind to be made.

The inclusion of income distributional parameters is an essential ingredient in the LM approach; it is also one of the more difficult issues to incorporate, since income distribution is often ill-defined, the mechanisms which determine it are not easily understood and the appropriate weights to be assigned to different income groups often are not explicit in the country, but must be inferred from other data. Bauer (4) would apparently be neutral between income increments to rich or poor, arguing that the rich save and invest and the talented need incentives - while only the very poor should be directly helped 1/. For aid organizations, favoring the poor is, perhaps, politically inescapable but this does not preclude indirect help stemming from investments where the "first-round" effects are not particularly oriented towards the poor.

The use of border prices raises the issue of the appropriateness of a general equilibrium approach to a non-equilibrium situation. The difficulties include the necessity of making important assumptions on present and future consumer preferences, technology and income distribution - and hence the definition of appropriate prices and weighting systems. The justification of the LM approach in this regard can be framed from two viewpoints.

1/ Which immediately reintroduces relativity - who is "very" poor, who is "quite" poor; is richness measured relative to domestic income levels or international levels?

Firstly, by including, in a disaggregated fashion, most of these key variables, explicit recognition is accorded to them, which both offers improvement over any analysis where they are excluded, and allows testing of the effect of varying the assumptions in sensitivity analysis. The second justification is essentially pragmatic; we are faced with a situation of uncertainty - especially in respect of the future time path of variables - nevertheless, planning and analysis are needed; LM offers an approach to the analysis 1/ which is workable, explicit in its assumptions and highly amenable to testing by sensitivity analysis. The results of the analysis in this study show considerable stability when subjected to sensitivity testing - and though none of the conclusions may be "right", it can at least be said that they hold for a wide range of values of the variables.

A full LM analysis is complex, and limitations of available data have necessitated various assumptions and estimates.

The major difference between this study and a full LM analysis is that here a cost-effectiveness comparison is made (i.e., the minimum cost 2/ solution has been sought), whereas LM is really a cost-benefit analysis, in which the excess value of the benefits over the costs is maximized.

1/ Streeten (5) has suggested that all such approaches embody so many present distortions that they fail to grasp the real institutional, political and social problems. LM in fact embodies many relevant variables and the problem is thus not the variables but the appropriate values and weights.

2/ However, the LM formulation of the Shadow Wage Rate includes one benefit item - increased worker consumption. Thus, the approach used is to minimize the net cost of the chosen technology, including benefits accruing via the costs of the investment.

The restriction is justified in several ways:

(a) the results are not diminished in value by forming only half of the full analysis--a full analysis would require precisely the same treatment of the cost side;

(b) the problem of evaluating the benefits of this type of investment is very difficult; the output of the investment, water, is not a direct input to further economic activity, but rather makes it indirectly possible by allowing settlement of presently uncultivated areas. If the cattle watered were treated as an "economic activity" by the people, this problem would be reduced--but the integral part which cattle form in the social structure precludes this, at least for the time being;

(c) since for social, political and economic reasons the area in question will be settled and will need water, the investments under consideration will be made in any case, so cost minimization is a satisfactory objective for the analysis.

2. Valuation of Goods

The valuation of the physical inputs and outputs of an investment receives major attention in LM (1,2) and here, rather than repeat or summarize in detail their exposition, a few comments are made to justify the approach and point up some of the issues and complications which result.

2.1 Use of Border Prices for Traded Goods: If a good is freely imported and exported, i.e., it is not subject to quota restrictions, the good is valued at its border price[1] (i.e., net of taxes or subsidies and "middle man"[2] mark-ups). This is not because foreign exchange is taken as a constraint, but rather because the function of the numeraire is to provide a common yardstick for measuring different things. Although LM and the UNIDO method (3) are now very similar, LM places greater emphasis on border pricing wherever possible, while UNIDO is more willing to fall back on domestic prices if necessary. Basically, LM favors free trade heavily. whilst UNIDO thinks it desirable. Earlier drafts of the UNIDO Guidelines used local prices much more, apparently on the grounds that local prices were the best indication of the value placed by

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[1] At the margin.

[2] But including real costs of middle-man operations, such as transport, distribution and marketing.

the consumer on a particular good. The merits of this argument, however, seem to be outweighed by the limited impact which the consumer has on the major distortions, which result from government policy; furthermore, the "yardstick" function of the numeraire is lost.

2.2 Prices for Traded Goods Subject to Quota Limits: Where a good is subject to quota limits on its importation, it is clearly incorrect to use the border price (unless the quota is not being filled) for valuation. In this case, the opportunity cost of the good in the (internal) economy must be assessed in terms of the border price numeraire.[1] This procedure is complicated and tedious, but fortunately was not needed in this analysis since no such goods were involved.

2.3 Prices for Non-traded Goods: A standard conversion factor (SCF) can be estimated, which is related to the ratio between border and internal prices for a "basket" of traded goods. In the situation where a good is not traded, the analyst then has three options open:

(a) directly revalue the non-traded good using the SCF;

(b) trace the elements of the manufacture of the non-traded good to identify traded components, which are valued as under 1 or 2 above, and apply the SCF to the residual; or

(c) identify traded goods for which the non-traded good is a substitute (as is often possible in the case of foodstuffs) and base the value on this, with any necessary premium or discount to reflect quality or consumer preference.

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[1] This is complicated since, firstly, the value of the good will be (domestically) increased if the quota is less than demand at the border price, and, secondly, the increased domestic value will lead to income to Government and private sources which must be revalued to social prices.

3. The Shadow Wage Rate

3.1 The Importance of the Shadow Wage Rate (SWR): In the analysis of projects in developing countries, the SWR has a role of particular importance--the more so when an attempt is being made to compare more and less labor intensive solutions. The SWR has a bearing on the distribution of consumption between contemporaries (revenue from projects will accrue more to wage earners if labor intensive technologies are used, and especially to poorer workers) and the distribution of consumption over time (the use of labor intensive solutions now may reduce the resources available for reinvestment and hence the rate of growth of employment and consumption). Here, then, is a variable with great potential impact both economically and socially if applied consistently to all projects 1/.

3.2 The Little and Mirrlees (LM) Formulations of the SWR: Not surprisingly, LM devote considerable attention to the SWR problem in their two books (1,2). There is one important difference between the recommendations of these two books and also some suggested modifications of application. The formula LM suggest is rather complex in both cases, and the analysis presented below is as follows: first, the variables are listed, defined and described; secondly, the two formulae suggested by LM are derived and compared. In the next section, the behavior of their model is described. In section 4, some comments on the model, and particularly some possible effects of the Zambian situation on the model, are made.

1/ In the present case, the analysis is not extended across competing projects, since no comparable analyses were available.

3.3 Variables in the SWR as Evaluated by LM: The point, made in more detail elsewhere (section 5), that all goods and services are valued at border prices (i.e., if a worker consumes maize, then the cost of this consumption is the cif price of maize, if it is imported, and the fob price if it is exported) applies also in the calculation of the variables.

The variables:

c^1	The total cost of the goods and services committed to consumption by employing a worker[1/].
c	The consumption of the wage earner.
m	The value of agricultural production lost as a result of a worker leaving agriculture.
S_o	The ratio of the present value of one unit of investment to one unit of current consumption.

The calculation of S_o is one of the most complex parts of the Little and Mirrlees analysis.

The argument runs as follows: if, instead of paying out part of the revenue of the project as wages, that sum were invested, it would produce a stream of income in future years. Hence, the value of present consumption must be weighed against the value of the stream of income which would flow from the potential investment. Now to make this comparison, we need to know:

(a) the yield of alternative marginal investments (R); and

(b) the rate at which future consumption benefits should be discounted (i).

[1/] Including any "overheads" which do not constitute benefits to the worker (see below, 2.2).

The relationship between R and i is complex; they are partially linked and partially independent. R, the yield on alternative investments, or "cut-off" rate of return, reflects the scope for other investments available to the country. If many profitable investments exist R will tend to be high and vice versa. Also, if a project increases the demands on investible funds - e.g., by significantly increasing the need for infrastructure or housing - R can be increased indirectly by project investments. The consumption rate of interest (i) reflects the rate at which future increases in consumption should be discounted. Again, project investments can affect this parameter, since income levels in the long run are determined partially by the nature of current investments. Factors which affect i include:

(a) actual income levels (the higher they are, the less valuable is extra income);

(b) growth versus income objectives (heavy emphasis on growth will increase the discount on consumption);

(c) the rate at which income is expected to increase.

The second two of these objectives are most clearly linked to R; if many good investment opportunities exist this will encourage emphasis on growth; if ongoing projects are successful and socially profitable, income will be growing in any case.

Political points of view also bear on this issue. Authors such as Bauer who are market-oriented and suspicious of government intervention would in any case dispute the premium placed on investment[1], with government

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1/ This is a philosophical rather than a methodological difference, since, like LM, Bauer also considers government income to be different in value to private income, and the LM methodology can as easily allow a discount on government income as a premium.

income as the numeraire, and prefer that market forces decide the proper discount rate without recourse to specific judgements on "separate" issues such as consumption.

Now the first of these two parameters involves using the Little and Mirrlees method on several other projects, firstly to establish what is a marginal project, and secondly to establish its yield. Although this process would be long in this case, if the Little and Mirrlees method were being used in a central planning agency, such data would be available.

The second parameter, the rate of discount for future benefits, is more difficult to determine by calculation, though the rate of growth of per capita incomes may be a guide since the value of future consumption increases is related to the level of consumption in the future.

In the two case studies in the Manual, the SWR is suggested without reference to productivity in agriculture, consumption rates of interest or the value of S_o. In another case study using this appraisal method, Lal (13) makes a very detailed analysis of the likely values of both the consumption rate of interest and the yield on alternative projects. Having done this, however, it is still necessary to estimate the time period up to which national investment will be in deficit (i.e., T at which $S_T = 1$) since this is the period during which increases in consumption are valued lower than increases in investment and hence find S_o. Lal estimates T to be 100 years for India.

$$S_o \approx S_1 = (1 + 1/2\ (R_1 - i_1))^T$$

where: R_1 = Accounting Rate of Interest

i_1 = Consumption Rate of Interest

The formula assumes uniform rates of change in R, and i_1. For Lal's estimates of R_1, i, and T, $S_o = 4.4$.

Despite the sophistication in calculating $(R_1 - i_1)$, T was still virtually a guess, and it is interesting that taking T as 80 years or 120 years would have changed S_o to 3.27 and 5.9 respectively.

3.4 <u>The Formula for SWR</u>: Having estimated the values of the variables C^1, C, M and So, it remains to compile the SWR.

In their first book LM suggest that the SWR is:

$$SWR = M + (C^1 - m) - \frac{1}{So}(C^1 - m) \text{ 1/}$$

The components are:

	m	the loss in agricultural production
plus	$c^1 - m$	the increase in resources devoted to consumption
minus	$\frac{1}{So}(c^1 - m)$	the benefit to society of the extra consumption, revalued to reflect the value of foregoing investment

The formula reduces to:

$$SWR = c^1 - \frac{1}{So}(c^1 - m)$$

In LM's second book, an important modification is introduced, and, since it is not explained in the text why this has been done, nor, in the criticisms of LM (6) has any comment appeared, it is worth analyzing the change here.

When a worker moves from agriculture into industry, his consumption usually increases when measured in money or real terms. Increases can fall into one of two categories: either the increase is a benefit to the worker (i.e., an improvement in his way of life) or it is simply an extra cost directly resulting from his new way of life.

1/ Note that here, for the sake of comparison, C^1 is used throughout for total consumption. LM use c in their first formulation, and C^1 in the second.

An example of an increase in money terms of consumption would be that an urban worker buys food which has been transported from the country, and therefore costs more (and has used more resources in its production) than the same good in the country—but no consumption benefit accrues to society out of this change, except the profit on the transport costs.

Alternatively, a worker in industry may need (say) protective clothing for his job and may buy this from his pay. Clearly he would not regard this as a consumption benefit, and to treat it as such by subtracting all or part of such consumption from the SWR would be to misrepresent the situation.

LM modify their model in their second book, where the intermediate term c, consumption of the worker, is introduced, and thus $(c^1 - c)$ represents what they call "transport costs...and urban overhead" (p.271n).

The formula now becomes:

$$SWR = m + (c^1 - c) + (c - m) - \frac{1}{So}(c - m)$$

comprising :

m	production lost in agriculture
plus $(c^1 - c)$	the urban overhead, and personal costs of employment to the worker
plus $(c - m)$	the extra consumption accruing to society
minus $\frac{1}{So}(c - m)$	the benefit value of the extra consumption

This reduces to:

$$SWR = c^1 - \frac{1}{So}(c - m)$$

4. Behavior of the LM Formula:

4.1 Effect of Changes in the Variables:

$$SWR = c^1 - \frac{1}{So}(c - m)$$

where c^1 = extra resources committed to consumption per new employee

c = extra resources committed to consumption excluding "overheads" which are non-beneficial to the employee

m = marginal product of the new employee in agriculture

So = ratio of the social value of a unit of investment to current consumption

$= (1 + 1/2\ (R_1 - i_1))^T$

where R = Accounting Rate of Interest, at which projects are assessed

i = Consumption Rate of Interest

T = Time period until investment will be at an adequate level (and hence $R = i$)

The shadow wage rate will:

(1) increase with increasing c^1 because c^1 is a measure of the resources lost to alternative uses;

(2) decrease with increasing c because c is a measure of the benefits enjoyed by a worker, and what proportion these are of the total cost, c^1;

(3) increase with increasing m, because m measures the opportunity cost of labor;

(4) increase with increasing R, because R reflects the opportunity cost of capital, and capital for investment is foregone by increasing employment and hence consumption;

(5) decrease with increasing i, because i reflects the relative value of current consumption and future consumption. If i is high, future consumption is less valuable, so more current consumption (and hence employment) is desirable;

(6) increase with increase T, since T is the length of time for which investment is more desirable than consumption, and the longer this is, the higher is the NPV of a unit of investment.

The extreme values for So are:

(a) 1 when R equals i;

(b) infinity when i = 0 and T is very large because future consumption is as valuable as current consumption for the foreseeable future.

In these cases,

$$SWR_{(So = 1)} = c^1 - c + m$$

and

$$SWR_{(So = \infty)} = c^1$$

In the first case, full weight is given to the extra consumption benefit and SWR is minimized.

In the second case no weight is given to the extra consumption, since this could "infinitely" better have been used for investment.

4.2 The Behavior of the Formula in Relation to the National Economy:

As described above, the LM formulation of the shadow wage rate incorporates macro-economic parameters as well as employee--specific parameters. This results in a changing overtime of the SWR, independently of changes in productivity, actual wage rates or opportunity costs of labor

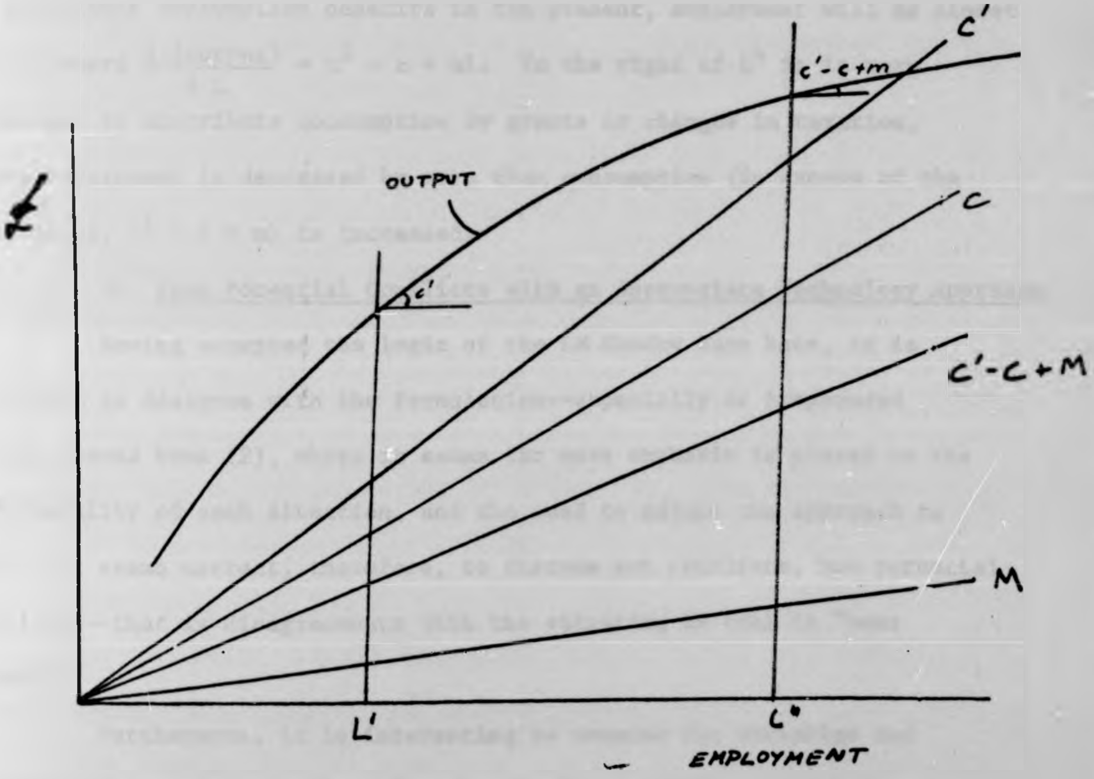

Figure 1: Likely Relationships Between the Variables in the SWR.

Extreme values are:

$$SWR_{(S = 1)} = c^1 - c + m$$

$$SWR_{(S = \infty)} = c^1$$

At L', (where $\frac{d\ (output)}{d\ L} = c^1$) resources available for reinvestment are maximized, and when an economy is growing very slowly, and opportunities for profitable investment abound, SWR will be close to this extreme.

When investment is more adequate, and it becomes more desirable to distribute consumption benefits in the present, employment will be closer to L" (where $\frac{d\ (output)}{d\ L} = c^1 - c + m$). To the right of L" it is more efficient to distribute consumption by grants or changes in taxation, since investment is decreased by more than consumption (in excess of the base level, $c^1 - c + m$) is increased.

5. Some Potential Conflicts with an Appropriate Technology Approach:

Having accepted the logic of the LM Shadow Wage Rate, it is difficult to disagree with the formulation—especially as propounded in the second book (2), where it seems far more emphasis is placed on the individuality of each situation, and the need to adjust the approach to suit. It seems correct, therefore, to discuss not conflicts, but potential conflicts—that is disagreements with the situation LM feel is "most likely".

Furthermore, it is interesting to examine the variables and criteria of the LM Shadow Wage Rate in the light of Schumacher's ideas on development.

There seem to be three points of possible disagreement:

(1) the valuation of output;

(2) the stabilization of rural society; and

(3) the "dynamic" effects of employment.

The valuation of output is fairly easily dealt with, and the conflict with the LM method is easily resolved. The problem is that having taken some care to choose the most appropriate product, it may well be that this produce is not a "traded good", but is a substitute for one. For example, simple, locally made footwear may indeed result in diminished imports, but as production rises, it may be that the product cannot be exported. Thus, while production is all internally consumed, valuation can be at the c.i.f. price of the substitute, but when importation ceases, the value of further output falls sharply.

The second problem, the stabilization of rural society, is much more difficult. LM touch on redistribution of income in their first book ((1) Chapter X), and give this objective more consideration in their second book ((2), pp 21-2, 55-58 and Chapter XIII). Here, a system of weighting is proposed, on the basis that the value to an individual of extra current consumption depends on the level of that individual's consumption, and at some base level of consumption, extra consumption is just as valuable as investment ((2) p.238).

Typically, one would expect rural projects to be of the type that benefitted the poorest members of society, and so, in the LM framework, extra consumption to these people would be accounted at full value as a benefit.[1/] Whether or not this is a high enough allowance is debatable, since the political, social and financial costs of migration to the towns is high, and it may be that some extra premium should be attached to "stabilizing" projects.

[1/] Or possibly more if their income is extremely low.

The final source of conflict between LM and the Intermediate Technology approach is the valuation of employment. LM value employment in terms of the output of the project, and some proportion of the extra consumption accruing to society. They take no account of Schumacher's "dynamic effects" (p3), which are to a large degree learning effects—demonstrating to a man that he can profit from economic activity and thus stimulating further activity in him and others. Thus employment itself can be considered to some degree an investment.

6. Application

The LM analysis has been described in some detail, and some possible problems and disagreements with the Intermediate Technology viewpoint have been suggested.

The LM is, however, a very usable tool, despite some difficulties with estimating the variables, especially S_0, as mentioned above. It is not therefore fair simply to list some rather intangible benefits. The difficulties stem mainly from the explicit recognition given to the more elusive elements of development economics, which simultaneously raises challenging issues.

6.1 Stabilization of the Rural Population: Although LM refer to the work of Harris and Todaro (7), where it is suggested that the creation of urban jobs at high wage rates has a multiplied effect on the migration rate (i.e., more than one worker per job is attracted from the rural areas), they seem to assume in their model that in general, one person moves in to the town per job created--though they suggest that some care be taken in making this assumption (2 pp.171-2).

On a one-for-one basis, it is rather difficult to explain the rapid growth of the shanty towns, and the Harris and Todaro approach seems more convincing.

The second important factor is the consumption pattern of those attracted to the towns. Recent Urban Budget Surveys in Zambia (8) show the following:

(1) consumption expenditure of the unemployed is high[1/] (4 pp.5,11, 15, 19, 23);

(2) consumption expenditure declines with income between income levels of 0-10 Kwacha/month and 20-30 Kwacha/month.

This suggests that creation of an extra job will:

(1) take one unemployed man, and provided his pay in employment is not over 50 Kwacha/month, create no increase in consumption;

(2) attract more than one person from agriculture, and generate a lot more consumption in the shanty towns, in terms of actual goods consumed and urban overheads.

To illustrate these effects the product of a family in agriculture in Mumbwa is at least K20/month, based on the value of their output of maize (9). If the family moves to Lusaka, its typical consumption will rise to about K63/month. Of this, about 45% is on food, 20% on clothing and footwear, 14% on housing and 20% on miscellaneous items (of which about 10% is for transport). Assuming the "urban overhead" to constitute 20% of food costs, 50% of clothing costs, all of the housing cost and half of miscellaneous items, we have:

c^1 = 63 K/month

c = 35.5 K/month

m = 20 K/month

[1/] Presumably due to the "costs of leisure"—financed from transfers, savings from previous employment, and borrowing from relatives—which is clearly a potential loss to investment.

The extreme values at So = 1 and So = ∞ are:

$$SWR_{(s = \infty)} = 63 \text{ K/month}$$

$$SWR_{(s = 1)} = 47.5 \text{ k/month}$$

Typically, however the value of SWR would be close to 60 K/month, since c rapidly becomes insensitive to increases in S.

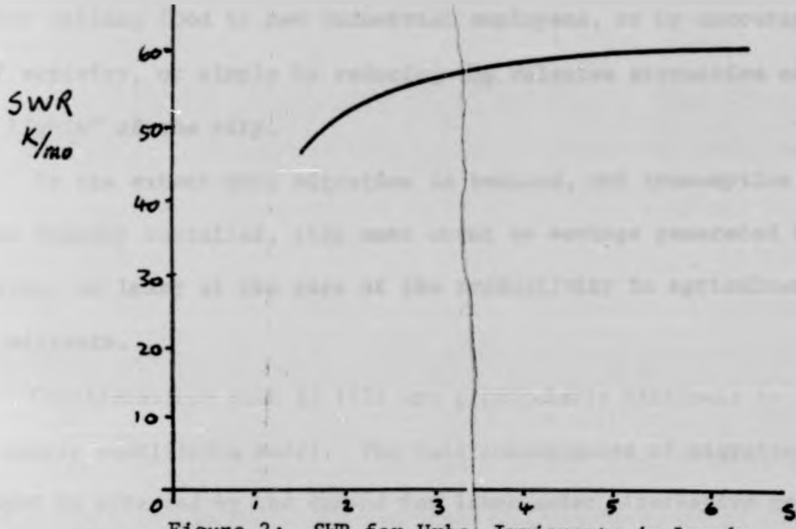

Figure 2: SWR for Urban Immigrants in Lusaka

The value of SWR is, however, sensitive to the rate of migration. In fact, in Lusaka, the consumption of an unemployed family is roughly the same as that of a family earning 70 K/month, so although the movement from unemployment to moderately paid employment produces no increase in consumption, the new immigrants, if they consume at the average rate, will increase consumption drastically, and, if some multiple of the available vacancies move to the city, then the SWR for an urban based project must be adjusted accordingly.

Projects in rural areas have the opposite effect. The more dynamic people who will seek and get employment in the competitive rural labor markets are amongst those mostly likely to migrate to the city in search of employment. Thus jobs in the country areas reduce migration, and reduce the growth of consumption in the urban areas—freeing resources for investment.

6.2 The Dynamic Effect of Employment: If, as a result of a rural project, further local activity is stimulated, this reduces the potential migration rate to the city—either by increasing, say, the market for selling food to new industrial employees, or by encouraging new types of activity, or simply by reducing the relative attraction of the "bright lights" of the city.

To the extent that migration is reduced, and consumption of resources thereby curtailed, this must count as savings generated by the project, at least at the rate of the productivity in agriculture of such migrants.

Considerations such as this are particularly difficult to account for in this static equilibrium model. The full consequences of migration in so far as it might be affected by the demand for labor under alternative project designs would be very difficult to trace. The assumption which made here, that creating one rural job (as opposed to one urban job) prevents one person migrating is apparently conservative in the light of the conclusions of the analysis since a higher rate of migration prevention would further reinforce the conclusions.

7. Summary and Conclusions

The SWR is an important and difficult parameter to calculate with accuracy.

The LM formulation has considerable attraction for use in the assessment of labor intensive projects, not least because it can be seen as several inter-reacting components, so that modification is relatively simple and the impact of different assumptions can thus be tested.

It seems, although the precise magnitude of such effects is difficult to estimate, that the influence of the migration mechanism may considerably outweigh "fine tuning" of the SWR by adjusting the relative value of consumption and investment.

The procedure used to estimate SWRs for the analysis is to split labor into categories and estimate the SWR, particularly in relation to the value given to extra consumption, on the basis of the arguments described above proposed by LM and Schumacher.

(i) Skilled Labor (e.g., Diesel Mechanic): Such labor will often be expatriate, or at least earning expatriate pay levels. It is usually town based, and would be the type of job which would attract people to the towns. Such people are wealthy by Zambian standards and are an essentially tradable commodity. Their cost is therefore assumed to be equal to the full cost of employment at border prices.

This is counted at full cost (c^1).

(ii) Artisan Labor: This type of labor is the "middle man" between the rural and urban sectors, and the type of labor most needed in Zambia. Incremental income to this class of labor is therefore as an investment cost 1/, since the expansion of this work force is fundamental to the economic development of the country. Typically, such labor is rurally based (or would be for this project) and consumption by this class is of the type which stabilizes society, by diffusing economic activity in the rural areas through example. Since minimal "urban overheads" ($c^1 - c$) are incurred by such people, this labor is counted at marginal agricultural product (m).

(iii) Local or Family Labor: This is counted at opportunity cost in terms of lost output. Any extra consumption accruing to this class would in any

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1/ This is a difficult assumption; such people are currently rare, and therefore command high incomes and a high opportunity cost. On the other hand, relatively few people are training for such jobs, and if, as assumed here, their impact and value to society is substantial, this premium is justified as an investment to encourage more such workers.

case probably have a full benefit weighting in LM terms, since they are relatively poor.

8. Evaluation of the SWR

8.1 Skilled Labor: As noted above, skilled labor in Zambia is very highly paid—because large numbers of expatriates work in Zambia, and Zambianization is usually done at more or less the expatriate pay level. A skilled mechanic would typically be paid abour £4,000-£4,500 p.a. Of this one-quarter or one-third can be repatriated, and taxes would amount to about 20%. Owing to the very limited internal production of clothes and other consumables, the vast majority of the consumption expenditure of expatriate and other high income classes is on imports.

On the basis of experience in Zambia, the average ratio of the internal price to the "world" price is probably about two.

Clothes, shoes and food would be roughly twice as expensive—cars and electrical household equipment are rather more than twice as expensive, but the not insignificant payments for services (e.g., to servants) would be less inflated. Thus:

	Internal Price £	World Price £
Salary (say)	4,500	
Tax	900	
Repatriation Allowance 1/	1,500	1,500
Consumption	2,100	1,050
		2,550

Assuming a working year of 48 weeks, this corresponds to £10.6 per day (K14 per day or K2 per hour).

8.2 Artisan Labor: Owing to the beneficial effects of artisan employment, as noted above, this class of labor is costed at its marginal

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1/ Depending on time of appointment

product in agriculture (MPA)--that is any increase in income accruing to such workers is counted directly as benefit.

The value of the MPA must be estimated with care. As Little and Mirlees point out (1, p.93-4) it is often assumed to be zero, and they take the view that though not as low as zero, the MPA may well be very low. They recommend (1, p.172-3) using a fraction (1/2) of the average productivity in agriculture as a guide to the MPA, or alternatively, calculating the total earnings of an agricultural worker over the year, and averaging this to get an estimate of the daily MPA.

Here, the view taken is that in Zambia the MPA is higher in relation to the average product than LM would suggest (they do point out that MPA varies between countries). This is based on three main factors:

(1) In the particular area under study, the farmers are of a relatively high standard. Draft power is widely used, and fertilizers too are in common use as are improved seed varieties;

(2) To calculate, as LM suggest, the average productivity in agriculture by dividing the total production by the agricultural work force, is to ignore the variation in productivity between different communities, and, more important, between men, women and children. Since the artisan worker will usually be a fit man, and also the type of man who farmed well, it would be difficult to suggest any particular relationship between his MPA and the average productivity in agriculture.

(3) Most importantly, in Zambia there is no shortage of land. In Asian countries especially, where land is a major constraint, it may be that the MPA is low due to overcrowding. In Africa, and in Zambia particularly, this is not often the case, and thus this major cause of sharply diminishing returns to labor does not apply.

The MPA does vary over the years, however, but it is assumed here that undertaking artisan employment will mean either giving up farming completely, or having to curtail farming in a random fashion, so that in the long run the average productivity over the year is relevant. The alternative case of scheduling non-farming activities in described below (8.3).

Some guide to the average product of labor in agriculture is available from two sources.

The UNZALPI study of farming in Zambia (9) lists outputs and inputs into farming activities in two rural areas. The Magoye Unit Farm Report (10) shows similar data for a farm run by the expatriate extension staff, using as far as they could judge, equipment, methods and materials available to rural farmers, and within their economic reach (e.g., oxen were used rather than tractors).

Table 1 below summarizes data from these two sources, in comparable units.

Table 1 - Crop Yield in lb/hr Worked [1]

	Maize	Groundnuts	Cotton
Magoye Unit Farm	19.24	1.3	2.27
Mumbwa Farmers	6.36	.75	1.83
Ratio	3.0	1.7	1.24

The Magoye data are averaged from five years' results, whereas data for the Mumbwa farmers (who were the most efficient group studied) are from one year.

Since only adult labor is employed on the unit farm, it is not surprising to find higher productivity figures there (supporting suspicions of the ML suggestion of taking average production for all workers as a measure of the product of an adult male).

In addition, the Magoye report summarizes (pp8-9) returns per hour worked, net of all inputs except labor. To convert this figure to border prices, as required for the LM analysis, the outputs and the inputs must be revalued.

1/ Sources: Magoye Unit Farm Report (6) and Unzalpi (5)

The internal price of maize is K4.30 per 90kg bag at line-of-rail depots. Production levels have been unstable due to the sensitivity of yield to the weather, but the comparatively high prices now paid to farmers will probably ensure that Zambia is in future a net exporter of maize. Regular export has recently begun to Zaire, and maize is sold at K53 per tonne f.o.b., which is equivalent to K4.77 per bag.

As regards fertilizer and seeds, the main inputs, it is difficult to revalue these items, since they are internally produced to meet local needs, and no accounts are available to trace back the production process to goods which are traded. It is therefore assumed that these inputs are already valued correctly for our purposes.

Groundnuts are worth considerably more for export than the producer price suggests. The c.i.f. Europe price implies a value of over K13 per bag to the producer, while producer prices[1] are K10 per bag (11).

The value of cotton produce is probably virtually equal to the producer price, since it was often exported at a loss, though not always (12), implying that transport costs could turn the scale--since these are relatively high for cotton. Cotton is now used at Kafue Textiles, a Zambian factory, which absorbs all internal production.

Table 2 - Labor Input and Return for Various Crops

	Total Hours Worked 1/	Return Per Hour (K) 2/	Total Return (K)
Maize	3,428	.261	894.7
Groundnuts	1,160	.065	75.4
Cotton	3,026	.11	332.8

1/ Mean hours/acre (Tables 6,7,8) x means acres grown (p.8).
2/ As shown (Table 18) having modified "gross margin" to reflect border price (i.e., + K.47 per bag for maize, K3 per bag for groundnuts.

Source: Magoye Unit Farm Report (6)

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[1] Paid by the National Agricultural Marketing Board (1974).

From the table, the mean total hours worked on the farm (sum of column 1) is 7,614. The mean total return (sum of column 3) is K.1,302.9. Thus the return per hour, weighted by activity is K.0.17 per hour. The weighting is necessary because good farming practice (rotation of crops) does not allow concentration solely on the most profitable crop. The mean total hours worked on the unit farm actually exceeded this total by over 50% of this, about half is due to time spent on improving cattle and improving the pasture—tasks which even a good Zambian farmer would be very unlikely to undertake. The remaining time was in unallocated land preparation and maintenance. These jobs must be done, so the return per hour must be decreased to allow for this non-productive, but necessary work.

Hence the average return per hour for labor on a well managed farm is $\frac{K0.17}{1.25} = K.136$.

Of course, the labor on this farm is particularly well organized, and it would be unrealistic to assume that village farmers reach this level of productivity. Returning to Table 1, the best farmers in the UNZALPI survey had per hour productivities between one-third and four-fifths of the Magoye outputs.

Bearing in mind that the figures are not directly comparable with the Magoye results due to the inclusion of child labor, it seems reasonable to estimate the productivity of a good farmer towards the upper end of the range—say at .7 times the Magoye figure—and to expect this to improve, over a considerable period of time, to equality. The Shadow Wage Rate for artisan labor is therefore estimated at K0.1/hr.

8.3 Family Labor: Treatment of family labor differs from that of artisan labor in two important respects.

Firstly, some work can be scheduled to fall at periods when labor is underutilized.

Secondly, much of the ongoing work can be done by less productive members of the family, since it is not physically demanding (e.g., driving animals, collecting manure).

Thus the shadow wage rate must be an adjusted version of that calculated for artisan labor.

In the case where family labor is used for construction or annual maintenance, this is assumed to be scheduled during labor surplus periods and have zero cost.

In the case of a daily or weekly task, this is costed at 50% of the artisan rate, on the assumption that labor of lesser productive capacity is used.

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Chapter 4

Demand Levels and Supply Sources Analyzed

1. Demand Levels

Four levels of demand have been analyzed for each of the technologies listed. The demands consist of three representative farm sizes, namely:

System 1—small farm with 10 family members and 10 cattle;

System 2—medium sized farm with 15 family members and 40 cattle;

System 3—large farm with 20 family members and 100 cattle.

In addition, the possibility of supplying several farms from one source exists. The large size of the farms and hence high costs of piping water (the pipes must be buried to protect them from fire damage) means that only two or three farms could reasonably be served per outlet.

System 4—several farms, 80 family members and 200 cattle.

The demands resulting from these alternatives vary through the year. While the human consumption is assumed constant through the year and taken as the average of European and African water usage rates [1/], the demand from the cattle is 45 litres/day in the dry season and zero in the wet season when water is available in ponds. The power demand is expressed in meter/liters of water. For the smallest system, a head of 15 meters is assumed, while the medium sized system is assumed to operate at a head of 20 meters and the bigger systems at 25 meters—the increased head reflecting the "drawdown" effect of higher pumping.

2. Alternative Solutions Considered

In the following chapter, five possible power sources are discussed in detail, and systems designed to meet the needs of different farm sizes are specified and costed.

[1/] See F. Congland, Field Engineering.

The power sources range from extreme capital intensity (windmills) to extreme labor intensity (manpower). They are:

(a) wind power;
(b) diesel power;
(c) methane power;
(d) animal power;
(e) manpower.

Storage Tanks

Any pumping system will require some storage reservoir (except possibly an electric motor driven pump) since it will not be sensible (say) to harness up oxen to pump just a few gallons of water for washing. Further, to allow servicing of the system, cleaning out the borehole or repairs, a store of water will be required.

Thus for each system a tank allowing storage of one week's dry season demand is included (except in the windmill case, where larger reservoirs are already included in the basic system).

This has the further advantage, particularly in the case of animal driven systems, of allowing several days supply to be pumped at a time. It will be noted that, in the case of the smallest demand levels, the large majority of the labor requirement arises not from the actual pumping activity, but rather from the need to harness and unharness the animals, and so a saving in labor can be made by provision of storage.

The costs of storage tanks are calculated as shown in the wind-powered solution, and, allowing for a one-week supply to be stored, these are:

Table 1 - Costs of Storage Tanks

System	Tanksize	Installation			Repairs (pa)	
	1	Cap	Lab. (man days)		Capital[1]	Labor[2]
		£	Bricks	Building	£	(man days)
1	7,500	10	12	14	1	2
2	19,000	19	23	26	2	3
3	40,000	29	35	42	3	4
4	2 x 48,000	70	84	98	7	10

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[1] 10% of material costs.
[2] 10% of building time.

Animal Power

Animal power is already very widely used among the Tonga for cultivation and transport. Primarily, oxen are used, but very occasionally donkeys are seen—usually being used by people from Rhodesia, where donkeys are in general use.

Animal power is not at present used for water pumping in Central Africa, although in many other developing countries, animals are the prime source of power for this use, but always for lifting water from large open wells.

Extensive testing of indigenous Indian devices (2,3) has shown that the continuous power output of a pair of oxen is about 0.8hp when harnessed to a centrally pivotted arm, and walking in a circle. This figure is rather less than is suggested by the FAO (1), but since the conditions of test are not as clearly specified in the FAO report, the Indian figures are used for calculations.

The range of equipment is rather limited: the indigenous Indian devices are not suitable for the low water tables found in Southern Zambia, and the only examples of deep well systems are the CADU machine (4) and the horse driven pump such as those manufactured by Guthrie Allsebrooke (5) in the early 1900s.

Both machines have an efficiency of about 35%. Current cost estimates are available for the CADU machine, but not the Allsebrooke model, so the former is used in the analysis.

The CADU device is illustrated in Figure 1. The oxen walk in an eight meter diameter circle, pulling the pivotted arm. A cable is attached to the arm, at a radius of one meter, and this transmits reciprocating motion to the pump.

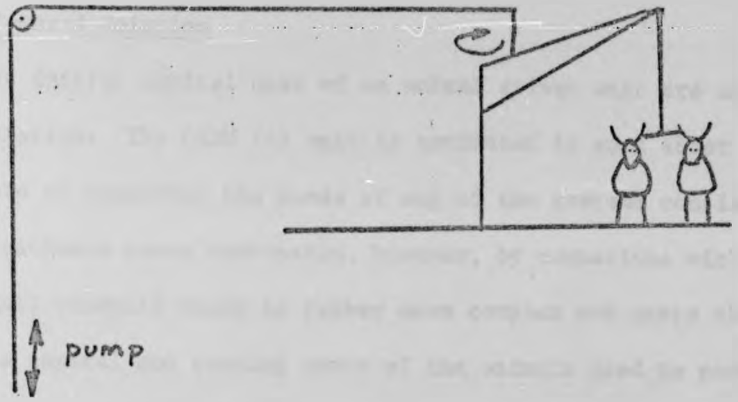

Figure 1 - Animal Powered Pump

Constructed entirely of welded steel, the device is estimated to cost £200. It has a lifting capacity of 81,000 meter liters/hour when driven by two oxen (an efficiency of about 37% compared to 40-45% efficiency for the Persian Wheel (2) and about 50% for the horse driven Guthrie Allsebrooke machine).

The Animal Powered Solution

The initial capital cost of an animal driven unit are necessarily rather speculative. The CADU (4) unit is estimated to cost about £200, and is capable of supplying the needs of any of the systems considered here. This estimate seems reasonable, however, by comparison with the cost of a small windmill which is rather more complex and costs about £300.

The capital and running costs of the animals used to power the machine have been computed as follows:

(1) Since the farmer would normally have animals available for training, the capital cost is considered to be the labor input of the training.

(2) The running cost is calculated on an opportunity cost basis. Ideally, a farmer would keep beef cattle and sell them, instead of untrained oxen. Thus, the "running cost" is the opportunity cost of not producing beef.

Beef cattle would increase in weight rather faster than oxen (which nevertheless appreciate in value themselves). The Magoye Research Station has calculated the opportunity cost of keeping work oxen in great detail (b), on the basis of the internal prices for meat and the inputs for keeping cattle, in 1971.

Since 1971 the prices paid by the internal buyers (the Cold Storage Board) have increased drastically--in 1971, prices averaged about £25 for 100 kg liveweight for "standard" grade meat, corresponding to K55 1/ per kg. cold dressed weight (7). The average price during 1973 for imported beef was K60 per 100 kg. cold dressed weight, but this increased rapidly at the end of the year, and reached K83 per 100 kg. in December. Transport

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1/ 1 Kwacha (K) = £ .62.

costs must be added to these prices, and, in the case of meat imported by air from Botswana, this would reach K20 per 100 kg. (8).

Thus the value of lost production in the Magoye calculations would be a substantial underestimate at current price levels. The complexity of the calculation carried out by Magoye (including the costs of dipping, veterinary services, fencing, etc.) and the absence of current data on these costs means that an estimate must be made of the opportunity cost of keeping work animals.

Magoye calculated the cost at K25 per animal per annum. The relevant value for beef now is at least three times the value then used, but the price of other inputs has also increased. It is therefore assumed for the calculation that the cost of keeping an ox is K50 (£31) per annum.

More detailed calculations of this figure are not really justifiable, since it is in any case only an upper limit. In most cases the farmer does not keep cattle for beef on a commercial basis, and often if not used as work animals the oxen would simply be kept idle (see Chapter 2 for a more detailed discussion of this).

Thus the opportunity cost of the use of the animals may often be zero.

Labor would be required for as many hours per day as the device is operated, but this could be done by a child or other relatively unproductive member of the family.

Since storage tanks are available, and the harnessing of the animals is time-consuming, it is assumed for the three smallest systems that pumping is done twice per week, and for the largest system, three times per week.

Table 2 - Capital and Running Costs of Animal Powered Systems

Costs

System 1—small farm

Demand 10 people	600 liters/day
10 cattle	450 liters/day
	1,050 liters/day

Assuming a head of 15 meters,

Demand	9,000 meter liters/day (wet season)
	15,750 meter liters/day (dry season)

Capital Costs

Machine	£200
Installation unskilled	20 man days (including training oxen)
skilled	one man day

Running Costs (assuming 10% p.a. of initial costs for repairs)

Repairs	£20 and 10 man days
Oxen	£0-62

Labor (assuming 1/2 hour for harnessing, etc. operation twice per week)

Harnessing	6.5 man days
Driving	7 man days

System 2—medium sized farm

Demand 15 people	900 liters/day
40 cattle	1,800 liters/day
	2,700 liters/day

Assuming head of 20 meters,

Demand	18,000 meter liters/day (wet season)
	54,000 meter liters/day (dry season)

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	54,000 meter liters/day (dry season)

Capital Costs

Machine	£200
Labor unskilled	20 man days
skilled	one man day
Running Costs:	
Repairs	£20 and 10 man days
Oxen	£0-62
Labor: Harnessing	6.5 man days
Driving	20 man days

System 3—large farm

Demand 20 people	1,200 liters/day
100 cattle	4,500 liters/day
	5,700 liters/day

Assuming head of 25 meters,

Demand	30,000 meter liters/day (wet season)
	142,500 meter liters/day (dry season)

Capital Costs

Machine	£200
Installation unskilled	20 man days
skilled	one man day
Running Costs:	
Repairs	£20 and 10 man days
Oxen	£0-62
Labor: Harnessing	6.5 man days
Driving	49 man days

System 4--several farms

Demand 80 people	4,800 liters/day
200 cattle	9,000 liters/day
	13,800 liters/day

Assuming head of 25 meters,

Demand	120,000 meter liters/day (wet season)
	345,000 meter liters/day (dry season)

Capital Costs

Machine	E200
Installation unskilled	20 man days
skilled	one man day

Running Costs:

Repairs	E20
Oxen	E62
Labor: Harnessing	10 man days
Driving	132.5 man days

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Manpower

The low level power requirements for small scale water pumping are clearly within the capabilities of manpower, and, especially at the smaller demand levels where other systems, especially diesel power, would be very under-utilized, this should be an economically competitive method.

The technology is simple and, of course, already widely used. It consists of a lift pump operated by a lever, which is normally operated by hand. The alternative of operating the pump by foot also exists, and one method of achieving this has been tried in this area by the Intermediate Technologist at the Family Farms Settlement. This consists of a two-pedal reciprocating device. The user sits with his feet on the pedals and pushes them alternately, raising and lowering the pump piston. Suitable counter-balancing ensures that the effort to lift the piston is reduced, while a positive force is required to lower the piston, so that both pedals require the same effort to operate.

This device was still at the prototype stage during my visit, but tests carried out on it suggested that a continuous output rate of about 105 watts was likely, compared to 93 watts when using a hand-pump (see Table 3). Figures are normalized to same head and pump efficiency).

Table 3 - Operational Data on Foot and Hard Pumps

	Total Head (m)	Strokes per min	Liters per min	Output kw	Stroke m		Force kg		Input kw	Efficiency of Pump
					R	L	R	L		
Foot Pump	20	33	14.2	.06	.6	.6	18	13.5	.105	.57
Hand Pump	20	22	12.6	.053	1.1		23		.093	.57

Source: measurements by author

The figure of .105 kw agrees well with the level of power to be expected, for one hour continuous operation, calculated by Weir[1], but the power input to the hand pump is well beyond Weir's expectation. The reason for this is probably that Weir's figure is for hand-cranking, which is entirely a hand-arm operation, whereas the hand-pump tested (again a design of the Family Farms Intermediate Technologist) is a long beam which requires pushing down with almost one's whole weight, thus utilizing the muscles of the back, arms and (partially) the legs for operation.

This leads to the conclusion that the power disadvantage of a properly designed lever-pump is not very large compared to a foot power pump. The advantage of the foot pump rests mainly on the opportunity to do other tasks with the hands, or read, while pumping, and increased comfort of operation, leading to longer operating times.

The cost of this hand-pump (over and above the cost of the lift pump and piping) is very low—it consists of a long wooden beam, two support posts set in the ground, and chain for the linkage. The time taken to build and install it is 3-4 man days of local labor.

The cost of the foot pump is relatively substantial since there are several levers, pulleys and cable plus the basic hand-pump equipment, and manufacture by welding or drilling and bolting is necessary.

On the basis of the prototype, material costs are probably £10-15, manufacturing time (skilled labor) three days, and installation time eight man days unskilled and two man days skilled labor.

1/ A. Weir, Dyapods—the efficient use of human energy in rural development in underdeveloped countries.
I.T.D.G. and School of Engineering Science, Edinburgh, 1972 (mimeo).

Table 4 - Capital and Running Costs of Man Powered Systems

System 1: Demand 9,000 meter liters/day (wet season)

15,750 meter liters/day (dry season)

Capital Cost

Pump	£20
Rods	15
Piping (@ £/10 ft)	22.50
Pump Handle	2
	59.50

Labor

Installation 3 days artisan

Running Costs

Repairs (say) one man day per year

Labor one hour/day (wet season)

0.7 hours/day (dry season)

System 2: Demand 18,000 meter liters/day (wet season)

54,000 meter liters/day (dry season)

Capital Costs (as above)

Pump, etc.	£59.50

Labor three days artisan

Running Costs

Repairs one day per annum

Labor 1.2 hours/day (wet season)

4.4 hours/day (dry season)

System 3: Demand 30,000 meter liters/day (wet season)

142,500 meter liters/day (dry season)

Capital Costs (as above)

Pump, etc. £59.50

Labor three days unskilled

Running Costs

Repairs one day per annum

Labor two hours/day (wet season)

9.4 hours/day (dry season)

System 4: Demand 120,000 meter liters/day (wet season)

345,000 meter liters/day (dry season)

Capital Cost

Dry season demand cannot be supplied by a one-man unit, and not realistically by a two-man unit (22.8 man hours per day are required, and eight hours per day would be a likely absolute maximum for this work).

This larger system will require a slightly larger pump (an extra cost of only £2-3) and a more sophisticated arrangement of the handle, allowing three men to work it; costing perhaps twice the basic estimate.

Capital Cost

As above + £4.50 = £64

Running Costs

Repairs (say) two man days per year

Labor

Eight hours/day (wet season)

22.8 hours/day (dry season)

Diesel Power

1. General

Diesel engines are one of the most widely used sources of power, both as regards the technical purpose and geographical situation of use.

The technology of diesel engines is now well known, and as a result an extensive range of engines is available from many manufacturers. The technology is also very highly developed, and corresponding machines from different designers are usually very competitive both in price and performance.

Diesel engines may be classified in two distinct ways—power output and running speed.

As regards power output, commercial units are available with outputs from 1.5kw to over 1,500kw.

Running speed is a very important variable in diesel engine design. Small engines up to 10kw can be divided into three classes:

(a) Low speed (1,000rpm and below)—These engines are "heavy duty" engines. All large diesel engines used for electricity generation are low speed engines, and there are also a few small diesel (down to 5kw) which are designed to operate at low speeds. The major objective of low speed operation is longevity, and although no absolute figures are quoted, it is known that a well maintained, intermittently used low speed diesel will last up to 50 years, and near-continuous operation should still result in a life of over 15 years. Even with the poor maintenance (and also poor system design—see later) often found in developing countries, small low speed engines still survive for many years, and it is thus most common to find this type of engine, usually a Bamford or a Lister, used for rural generation and pumping.

A low speed engine is characteristically very heavy, very robust, moderately economical as regards fuel (around 0.5lb/bhphr in the power range up to 10kw), and very expensive. Because of the characteristics noted, low speed small diesels are used invariably as stationary engines for driving pumps, electric generators or other systems where long hours of operation and/or high reliability are required;

(b) Medium speed (approximately 1,000-2,000rpm)

Relative to low speed engines, this group is certainly much lighter (an 8bhp medium speed engine may weigh under one-third the weight of a low speed engine of similar output), a lot cheaper per unit of power, and quite economical on fuel. General comments on fuel consumption are difficult to make, but only considering low power engines, it seems that medium speed engines are marginally the most economical, although the now discontinued range of Bamford low speed engines were very economical, whilst low and high speed engines are slightly less economical on average. Often, however, variations within a group are more significant than variations between groups. It is difficult to judge the relative longevity of higher speed engines compared to low speed engines. Although manufacturers claim that medium speed engines are designed to last just as well as low speed engines, experienced users in developing countries generally buy low speed engines, despite the price premium of around 100%. It may well be that low speed engines are far more tolerant of poor servicing, and for that reason are often more reliable and longer lasting when used in developing countries;

(c) High speed engines (2,000 plus rpm)

The probable disadvantages of higher speed engines have been noted above, and apply even more in the case of the highest speed units operating at over 3,500 rpm. Against the possibly shorter life and marginally higher fuel consumption must be balanced (relatively) very low weight and low cost. The weight characteristic particularly has lead to the use of these engines in mobile units, or as the power source for vehicles.

As examples of the differences between these classes of engine, a typical 8bhp unit from each group is described below.

Table 5 - Fuel Consumption and Cost Data on Diesel Engines

Unit	Consumption lb/bhp.hr	Weight lb	Price £	rpm
Lister 8/1	0.50	777	223.00	850
Petter PHI	0.43	408	185.00	2,000
Petter ACI	0.45	104	136.00	3,000

Source: Manufacturers' published data.

2. Factors in the Design of Diesel Powered Systems

The most noticeable common aspect of rural diesel installations for pumping water and generating electricity is that the engine is nearly always too big for the job. There are several reasons why this may be:

(a) so that the engine is run below its maximum output, in the hope that it should last longer (this may stem from experience with petrol engines, particularly in cars);

(b) to allow room for expansion so that the system capabilities can be enlarged without recourse to a new, bigger engine;

(c) to cope with peaks in demand, thus having over-capacity for all other times.

In fact, diesel engines are specifically designed to run near to maximum power. Used thus, they utilize the fuel most efficiently, burn it more cleanly, and so avoid "carboning-up" (i.e., becoming internally dirty) and will generally run better and for longer without trouble.

Diesel engines are often seen driving "force" pumps. This type of pump has a piston which, on being lifted, pulls a column of water up towards the surface. Valves then close, and the piston is lowered back to the bottom of the cylinder ready for the next lifting stroke. It is quite obvious that this is a completely unsuitable load for a diesel engine, for the following reasons:

(a) the load on the engine is very small during the downstroke--indeed the piston may well fall under its own weight. Thus for half the cycle (probably three or four power strokes for the engine) the load is much below that needed for clean, efficient engine operation;

(b) rudimentary power calculations, together with the limitation that the cumbersome pump mechanism (which, in the case of a typical borehole involves about 100 ft of steel rod being pulled up and down) can only operate safely at low speeds, show that such a system cannot possibly utilize the level of power available from the motor, even assuming that a very large pump is used.

Criteria for designing a pumping system driven by a diesel should be:

(1) the pump should need a non-varying driving force;

(2) the pump should be capable of utilizing the full power of the engine;

(3) inasmuch as the output of the engine exceeds that power required for supplying daily needs, the limitation in output should be effected by reducing running time, not output rate. Further, if possible, it is more economical to use a pump which runs at the same speed as the engine, thus eliminating the need for a gearbox.

The so-called "Mono" pump in fact meets all these requirements. The pump is physically very simple, involving a sleeve in which a helical corkscrew is rotated, thus lifting water. The sleeve is made of a rubberized material and is very resistant to wear by small particles which may temporarily be trapped. The inside of the sleeve is in fact a double-helix which ingeniously contrives to make the pump a positive displacement device, i.e., when it is not rotating, water does not run back through it as would be the case with, say, a centrifugal pump.

The last advantage of this type of pump is that it is very small in diameter, unlike most rotary pumps, and thus is ideally suited to use in boreholes.

3. The Diesel Power Solution

The range of diesel engines available has been described above. Clearly a significant trade-off exists between reliability/longevity and initial price—a point not disputed by the manufacturers.

"If longevity, simplicity of operation and minimal service standards are your criteria, then the choice must be the slow speed, 6/1 engine. On the other hand...if price is the most relevant factor...the (high speed) range should prove perfectly satisfactory." 1/

The cost of a slow speed engine is roughly twice the cost of a high speed engine. This is a substantial premium to pay, but one which diesel users seem prepared to pay. The vast majority of diesel engines which I have seen installed in rural areas for pumping water or generating electricity are of the Bamford or Lister low speed type. In discussion, the staff of Tarry's Ltd. (one of the biggest suppliers of farming and allied equipment in Zambia) suggested that the newer high speed diesels were not nearly so reliable as the older low speed designs—it was not uncommon to perform the first service on a low speed engine after ten years of operation—and they would still recommend this type of engine.

There are two further reasons for preferring the low speed type. Firstly, given the difficulties of transport and communication to the

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1/ Letter from Lister Ltd., 1974.

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rural areas, and the uncertainty of supply of spare parts, minimization of servicing and repairs is a very high priority. Secondly, economic use of a diesel driven pump will imply that a relatively large system depends on the output; many animals, or a lot of irrigated land. This being the case, reliability of supply is more important than in a smaller system, where temporary alternative supplies by human transportation on bullock cart are quite feasible.

Thus, one of the diesel powered systems considered here utilizes a low speed Lister engine.

Of the two models available, the air-cooled "VA" is chosen, being the simpler in that it has no auxiliary water cooling system which could fail, resulting in over-heating and damage to the engine.

There are also arguments favoring the use of a high speed engine, besides initial price.

First, the engine is much smaller and lighter, and installation is easier and cheaper. Also the engine can be moved quite easily from one location to another, so that, for example, a system using several identical engines could be "backed up" by a spare engine which could be moved at short notice to replace a broken down unit.

The second advantage of the higher speed engine, which stems from the lower initial cost is that within five years, rural electrification may have taken place, and a source of power with variable costs lower than for a diesel system may make replacement economic. In the case of the high speed engine, replacement may be needed anyway--whereas the low speed engine would be fit for perhaps ten more years use—longevity paid for in the initial investment, and subsequently wasted.

Manufacturers are unwilling to commit themselves on questions of longevity and servicing costs, but the combination of my own correspondence with Lister's and a report by the Brace Institute, which refers to Firm "L", and engines with the same model numbers as Lister's, enables a confident estimate to be made—particularly, as the Brace report notes (p 30), since the comments of Firm "L" on the figures in the report implicitly acknowledge the accuracy of the estimates.

Thus, for the low speed engine, a life of 15 years is assumed, and maintenance charges are taken as 7-1/2% of capital cost per annum, though this figure is open to some debate.

The method of project analysis being used requires that all costs be taken at world prices. Where a good is not a traded commodity (i.e., one for which an import or export price has been determined), the good is valued by trading its components back until traded goods are found. Thus, of the maintenance costs, probably half will consist of the actual replacement parts, which clearly are traded goods which are valued at import price, while the remainder will comprise largely the labor cost of the service.

Whilst it may seem inaccurate at first glance not to decrease the wages component of the maintenance cost when converting to "world" prices, the excessively high wages paid in Zambia mean that the actual cost (in Zambia) of service may well substantially exceed the 7-1/2% level, and it is assumed here that deflation of the cost to world prices would merely put the service cost back to the "normal" level.

The most difficult problem in predicting the costs of operating a diesel engine is the behavior of fuel prices. Until recently prices of refined and crude products have been quite stable, and, since Zambia imports fuel, the "world price" was easily established. Since December, 1973, however, there has been a dramatic rise in oil prices:

Date	Price[1] ($/barrell)
April 1972	2.30
November 1972	2.30
May 1973	2.28
September 1973	2.41
December 1973	3.50
February 1974	8.95
April 1974	9.07
May 1974	9.20

This situation is so recent and the changes so rapid and large that it is impossible at this stage to predict likely future prices.

Relevant, but hardly dependable points which can be made are that the peak in prices (on the free market) seems to have passed, and that the producing countries have stressed that they hope to avoid any severe repercussions of the increased prices against less developed countries.

It may be that the present level of prices will continue (as far as less developed countries are concerned), or at least will not rise at the recent rate.

In predicting operating costs, therefore, the current price of about $9.20 per 35 gallons is used as a base with alternative calculations assuming a 5% increase rate in oil prices.

The costs predicted by Brace, which were apparently accepted by Lister (see above) were for the slow speed type of engine. My own correspondence with Listers confirms that the higher speed engines will be shorter lived, less reliable, and also more expensive to repair (since

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1/ Prices are for refined diesel fuel from "Petroleum Economics".

the construction is more complex). No actual relative figures were obtainable, but it is assumed for the purposes of calculation that the life is reduced to ten years, and the maintenance cost (as a percentage of initial cost) is doubled.

Figures such as this must always be speculative, but the information described above, plus conversations with suppliers in Zambia, seem to justify these assumptions.

Table 6 - Cost Data for Low and Medium Speed Diesel Powered Systems

Capital Cost (cif)	Lister VA (low speed)	Lister SRI
	£	£
Engine:		
Capital Cost 1/	314.80	147.00
Pump	(Mono B620) 111	(Mono A420) 77
Drive Head	180	44
Shaft	55 2/	38 2/
Stabilizers	8	8
Frame	63	40
Clutch	66	31
2" Main.	57 2/	35 2/
	854	420

1/ Including cooling air ducts, far screen, air cleaner, oil filter, pulley and speed control.

2/ For pump sited at 25 meters depth.

Installation (labor requirements)

	Man Days	
	Unskilled 1/	Skilled 1/
1. Dig Foundations	1	
2. Make Bricks 2/ (1,700)	25	
3. Lay Foundations		2
4. Build Hut	5	
5. Install Engine	1	1
	32	3

Running Costs

	Lister VA	Lister SRI
Maintenance		
Engine	18.75	22.05
Pump	14.72	7.44
	33.57	29.49
Fuel Consumption (lb/ 100,000M L/day 5/) (based on specified pump performance)	.626	.612
Cost (per year)	£2.78	£2.72

Summary

Initial Cost 1/	Lister VA	Lister SRI
	£854	£420
Life	15 years	10 years

Variable Running Costs

System 1

Average output over year: 12,375 meter liters per day

$$\therefore \text{Annual fuel costs} = 2.78 \times \frac{12,375}{100,000}$$

$$= £.3444 \text{ (low speed engine)}$$

$$\text{or } 2.72 \times \frac{12,375}{100,000}$$

$$= £.336 \text{ (medium speed engine)}$$

System 2

Average output over year: 36,000 meter liters per day

∴ Annual fuel costs = £1 (low speed engine)

= £.98 (medium speed engine)

System 3

Average output over year: 86,250 meter liters per day

∴ Annual fuel costs = £2.45 (low speed engine)

∴ Annual fuel costs = £2.35 (medium speed engine)

System 4

Average output over year: 237,000 meter liters per day

∴ Annual fuel costs = £6.46 (low speed engine)

∴ Annual fuel costs = £6.32 (medium speed engine)

1/ Labor is classified as artisan where local people could perform the job without training.

2/ Quoted by F. Longland in "Field Engineering" from Kenyan Public Works Department.

3/ According to "Mono Ltd.", 3% p.a. is an adequate maintenance allowance for operation in Africa.

4/ Assuming fuel consumption as quoted by makers, allowing for altitude de-rating, all as per B.S.649 specifications.

5/ Fuel consumption is based on a unit of 100,000 meter liters/day, i.e., the fuel needed to raise 1,000 liters per day from 100 meter depth, or 10,000 liters/day from ten meter depth, etc.

Methane Power

Pure methane is a colorless, odorless gas which occurs in nature in association with coal and oil deposits. The gas can be produced by distillation of coal, and methane from this source was widely used for heating and lighting.

Methane is also produced during the decompoistion of organic materials in the absence of air (anaerobic decomposition). This can occur naturally—marsh gas or "Will o' the Wisp" is a well known example.

As a source of power, methane, which burns easily and steadily in air, has considerable attractions.

Firstly, it is ecologically a very acceptable process. The inputs to the manufacture of the gas can be almost any animal or vegetable waste, including dung and offal, or deliberately "harvested" vegetable matter (grass, leaves, etc.). Even if vegetable matter is the major feedstock, it is necessary to include some animal waste or offal to maintain the process, since the presence of some nitrogen is essential. Many of the inputs to this process could normally be the constituents of compost for fertilizer, but the methane process has a clear advantage, because the residue from methane production is a better fertilizer than the compost. This is because the decomposition takes place in an airtight, watertight container (composting is done in the open air) so that nitrogen, the most important constituent of the fertilizer, is prevented from escaping in the form of ammonia (NH_3), and other soluble materials do not back away.

In India, dung is a widely used fuel for cooking. Again, the use of dung in a methane plant would be more desirable, since then its fertilizing properties are still available, even after the energy has been tapped.

The second attractive characteristic of methane as a power source from the ecological viewpoint is that the products of combustion, carbon dioxide and water, are harmless. It is possible that if the combustion is incomplete, carbon monoxide may be produced. Although poisonous if inhaled, this gas will quickly oxidize to carbon dioxide, so that arrangement of the flue so that the gas is emitted at some distance from any people easily overcomes this potential danger.

A further advantage in the context of use in developing countries is that the technology is very simple, and all the required equipment can easily be provided locally.

The Technology for Production

As indicated above, a methane generating plant is basically a sealed tank, usually referred to as the digester, in which the decomposition takes place. This is connected to another tank (the gasometer) where the gas is collected (see Figure 2). Alternatively, the gasometer/digester can be in a single unit, with the gas collecting above the decomposing sludge. Although somewhat simpler, this necessitates stopping gas supply during recharging of the digester.

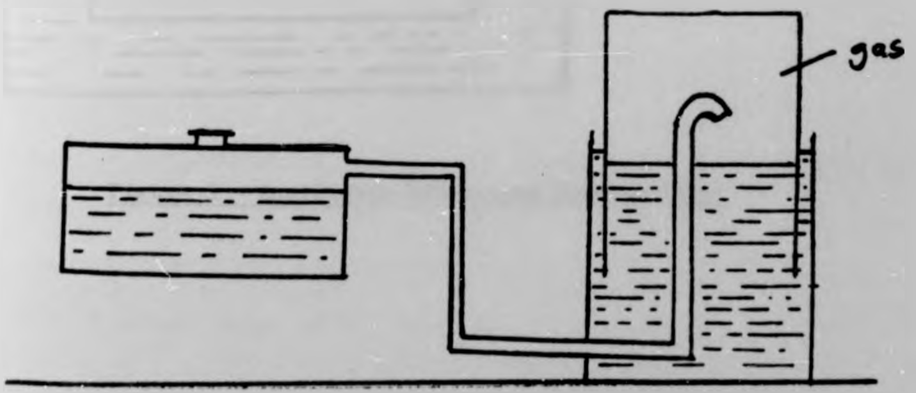

Figure 2 - Methane Gasometer

Figure 1 shows a simple layout, utilizing oil drums of different sizes. Larger units working in the same manner can be constructed using concrete containers built at the site.

The method of operating such a unit is to partially fill the digester with a mixture of three parts dung to one part grass (by dry weight) for the initiation of the process, then for successive charges, a ratio of 1.5 or 2:1 residue of the previous fermentation to grass is adequate to restart gas production. This type of process, where one charge is fermented until the gas ceases to be produced, the sludge is removed and another charge initiated, is called batch production.

Alternatively, continuous production is possible (Figure 3).

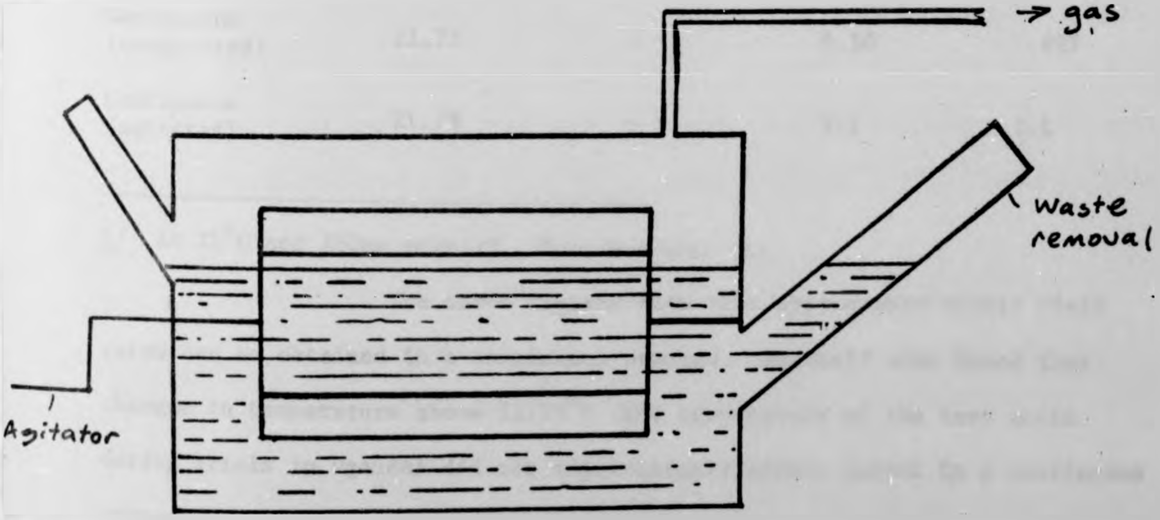

Figure 3 - Continuous Production Methane Plant

Here, provision is made to feed new grass into the fermenting mixture, and to remove exhausted waste, without interrupting the process. An agitator is needed in this case to keep the sludge mixed.

Comparison of continuous with batch production shows that the more elaborate continuous system produces methane rather more quickly, but produces less methane per unit of feedstock.

Typical production figures are:

Table 7 - Methane Production Data

Method	Temp. °C	Length of Fermentation	Predicted Production	
			cu.ft/lb 1/ Feedstock	Digester 1/ vol/day
Dung + Grass	32	40	9.36	.52
	21.75	40	3.78	.24
	21.75	60	6.57	.26
Residue + Grass	32	40	5.98	.41
	21.75	40	6.81	.348
Continuous (unagitated)	21.75	-	5.10	.827
Continuous (agitated)	21.75	-	5.1	1.1

1/ At 21°C and 660mm mercury From Boschoff (1).

The above figures show that appreciably higher yield rates can be obtained in a continuous process. Boschoff also found that changes in temperature above 21.75°C (the temperature of the test units during trials in Uganda) did not significantly affect output in a continuous process.

Boschoff reports that about 40% of the gas produced in the continuous process is methane. Elsewhere, the proportion of methane (2) in the gas produced is given as 52-63%. This may well reflect a higher proportion of animal waste in the feedstock.

The Technology for Use

There are three ways in which methane could be utilized as a power source:

(i) as a heat source for cooking, etc. in the way that town gas is now used in developed countries;

(ii) as a fuel for a conventional petrol type engine or steam engine;

(iii) as a fuel for a machine specifically designed to run on methane.

Methane is not a particularly attractive source of heat for cooking in the environment under consideration. Wood is readily and widely available, and used either directly or as charcoal. Tree conservation is not a problem over the vast majority of Zambia; around the major urban centers such as Lusaka and Ndola there is restriction of the activities of charcoal producers—and even there, the "restriction" is more designed to ensure planned use of resources than as a result of a serious fear of shortage. In farming areas, proper clearance of trees is a benefit rather than a cost, since this is often the major constraint on farm size (3).

Solar power for cooking is in any event a better alternative to charcoal or wood than methane. It is normal to eat the main meal at about 11 am in southern Zambia, and the very plentiful sunshine ensures the feasibility of solar powered cooking.

Used as an alternative fuel for a petrol-type internal combustion engine, methane has the apparent advantage of being a fuel which, if not free, is virtually free for the taking.

It is quite feasible to use methane as a fuel for an internal combustion engine with spark ignition (i.e., a petrol-type engine, not a compression ignition diesel type engine). Some manufacturers offer kits for conversion fo running on gas—usually propane—which with slight modification could be used for methane.

An expert[1] in this field, however, suggested that although the life of some engine components (piston rings and sparking plugs) will be extended, other parts will wear more quickly, and considerable care and some re-design may be required to ensure satisfactory valve wear. On this basis, unless diesel fuel is very expensive, diesel engines are preferable to methane-fueled petrol-type engines.

Since it will be shown that methane can be used more efficiently, in a cheaper installation, the use of methane to fuel a spark-ignition engine is ruled out.

A steam engine fuelled by methane has some similar disadvantages. Again, methane as a fuel can be more efficiently used in a different machine (see below), therefore if pumping capacity rather than mechanical power is needed, the solution described below is the best way to utilize methane.

The Humphrey pump is a device designed to pump water using methane or some other gas. It is shown diagrammatically in Figure 1.

It operates rather like a single-cylinder internal combustion engine, the most obvious difference being that instead of a solid piston, the fluid being pumped forms the seal in the cylinder.

1/ I am indebted to Mr. C.A. Beard of Ricardo Engines Ltd. for invaluable advice on the possibilities of methane as an alternative fuel for petrol engines, and the relative merits of petrol- and diesel-engine designs.

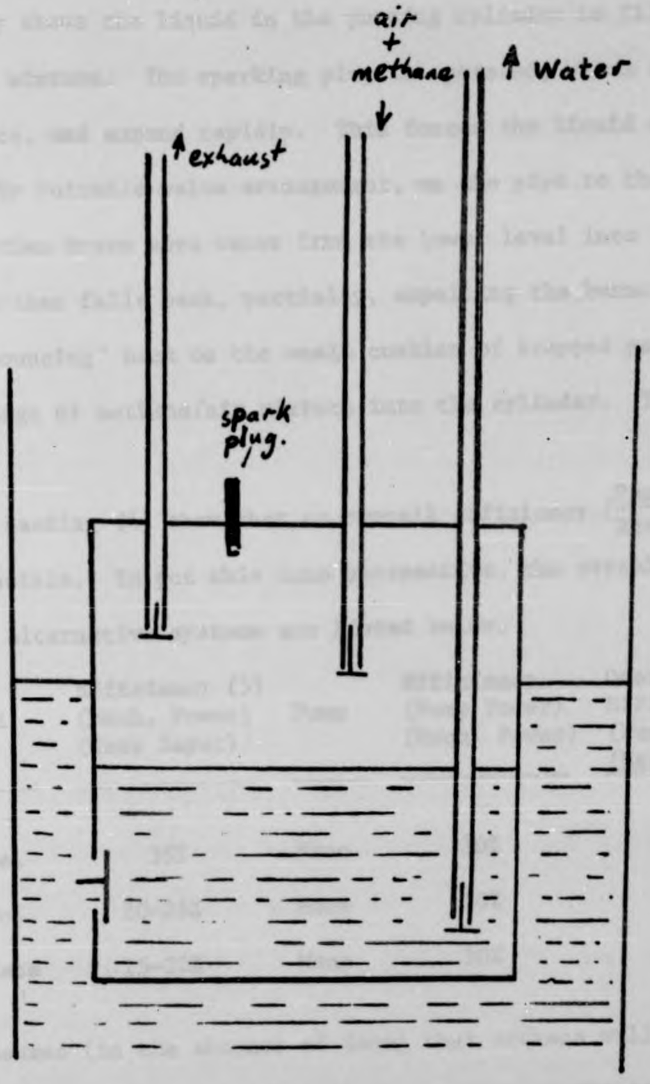

Figure 4 - The Humphrey Pump

The cavity above the liquid in the pumping cylinder is filled with an air/methane mixture. The sparking plug is operated, which causes the mixture to ignite, and expand rapidly. This forces the liquid out of the cylinder, and, by suitable valve arrangement, up the pipe to the storage tank. This action then draws more water from the lower level into the pumping system. The column then falls back, partially, expelling the burnt gas from the cylinder and "bouncing" back on the small cushion of trapped gas, thus drawing a fresh charge of methane/air mixture into the cylinder. The stroke is repeated.

Tests at Reading (4) show that an overall efficiency $\left(\frac{\text{Pumping Energy}}{\text{Energy in Gas}}\right)$ of about 20% is possible. To put this into perspective, the overall efficiency of some alternative systems are listed below.

Engine	Fuel	Efficiency (5) $\frac{\text{(Mech. Power)}}{\text{(Heat Input)}}$	Pump	Efficiency $\frac{\text{(Pump Power)}}{\text{(Mech. Power)}}$	Overall Efficiency $\frac{\text{(Pump Power)}}{\text{(Heat Input)}}$
Compression Ignition	Diesel	35%	Mono	30%	10%
Spark Ignition	Petrol	20-25%	Mono	30%	7%
	Propane	15-20%	Mono	30%	5%

It is assumed (in the absence of data) that methane will perform similarly to propane, about 5% of the heat value of the gas being available for pumping. Thus, the Humphrey pump, with an overall efficiency of 20%, and a lower capital cost than a diesel or petrol engine, is clearly the best way to utilize this source of power.

Methane Powered Solution

The most effective way to use methane gas for water-pumping is by use of a Humphrey Pump (4).

The cost of such a device has not been estimated in detail, but should be "considerably less" than a comparable diesel unit, with greater flexibility in the choice of materials and less demanding tolerances for manufacture (4). Furthermore, and especially relevant to small scale use, it can easily be made in small sizes, suitable for supplying the levels of water demand envisaged here (whereas only relatively very oversized diesels are available, which, for the lowest demands considered, produce a day's requirements in a few minutes).

The capital cost versus power output of medium speed diesels has been plotted in Figure 1. This shows a clear relationship, of the form:

Cost = Constant + Fx Power

If cost is in pounds and power in kilowatts,

Cost = 120 + 13.5xPower

In fact, the curve is discontinuous since no engines are available with a power output below 2.5 kw.

This constraint should not apply to Humphrey Pumps, where the dimensions can easily be adjusted to reduce output.

Thus, by making an assumption about the ratio of costs of diesel engines to Humphrey Pumps, and assuming this to hold over the range considered, likely costs of Humphrey Pumps can be projected.

The Humphrey Pump is clearly far more simple than an internal combustion engine, it has no piston, crankshaft, gearing or any close-tolerance dimensions except the valves; further, its structural specifications do not require the extreme stiffness of an internal combustion engine. It seems that a substantial cost advantage can be expected, therefore, but any estimate must of course be tentative. This being the case, the costs have been compiled for three possible cost ratios:

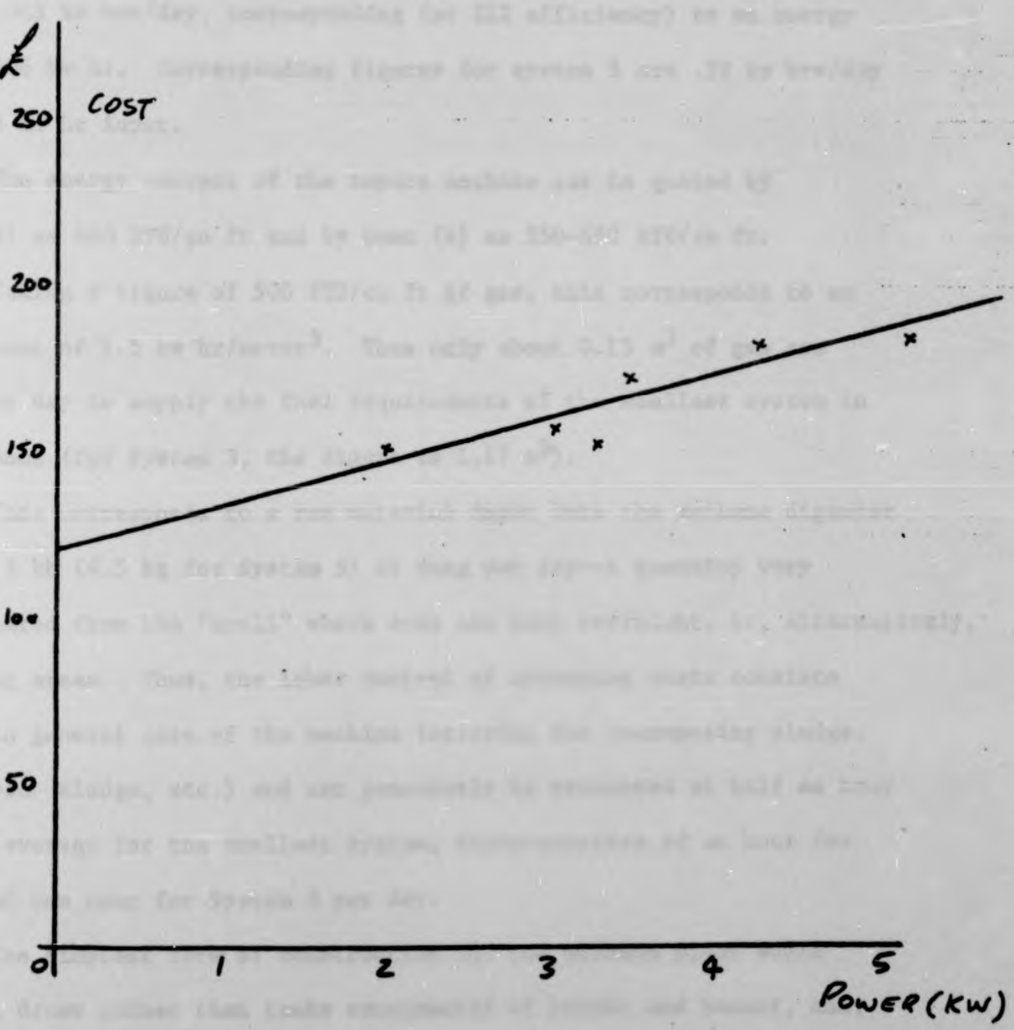

Figure 5 - Cost of Power for Diesel Engines

(1) a "most likely" estimate of a 2:1 advantage;

(2) a pessimistic estimate of a 1:1 ratio;

(3) an optimistic estimate of a 5:1 advantage.

The efficiency of the Reading design is 21%. The *maximum* (i.e., dry season) energy output in terms of water pumped for the smallest system is .043 kw hrs/day, corresponding (at 21% efficiency) to an energy input of .206 kw hr. Corresponding figures for system 3 are .39 kw hrs/day output, 1.8 kw hr input.

The energy content of the impure methane gas is quoted by Boschoff (6) as 460 BTU/cu ft and by Dunn (4) as 550-650 BTU/cu ft.

Taking a figure of 500 BTU/cu ft of gas, this corresponds to an energy content of 1.5 kw hr/meter^3. Thus only about 0.13 m^3 of gas are required per day to supply the fuel requirements of the smallest system in the dry season (for System 3, the figure is 1.17 m^3).

This corresponds to a raw material input into the methane digester of about 0.5 kb (4.5 kg for System 3) of dung per day—a quantity very easily gathered from the "krall" where cows are kept overnight, or, alternatively, from grazing areas. Thus, the labor content of operating costs consists primarily in general care of the machine (stirring the decomposing sludge, removing spent sludge, etc.) and can generously be estimated at half an hour per day on average for the smallest system, three-quarters of an hour for System 2 and one hour for System 3 per day.

The simplest form of construction for the methane plant would utilize oil drums rather than tanks constructed of bricks and cement, and, with welding apparatus, should be easily constructed by a skilled man in three days. Installation of the storage tank could be done by unskilled labor in 3-4 days, with skilled supervision, and installation of the pump would probably take a similar time.

The pump considered for Systems 1-3 is not adequate for System 4, a unit some 2.3 times larger being required. In terms of Figure 1, this is still a power level very close to the y-axis (i.e., the "fixed cost" level of the diesel cost versus output curve) but some increase in cost over the estimates used in evaluating systems 1-3 must be expected. This increase is assumed to be 20%.

Table 8 - Summary of Methane Production Costs

System	Pump Costs High £	Pump Costs Medium £	Pump Costs Low £	Methane Capital £	Plant Installation Labor Skilled Days	Plant Installation Labor Unskilled Days	Running Costs (labor hours)
1	120	60	24	20	5	7	180
2	120	60	24	20	5	7	225
3	120	60	24	20	5	7	270
4	144	72	29	20	5	7	360

(1) W.M. Boschoff, Methane Gas Production by Batch and Continuous Fermentation Methods, Tropical Science, Vol. V, No. 3.

(2) Processing and Utilization of Animal By-Products, FAO Agricultural Development Paper No. 75.

(3) A.C. Fish, the Charcoal Industry in Zambia: A Preliminary Study. Economic Note No. 1/73 Forest Dept. Ndola 1973.

(4) P.D. Dunn. Humphrey Pump for Use in Developing Countries, Paper to University of Edinburgh Appropriate Technology Conference, September 1973.

(5) Small Scale Power Generation, United Nations, Department of Social and Economic Affairs, 1967.

(6) W.M. Boschoff. The Application of Methane Installations in the Tropics (mimeo).

Windpower

A mass of air moving over the surface of the earth has, by virtue of its motion, a quantity of energy stored in it. By slowing that body of air to a lower speed by means of a mechanical device, some of that energy can be extracted and put to some other chosen use. Wind machines, be they sailing boats or windmills, all use this phenomenon to redirect the energy content of the wind to some "useful" activity from man's point of view. The attractiveness of the wind as a source of energy is that the energy is free— that is the fuel cost of the device is zero and the source of energy is already distributed over remote areas without the need for pipelines, power cables or railways carrying coal. The energy content of wind is substantial. The amount of energy is:

$$p = .000638\ A\ V^3 \qquad (1)$$

where P = power (kw)

A = cross sectional area of wind stream (m^2)

and V = wind velocity ($m\ sec^{-1}$)

For example, in a relatively low wind speed of 4 $m\ sec^{-1}$ (about 9 mph), the energy in an airstream 10 meters by 10 meters is over 4 kw, a substantial amount of power. Since airstreams may often be measurable in square kilometers rather than square meters, it is obvious that this is a very large untapped source of power.

Of course, although the total amount of power stored in the wind is substantial, there are retrieval problems. These fall into four main categories:

(1) Variability of the Windspeed: Whilst a diesel engine or mains electricity can be switched on and off at will, the timing of the wind, though often broadly predictable is never certain, and the speed of the wind (and

note that the energy in the wind is a function of the speed cubed) is even less certain. So if definite demands must be met, a storage system must be used to ensure supplies during calm periods.

Further, apart from variation of the wind over time, wind also varies considerably from place to place. On a local scale, the site of a well may be in a sheltered area where the wind is much lower than in other areas nearby. On a larger scale, too, the apparent suitability of an area must be closely tested. For example, roughly half-way between Lusaka, which is the windiest place in Zambia, and Livingstone, another area having relatively high winds, lies Choma, where the winds are by far the lowest in the whole country, with each day having as much as 30% no-wind conditions (comparable figures for Lusaka and Livingstone are 1% and 13% respectively) (2).

(2) Equipment Efficiency: Analyses have been made by A. Betz (1) and others on the theoretical efficiency of various types of wind machine. Here, however, the concern is with the practical efficiencies at which actual machines operate. The most modern high speed machines extract nearly 50% of the actual available energy in the wind, whilst the common multi-bladed fan mill is above 30% efficient, a little less than the four-sailed Dutch type. Other machines are even less efficient, the worst (but also the cheapest) being less than 10% efficient.

(3) Size of Equipment: Air is not a dense medium, and this means that large machines are needed to extract worthwhile amounts of energy from it. It may well be reasonable to conceive of airstreams of very large dimensions, but the practical problems of wind machines greater than (say) 20 meters diameter are severe. This does have the advantage that any action in this field by man is very unlikely to have significant climatic

or other effects.

Despite these problems, some very large machines have been designed and built with power outputs as high as 1,250 kw (3).

(4) <u>Cost of Equipment and Comparison with Alternatives</u>: As a result of the size and efficiency factors mentioned above, windmills tend to be expensive by comparison with more conventional equipment for power generation. Attempts have been made (4) to compare the cost of generation by diesel power, particularly with the cost of generating from wind power. A criticism which applies to all such studies seems to be that by using a depreciation method of cost calculation which spreads the initial cost of the windmill over the years of its life, the fact that a windmill costs so much more initially[1] seems to be balanced by the recurring fuel costs of the diesel.

A more rigorous D.C.F. analysis highlights this fact, which is of particular note in the case of a capital-short developing country. On the other hand, the sensitivity of the diesel-power solution is never tested with respect to the price of the fuel, which may well be a most important variable.

Another example of an attempt to demonstrate the competitiveness of wind power is a report by the Brace Research Institute (5).

Here, as well as using the straight-line depreciation method for calculating the <u>annual</u> "depreciation cost", two factors are introduced to allow for the expected reduction in capital costs resulting from larger scale manufacture of the machine. The first factor, suggested by Golding, is an estimate of the likely unit cost reduction resulting from producing 40 windmills instead of one. Golding suggests a figure of 0.7. As an

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[1] For example, a 2 kw diesel generator costs under £300, whilst a 2 kw wind generator costs over £1,000 <u>excluding</u> storage batteries.

alternative, research by Masefield (5) has shown that in the light aircraft industry, a 20% unit cost reduction results for each doubling of the number of units produced.

This factor would suggest that a production run of 40 would yield a unit cost of 0.3 times the original one-off cost.

The prototype cost of the Brace windmill is $9,000, composed of $6,000 for materials, and the rest for fabrication. The design sensibly incorporates mass produced items wherever possible; the back axle of a lorry is used as the power transmission unit for example. This being the case, it seems highly unlikely that the sort of cost reduction figure calculated by Golding is relevant, since major components of the system will not be affected in price by the very small increase in demand represented by 40 windmill units. The further application of the light aircraft factor (actually an average of the light aircraft factor and the Golding factor is used) is even more difficult to justify, since this reduces the total cost of the machine to less than the original materials cost! Furthermore, the cost of maintenance, new parts and lubricating oil is taken as a percentage of initial capital cost, though why oil consumption (or even maintenance costs) per unit should decrease with production rate is not made clear.

It is also noticeable that cost calculations in "economic viability" reports tend to use quite high mean windspeeds. Of course these occur, but, for example, in the Economic Possibilities of Windpower (1), the "Possible Energy Costs" are calculated for 10, 15 and 20 mph, whilst a list of 45 selected wind stations shows that none has a 20 mph mean windspeed, 20% have 15 mph and only 70% have even 10 mph.

Thus it is necessary to analyze in some detail the various methods by which windpower can be utilized, and the wind regime in which they are to be used.

Machine Types

Wind driven machines can be classified in several ways; by speed of rotation, axis alignment or final usage of the power, for example. It is not the intention of this study to list windmill types exhaustively, but rather to assess those relevant to the need for pumping power on the particular settlement in question (though mention is made of units of particular interest to developing countries generally). The machines are listed in a roughly ascending order of complexity.

The Jumbo-type Wind Machine: Many examples of this machine are described by Barbour (6). The machine consists of a box, with an open top, at which level an axle is mounted horizontally. Large paddles are attached to the axle, and, being shielded from the wind when below the level of the box top, the force of the wind on the upper paddles tends to rotate the

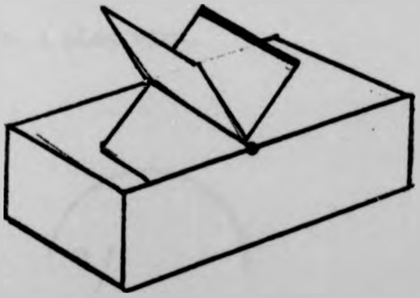

Figure 6 —"Jumbo" Mill

axle. This is a very crude and inefficient machine, suitable only where the wind is very reliable in direction (the box was often very large, perhaps 10 meters wide, and not adjustable directionally) and strength so that useful amounts of power may be extracted despite the inefficiency of operation. Inefficiency, of course, should be defined with care. Although such a machine makes use of only a very small part of the energy in the wind, the Jumbo was used mainly in Nebraska, a very windy area and was generally home-made for a few dollars, so that the efficiency in terms of power per dollar invested was high.

The relatively low windspeeds in Zambia make this machine an unlikely proposition, but it is an interesting introduction to the idea of a locally made power source to capitalize on the peculiarities of local conditions.

Similar machines, with the same limitations, have been used in Egypt, the difference being the use of cloth sails, and rotation around a vertical axis.

The Savonius Rotor (7): This device, tested by J. Savonius in Finland between 1925-28, is a vertical axis machine. The rotor consists of two half-cylinders facing one another, with their axes of symmetry somewhat displaced. Figure 7 shows a plan view.

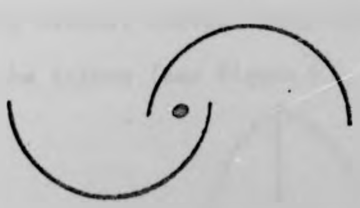

Figure 7 —Plan View of Savonius Rotor

Savonius experimented with various configurations, concluding that:

(i) semi-circular rotor arms are most effective; and

(ii) an overlap of about 1/3 of the diameter of a rotor is optimum.

The effectiveness of a semi-circular rotor arm is convenient, since this cross-section is the most readily available by cutting oil-drums, etc.

The overlap, not intuitively the best solution, causes some re-direction of the airflow from the "open" side into the "closed" side, causing an extra pressure, aiding rotation, on the inside of the "closed" side.

A Savonius Rotor has been constructed using oil drums as the rotors (8) and tested (9) to assess its efficiency as a convertor of wind energy into mechanical energy. The tests conclude that the output of a multi-bladed fan mill is about 1.8 times the output of a Savonius rotor of similar swept area.

Considerations of choice of machine size and load size for a given windspeed distribution are essentially the same as for the multi-bladed fan mill (see below).

<u>The Catenary Bladed Machine</u>: This machine seems to be the only recent innovation in the field of wind power, and it is strikingly simple. It consists of a central rotating column, to which are attached two or three aerofoil section blades, curved along their length and attached to the top and bottom of the column (see Figure 6).

Figure 8 —Side View of Catenary Mill

The curve of the blade is what gives this machine its name. A perfectly flexible blade, under the action of the relevant centrifugal and aerodynamic forces would adopt a catenary shape. Thus, by forming the blades into this shape during manufacture, no bending stresses are induced by operation of the equipment.

Research into the performance of this machine is being carried out at the National Research Council of Canada, by Rangi and South, and their results so far (10, 11) indicate that this is a most promising machine. It is a high speed machine, the ratio of the fastest moving part of the rotor blade (the "tip speed" is the term of wind machine analysis) being about six times the windspeed for the best efficiency, and at this ratio, the machine extracts 36% of the available power from the airstream[1/]. The drawback of the design (which it is hoped will be overcome) is that the machine is not "self-starting". This means that if the wind stops, then restarts, the machine will not pick up speed again. In fact, it will coast at a relatively low speed, but not reach its fully operational speed without external aid. This is of some importance in Zambia, where there are often lulls in the wind.

[1/] Throughout this section, efficiency is defined in terms of the power extracted from the air as a percentage of the total power in the airstream. There is some confusion about this in the literature. Some writers prefer the ratio of the actual power extracted to the theoretically <u>extractable</u> amount of power, as defined by Betz (1). For example, if the total power in an airstream were 1 kw, and the output power of a wind-driven device were .3 kw, then the convention used here would define the efficiency as 0.3, or 30%, whereas the convention used by others, including Rangi and South, would say that the maximum amount of power which a wind machine could extract from the airstream is 0.593 kw (due to theoretical aerodynamic considerations), so the actual extraction of 0.3 kw represents an efficiency of 0.3/0.593 = 0.51, or 51%.

The Rangi and South design has the advantages of simplicity and cheapness. The blades they used were standard extruded aluminium sections, which a developing country could buy cheaply in large quantities, or make without technical difficulty. The design, being a vertical axis machine, requires neither a right-angle drive to transmit the power down to ground level, nor any mechanism to align the device into the wind. It is difficult to estimate costs, but Rangi and South note that the weight of their machine is about 20% of the weight of a similarly rated conventional machine, which, since the manufacturing techniques are comparable, suggests a substantial cost advantage to their machine.

The Fan-mill: The multi-bladed fan mill is the design most used at the moment in Africa, and has probably been the most successful and widely used wind machine ever devised.

It is a low speed machine, having a tip speed to windspeed ratio of less than one for optimum efficiency.

The rotor has many blades, usually 20 or more, and is mounted on a tower, usually six meters or more high.

Attached to the rear of the windwheel shaft is the gearbox. Usually, this converts the rotary motion of the wheel to a reciprocating motion, though records exist (12) of various rotary uses of the power from a fan-mill. The reciprocating motion is ideal for driving a cylinder pump, and this is the usual application.

For safety, the tail vane which aligns the fan wheel to the wind is so arranged that, if the wind speed becomes too high, the wheel is turned edge-on to the wind, effectively stopping it and reducing the risk of damage due to overloading.

The characteristics which have resulted in the success of this device are:

(i) Reliability: Areas where wind power are used are generally remote, and thus servicing, maintenance and repairs are difficult, and breakdowns can have very serious consequences. Fan-mills are of very rugged design, with very large robust moving parts. The gearbox runs in an oil bath, and, whilst the annual recommended maintenance for most makes consists solely of changing this oil, there can be little doubt that machines have been run for many years without even this simple precaution.

Every indication is that this design has a life expectancy certainly in excess of 20 years, and probably without limitation if care is taken in lubrication and corrosion prevention.

(ii) Output Characteristics: Although not the most efficient convertor of wind energy into mechanical energy, the fan-mill has one important characteristic for its usual role as a water pump drive in remote areas: its torque output is at maximum when it is held still in a wind. Thus, it is capable of not only starting without external help, but also of driving a positive displacement pump, which requires as large a force to start it as it does to maintain it in motion. This point is more fully dealt with in Section 3.

The Four-Sail Dutch-Type Windmill: In many ways this design is intermediate between the fan-mill and the high speed airscrew type. Both in operational speed and efficiency it is between the two, though in its heavy, robust design the sail windmill is more akin to a fan-mill. The technology of the design is quite sophisticated, and builders were recognized craftsmen.

The traditional, famous design has been used in Denmark and other European countries, particularly Holland, for over 700 years. The Industrial Dutch type produces about 30 kw and at the height of the importance of wind power many small, commercially-made units were installed on private houses, these being capable of about 3 kw output (4).

The design has a tip speed to wind speed ratio of about 2.5, and is quite efficient converting about 30% of the available power in the wind (4). The torque output is low at start-up, though the machine itself will self-start with the wind. A feature in this design is the use of a small wind wheel at the "back" of the tower which produces power to turn the main wheel into the wind at times when the wind has veered round to one side.

<u>The High-speed Airscrew-type Windmill</u>: This is the most efficient known convertor of the energy in wind into mechanical energy. In general configuration, the machine is like a fan-mill, but the windwheel itself in this case has only a few blades, which are aerodynamically designed and look like the blades of an aeroplane propellor. The machine operates optimally at a tip speed to wind speed ratio of about 7, and may not self-start. It may be that for an optimum operational design (i.e., most efficient conversion of the wind power at the high tip speed ratio) some sacrifice is made in low speed torque characteristics, and thus a self-starting design

is possible but not generally desirable in a windy location.

Experience with these machines is not great. Usually designs have been built, tested, modified, retested, etc. without even establishing the long term reliability. In principle, the reliability should be high, but probably not as good as the fan-mill, owing to the higher operational speed and less robust nature of the components.

The Performance of Wind Machines

It has been noted above that the various types of wind machine have widely varying efficiencies. Also it has been noted that some machines are capable of restarting unaided after a lull in the wind, and that the torque/speed characteristics are different in each type. To appreciate the significance of these parameters, it is necessary to consider the system as a whole, that is the wind regime, the machine itself, and the load it is driving.

Wind Regime: The wind regime in the area under consideration has been studied, though not in sufficient detail to allow precise predictions of specifications of the daily and annual variation of wind speed. The data collected, however, is probably sufficient to allow a reasonable estimate of the variation, and data is currently being collected to confirm this.

On the basis of what is known[1], the characteristics of the local wind are:

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[1] See Annex III.

(1) that it is variable, with occasional lulls during the day, and frequent windless periods during the night; and

(2) that general wind speeds are quite low. The average throughout the year is probably about 6 mph (Lusaka average is 7.4 mph, Livingstone, 5 mph).

Characteristics of the Wind Machines:

(1) Efficiency

The relevant efficiencies of the machines in converting wind power into mechanical power have been mentioned above. In summary, the peak efficiencies which could be expected are:

Jumbo	10%
Savonius Rotor	15%
Fan-mill	27%
Catenary Mill	40%
Four-sail Dutch-type	32%
High Speed Airscrew	45%

(2) Power

(a) Variation of Power Output with Tip Speed to Wind Speed Ratio

The power output of the various wind machines has been broadly specified in terms of the equation for the amount of power in an airstream.

$$P = 0.000638\ A\ V^3$$

and by the efficiencies at which the machines convert this power under optimum running conditions.

"Optimum running conditions" in a given wind will be determined by the geometry of the machine, but some general points are applicable to all machines.

Firstly, treating the ratio of the tip speed to the wind speed as a variable, the machine will clearly produce zero power output when this is zero (i.e., the machine is stopped), and at the other extreme, there will be a speed which the rotor will not exceed, even with no applied load, when the torque, and hence the power output, again is zero. Between these two extremes the power output is positive—though it may not be continuously so. Rangi and South (11) discussing the output of the catenary mill, report that when starting from rest in a steady wind, the machine reaches a no-load equilibrium at a low speed, then needs outside help to "break through" to higher speed operation.

The power output for various machines is shown in Figure 9 (following Golding, ref. 9), with the performance of the catenary mill (following ref. 11) and the performance of a Savonius rotor.

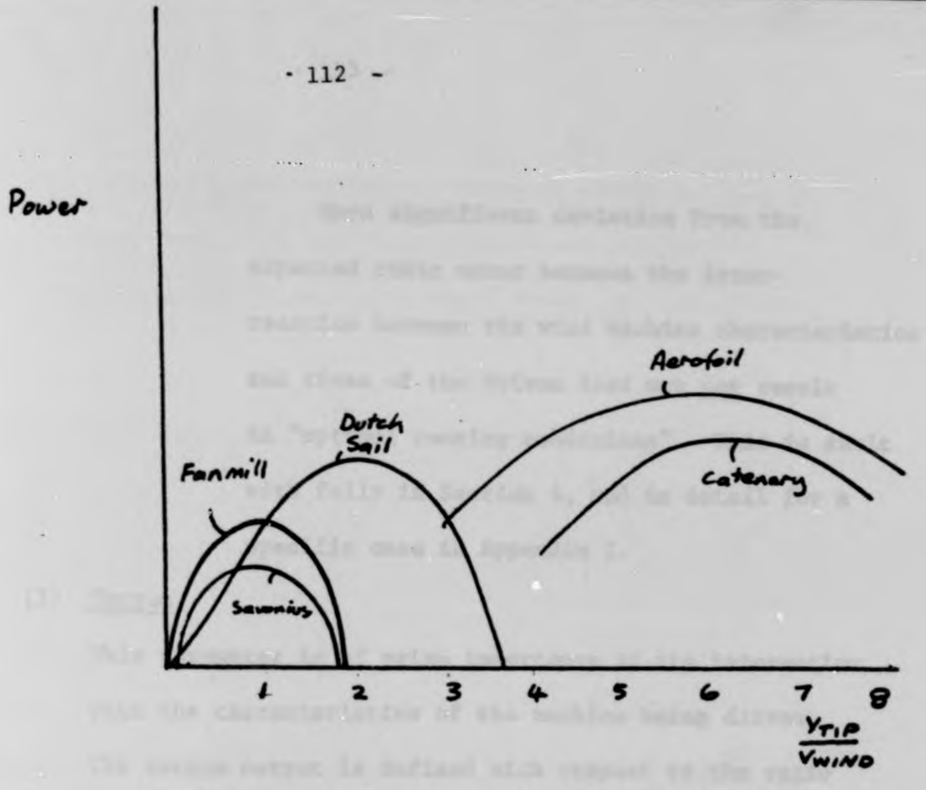

Figure 9 - Power Output Versus Speed for Various Windmill Types

(b) Variation of Power Output with Wind Speed

For all these machines, the "optimal running conditions" power output versus wind speed is close to a cubic relationship, as predicted by the theoretical power in an airstream equation.

Deviation from this can be expected inasmuch as particular machines may have designs which are refined for operation in a particular band of windspeeds, and are less efficient than might be expected at other speeds.

More significant deviation from the expected cubic occur because the inter-reaction between the wind machine characteristics and those of the driven load may not result in "optimal running conditions". This is dealt with fully in Section 4, and in detail for a specific case in Appendix I.

(3) Torque

This parameter is of prime importance in its interaction with the characteristics of the machine being driven. The torque output is defined with respect to the ratio of the tip speed to the wind speed ($\frac{VT}{VW}$). Thus, the torque at "start-up", when either the machine is being put into operation, or it has stopped during a lull in the wind, and the wind has commenced again, is defined as the torque when the tip speed to wind speed ratio is 0. As the machine picks up speed (or is accelerated by applying power from a source other than the wind) this ratio increases. At some ratio depending on the characteristics of the machine, the torque reaches a maximum, and increases in VT/VW beyond this reduce the torque output.

It should be noted that the power output is proportional to the torque output multiplied by the tip speed, and that for a given power output the high speed machines (Savonius Rotor, Fan-mill, Jumbo) produce a high torque. These relationships are illustrated graphically below for constant values of wind speed.

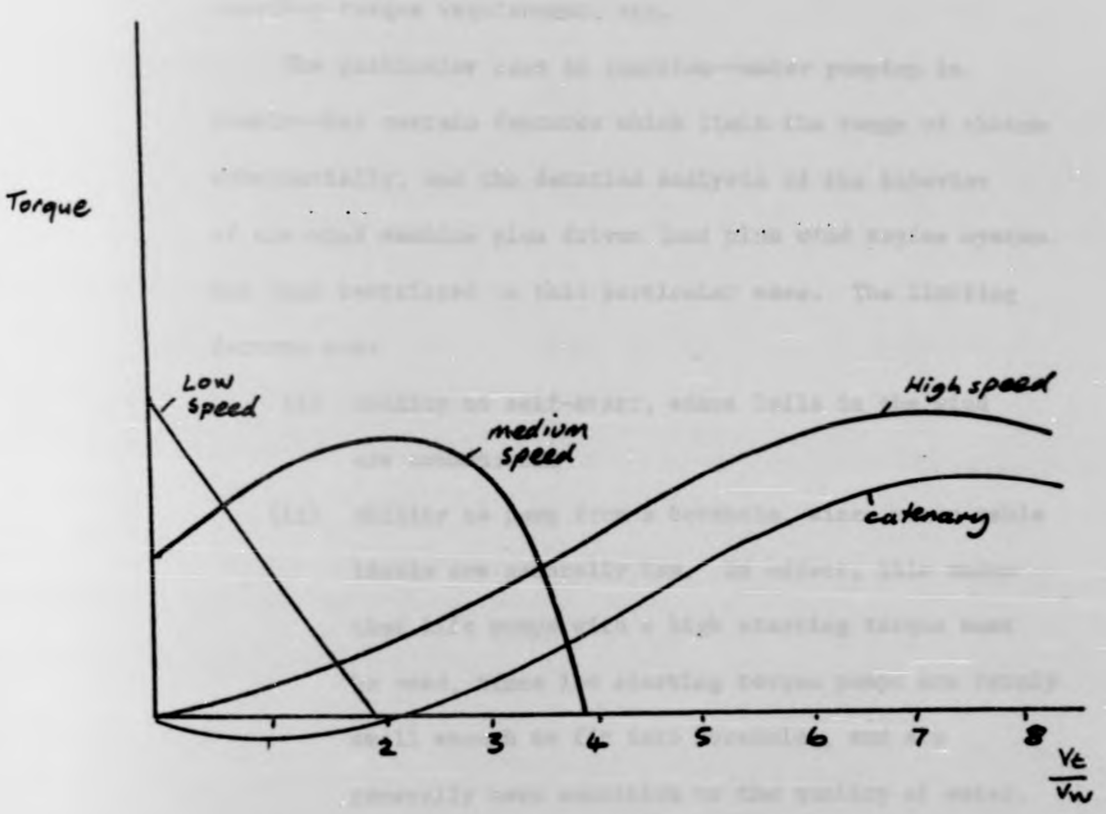

Figure 10-Torque Versus Tip Speed to Wind Speed Ratio for Various Machines

The configuration of a machine will define these curves precisely—the above curves, derived from references, are intended only to demonstrate the general characteristics of various machines.

Characteristics of the Driven Load:

There are many different uses to which the power of the wind may be put. Each use has its own peculiarities: constant speed drive, limitation of maximum load, low starting torque requirement, etc.

The particular case in question—water pumping in Zambia—has certain features which limit the range of choice substantially, and the detailed analysis of the behavior of the wind machine plus driven load plus wind regime system has been restricted to this particular case. The limiting factors are:

(i) ability to self-start, since lulls in the wind are common; and

(ii) ability to pump from a borehole, since water table levels are generally low. In effect, this means that lift pumps with a high starting torque must be used, since low starting torque pumps are rarely small enough to fit into boreholes, and are generally more sensitive to the quality of water.

Summary and Conclusions

In the comparative analysis of technologies, the fan-mill has been used as representative of wind power. This choice was made for the following reasons:

(1) the wind speeds in the area are generally low, which immediately rules out the extremely inefficient jumbo-mill;

(2) subsequent local test of a Savonius rotor have been unsuccessful—this machine is also too inefficient for the very low wind speeds;

(3) cost and performance data on the Catenary-bladed mill, the Dutch mill and the high-speed airscrew mill are not available;

(4) fan-mills are quite widespread in the area and many have been in use for decades, confirming that they are a viable design in the area; and

(5) the exceptional reliability and very suitable characteristics of these machines (particularly that they self-start when pumping from a borehole) make them the best choice in a situation of rather limited knowledge.

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Windpowered System

In the case of windpower, unlike the other alternatives considered, investment in a particular system does not give a fixed available daily output. Not only does the wind vary from day to day on a random basis, but also the output of a windpowered system varies substantially between seasons of the year, with December, January and February the least windy months. In fact, this is no great disadvantage, since these months are in the middle of the rainy season (which is very reliable) and water is not likely to be in shortage.

This does, however, pose a problem of comparison, in that the most efficient windpowered system, in economic terms, has an output distribution over time which matches the demand distribution—but it does not have the reserve capability of the other systems, so that a late start or early finish to the wet season might necessitate driving cattle to water, as is commonly done at present.

It is difficult to justify any particular formula as a fair method of comparison—to choose a wind system which would produce at least the same output as an alternative system on any normal day (ignoring for the moment random daily fluctuations in windspeeds) would mean choosing a system which, during the windier months, would be vastly oversize—by a factor of three or four. Alternatively, a constant volume per day can be supplied by having a wind pump which, over the year, pumps enough water to meet a fixed daily demand, but uses a storage reservoir to allow full utilization of the output. This again penalizes the wind system, since it will mean using a very large reservoir, above ground so that the water can be distributed by gravity—an expensive system.

To try and ensure that the windpowered system will provide as reliable a water supply (when required) as any other system, the following criteria are applied:

(1) that the system should provide the design quantity of water in the event of a 10% shortfall in overall wind speed averages (an extreme assumption according to Golding (13));

(2) that the system should supply adequate water for human consumption during the wet season, and human and animal consumption during the dry season; and

(3) that there should be a reservoir of one month's supply available at the end of the dry season, so that, in the event of an uncertain start to the rains, adequate supplies are available. This is important, since at this time, ploughing and planting are in progress, and time will be too valuable to spend driving cows to water.

Thus, Table 1 shows the basis for design of windpowered system, assuming a 10% decrease in all windspeeds (calculated in accordance with Annex I.

Each particular demand considered (small, medium and large farms, and the whole settlement) is specified in terms of wet and dry season demands, and storage requirement. Then by studying Table 1 in conjunction with the demand pattern, it is fairly easy to estimate the most severe situation; and to test whether satisfying that part of the annual cycle automatically resolves the other demands.

Storage Tank: Capacity 31,500 liters

A tank of 9,000 liters capacity was recently built in the area. Inputs were as follows:

600 bricks (bought secondhand)

8 cwt cement (local price £7.12)

10 man days labor

Bricks are not always obtainable secondhand, so in estimating the expected cost, allowance is made for manufacture of bricks. The cement price is not adjusted to "world" price since it is in any case not far above "world" price, and differences would be accounted for by transport costs.

Materials costs will be roughly proportional to area of walling constructed. The volume is proportional to the cube of the linear dimensions, and the area proportional to the square, thus materials costs might be expected to increase with volume to the power 2/3. Most of the labor costs are also related to the area of walling, so the same factor can be used here.

Hence, increasing the tank size from 9,000 to 15,250 (assuming two tanks are built, so that repairs and cleaning can be carried out, without interruption of supply) increases input by $(\frac{15,250}{9,000})$ 2/3 = 1.4 per tank.

Hence, expected costs of storage tank:[1]

Manufacture of Bricks (1)	= 25 man days
Cement	= £19.94
Labor	= 28 man days

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[1] There is a potential trade-off between building a tank and installing a larger windmill to "guarantee" supplies. The inconsistency of the wind make some sort of storage essential and the low cost of even substantial storage, as here, would not enable purchase of the next size larger wind pump.

Table 9 - Costs of Wind Powered Systems

System 1—small farm

Demand 10 people	600 liters/day
10 cattle	450 liters/day
	1,050 liters/day

Assuming a head of 15 meters,

Demand = 9,000 meters liters/day (wet season)

= 15,750 meters liters/day (dry season)

Storage at beginning of wet season (end month 10)

= 1,050 x 30

= 31,500 liters

= 31,500 x 15 meters liters

The smallest commercial unit (6 ft diameter 2.6 meters^2) easily produces the required output.

Costs

Windmill, tower, pump, rods, couplings, foot valve, etc.		E330
Installation	unskilled	6 man days
	skilled	2 man days

Total for System

Capital Costs		E350
Labor Costs:	unskilled	59 man days
	skilled	2 man days

System 2--medium sized farm

Demand 15 people	900 liters/day
40 cattle	1,800 liters/day
	2,700 liters/day

Assuming a head of 20 meters,

Demand = 18,000 meters liters/day (wet season)

= 54,000 meters liters/day (dry season)

Storage at beginning of wet season (end month 10)

= 2,700 x 30 liters

= 81,000 liters

The critical constraint on this system turns out to be provision of dry season demand in month 5. This requires a machine of approximately four square meters area (based on a cut-in speed of 2.5 meters/sec) and this is enough to satisfy all other requirements.

Costs (nearest commercial unit)

Sydney Williams 8 ft windmill, pump, tower, etc.		E494
Installation	unskilled	6 man days
	skilled	2 man days

Storage Tank: capacity 81,000 liters

(costs calculated as above for two 40,500 liter tanks)

Manufacture of bricks = 78 man days

Cement = E62

Labor = 87 man days

Total for System

Capital Costs		E556
Labor Costs:	unskilled	171 man days
	skilled	2 man days

System 3—large farm

Demand	20 people	1,200 liters/day
	100 cattle	4,500 liters/day
		5,700 liters/day

Assuming head of 25 meters,

Demand = 30,000 meters liters/day (wet season)

= 142,500 meters liters/day (dry season)

Storage at beginning of wet season = 171,000 liters

Again, as in System 2, the critical constraint is provision of dry season demand in month 5, and this determines the size of the machine at 10.5 sq. meters (corresponding to a diameter of 12 ft).

Costs

Sydney Williams 12 ft mill, tower, etc.		E806
Installation	unskilled	6 man days
	skilled	2 man days

Expected cost of storage tanks (as above for four tanks)

Bricks = 158 man days

Cement = E126

Labor = 182 man days

Total Costs for System

Capital Costs		E932
Labor	unskilled	348 man days
	skilled	2 man days

System 4--supply to several farms

Demand 80 people	4,800 liters/day
200 cattle	9,000 liters/day
	13,800 liters/day

Assuming a head of 25 meters,

Demand = 120,000 meters liters/day (wet season)

= 345,000 meters liters/day (dry season)

Storage = 414,000 liters

The constraint for this system is provision of dry season demand in month 5. This requires a windmill of 25.9 sq. meters area. The nearest available size is 18 ft diameter (= 26.5 sq. meters).

Costs

Sydney Williams 18 ft mill, pump, tower, etc.		£2,057
Installation	unskilled	8 man days
	skilled	2 man days

Expected Cost of Storage Tanks

Storage of 414,000 liters in two tanks would require tanks much larger than are currently being used. Costing is done on the basis of four tanks, since current building methods may not be adequate on a much larger scale.

Costs (as calculated above)

Bricks (lab) = 284 man days

Cement = £228

Labor = 360 man days

Total Costs for System

Capital Costs		£2,285
Labor	unskilled	652 man days
	skilled	2 man days

The Wind Regime + Windmill + Driven Load System

The final objective of analyzing the performance of a combination of components is to establish the output of power which it will achieve during the year, or perhaps a few critical months in the year.

Consideration of whether a combination will self-start, for example, is an important aspect of this--but still only part of the whole.

A full analysis of one common combination—particularly relevant to the area of Zambia being considered—is presented below. A more concise, mathematical treatment is shown in Annex II, where a full computer analysis of optimizing the choice of the pump size is carried out.[1] The method is easily modified to assess any combination of characteristics.

The basic case considered is that of a fan-mill driving a lift pump--the most common combination in use.

It is shown that the mismatch of characteristics between the fan-mill and the lift pump results in optimum efficiency operation at only one wind speed.

Fan-mill + Lift Pump

The energy in the wind, as has been stated, is proportional to the speed cubed. Thus, a wind machine might be expected to produce power for the load it drives in proportion to the windspeed cubed. The inter-reaction between the characteristics of the wind machine and those of the load being driven are the determinants of the relationship.

In the case being considered, the lift pump, the torque requirement is constant, and the power needed is directly proportional to the speed of operation.

---

[1] See Annex II, p. 9.

Figure 1 shows the performance curve of a fan-mill versus tip speed to windspeed ratio (as previously shown at Figure 4) for various

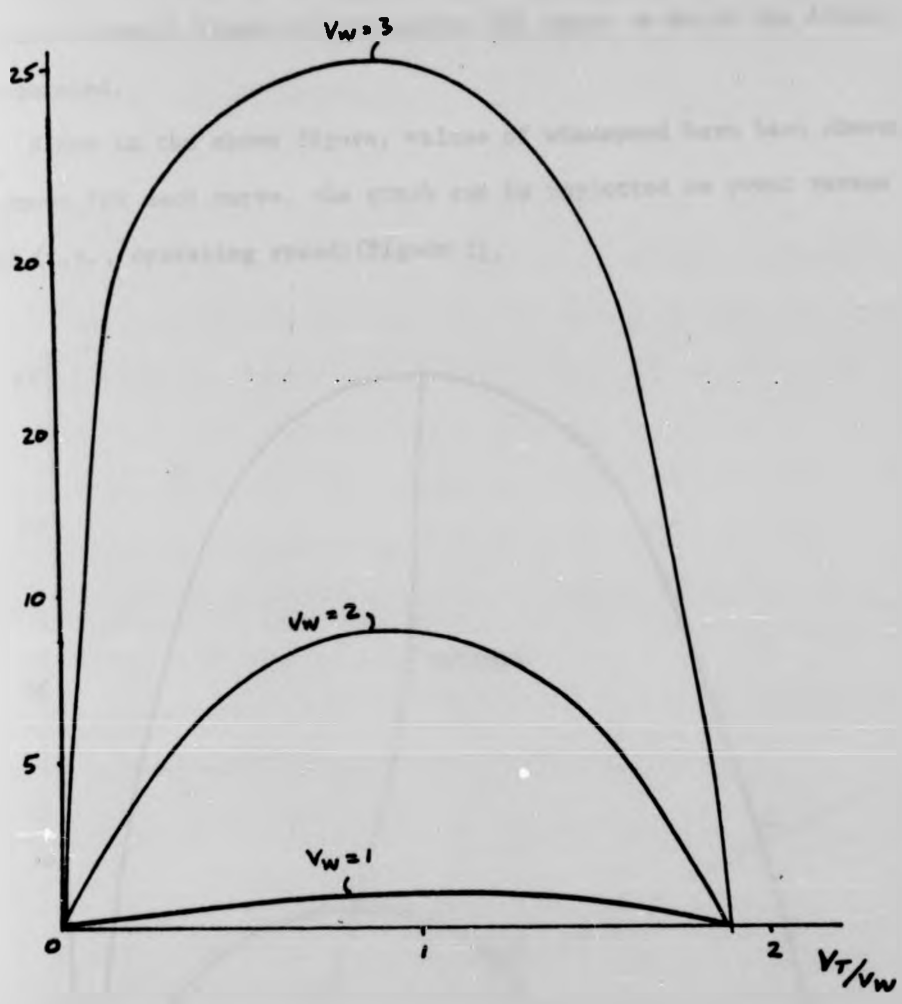


Figure 1: Power Versus VT/VW for a Fan-mill

values of VW. The characteristics of the driven load are known in terms of power required and operating speed. Thus, the above graph must be redrawn to be compatible with this (since VT/VW is not a direct measure of the operating speed).

Operating speed is a direct function of tip speed, since the speed of the windmill blade will determine the speed at which the driven load is operated.

Since in the above figure, values of windspeed have been chosen, and are known for each curve, the graph can be replotted as power versus tip speed (i.e., operating speed)(Figure 2).

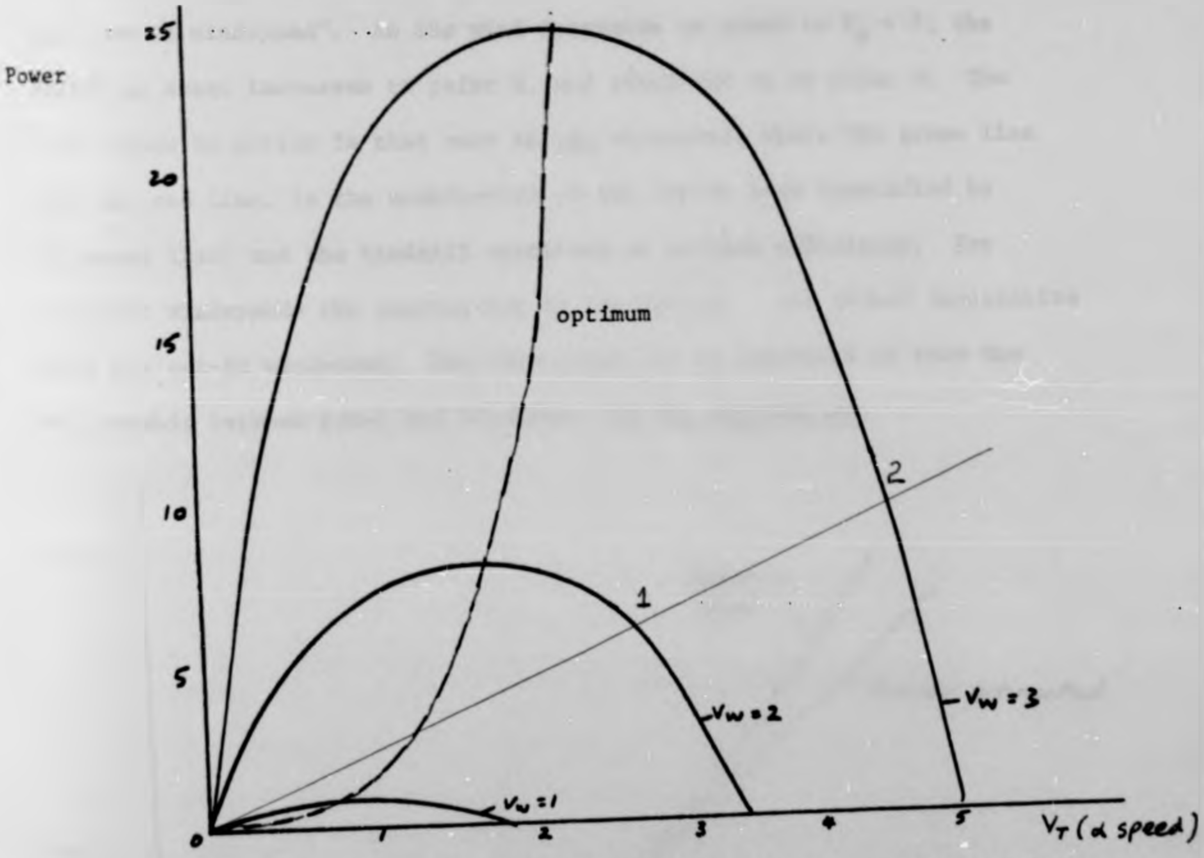
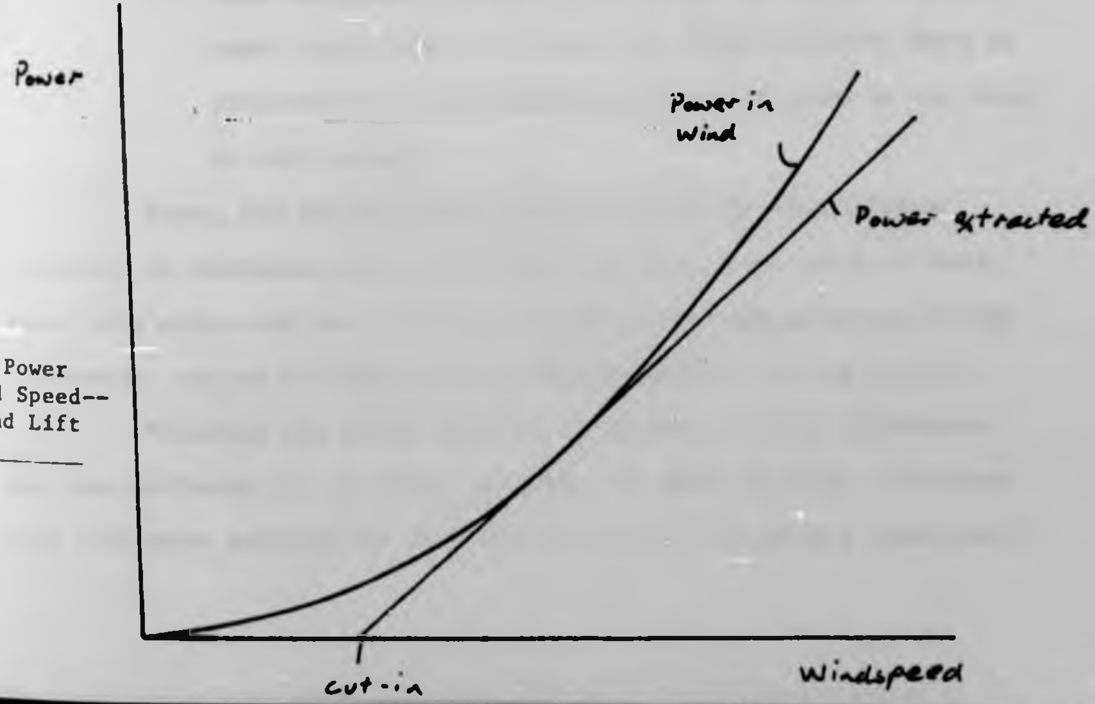


Figure 2: Power Versus Operating Speed for a Fan-mill and Lift Pump at Various Wind Speeds

The green line shows the power/operating speed characteristic for a lift pump, as previously described; the red dotted line shows the relationship between operating speed and power output for operation at optimum conditions for each windspeed.

Consideration of the green line shows that when $V_W = 1$, there is not enough power at any operating speed to drive the load. At $V_W = 2.0$, there is enough power to reach point 1. At some intermediate windspeed, the windmill can just operate the load—this windspeed is referred to as the "cut-in windspeed". As the wind increases in spead to $V_W = 3$, the operating speed increases to point 2, and similarly on to point 3. The main effect to notice is that only at one windspeed, where the green line cuts the red line, is the combination of the driven load (specified by the green line) and the windmill operating at optimum efficiency. For all other windspeeds the combination is sup—optimal and indeed inoperative below the cut-in windspeed. Now this graph can be replotted to show the relationship between power and windspeed for the combination.



e 3: Power
s Wind Speed--
Mill and Lift

Again, the red line shows the "optimum" relationship—the power proportional to the cube of the windspeed. The blue line, the actual relationship, is now, however, not a cubic relationship but a straight line relationship of the form.

Power = K (VW - C) (1)

where K = constant

and C = cut-in windspeed

A formal proof of this relationship is shown in Appendix I, and it is noted that K is proportional to the square of the cut-in speed.

Equation 1 means that a low cut-in speed will result in:

(1) operating in all but the very lightests winds; and

(2) low efficiency (thence power output) in high winds.

whereas a high cut-in speed will result in:

(1) long periods when the wind is insufficient to drive the machine at all; and

(2) high utilization of the large amounts of energy in higher speed winds (and the slope of the power/windspeed curve is proportional to the square of the cut-in speed so the effect is very marked).

Hence, for the particular case of a specific windmill/pump operating in windspeeds which vary with time, an optimum value of cut-in speed will exist—not too low so as to lose much of the advantage of high windspeeds, and not too high so as to be inoperative for long periods.

Following the formal analysis in Appendix I, this calculation has been performed for two sites in Zambia for which detailed, year-round wind data exist and also for the site in question for which a rather small sample of data has been collected (presented and analyzed in Appendix II).

ANNEX II

Analysis

The geometry of the windwheel will determine the "free rotation" speed in any given wind, that is to say the speed at which the wheel would rotate if it ran on frictionless bearings, and had no load applied to it. Denote this speed as kVw, where Vw is the windspeed, and k is a constant, defined by the geometry of the windwheel.

The power output of a windwheel is proportional to the rotation speed multiplied by the torque (force of rotation).

When the wind is Vw, and the rotation speed is kVw, the output power will be zero because, by the definition of k, at this speed the torque output is zero. At the other extreme when the machine is stationary in a wind VW the torque is maximized, but the power output is again zero, this time because the speed of rotation is zero.

Thus, a power output is only achieved when the machine rotates at a speed above 0 and below kVw.

At such an intermediate speed, the actual rotation speed will correspond to the free rotation speed at some lower windspeed, say Vw', and this rotation speed will be kVw'.

The torque output at this speed will obviously be a function of the difference between the free rotation speed (kVw) and the actual rotation speed (kVw')--in fact, this difference measures the extent to which the machine "catches" the wind (clearly when rotation freely in the kVw mode, the machine does not 'feel' the wind at all).

The torque is a function of the wind pressure on the blades, which is proportional to the square of the windspeed on the blades. Since

$k(Vw - Vw')$ measures the apparent windspeed on the blades, the torque will thus be proportional to this value.

The rotation speed has been defined already as kVw, and so the power is proportional to:

$$\text{Power} \propto k^2 (Vw - Vw')^2 . \, Vw'$$

or, since k is a constant,

$$\text{Power} \propto Vw'(Vw - Vw')^2 \text{———————} 1$$

A lift pump is a constant torque device, virtually, and only inasmuch as the speed of operation varies the viscous forces does it diverge from this.

This means that $(Vw - V'w)^2$—the torque parameter—is a constant, and $(Vw - V'w)$ will equal "c", the cut-in speed at which the difference between Vw and V'w is adequate to move the pump.

$$\therefore (Vw - V'w)^2 = c^2$$

and, for a lift pump,

$\text{Power} \propto Vw'c^2$ (from 1)

but,

$$Vw' = Vw - c$$

$$\therefore \underline{\text{Power} = c^2 \, (Vw - c)}$$

From 1.

$$\text{Power} = Vw' \, (Vw - V'w)^2$$

If Vw is constant, maximum power occurs when

$$\frac{d \, \text{Power}}{d \, Vw'} = 0$$

$$Vw' \, (Vw - V'w)^2 = Vw' \, (Vw^2 - 2VwV'w + V'w^2)$$

$$= (Vw'Vw)^2 - 2VwVw'^2 + V'W^3$$

$$\frac{d\ \text{Power}}{d\ Vw'} = Vw^2 - 4VwVw' + 3V'_w{}^2$$

$$= 0 \ @ \ \frac{Vw'}{Vw} = \frac{1}{3}$$

Thus, to maximize power at a given windspeed:

$$\frac{Vw'}{Vw} = \frac{1}{3}$$

and if $c = Vw - Vw'$

i.e., $\frac{c}{Vw} = 1 - \frac{Vw'}{Vw}$

$$\therefore \quad \frac{c}{Vw} = 1 - \frac{1}{3}$$

$$\underline{\frac{c}{Vw} = \frac{2}{3}}$$

Application

Choice of an Optimum Windmill/Pump Combination for a Given Windspeed Distribution: The power available in the wind is proportional to the cube of the windspeed. The power which is actually derived from the wind by a machine depends on the characteristics of the machine and the load it is driving.

Here, a very common case is considered; the driving of a lift pump by a low-speed fan-mill.

The main characteristic of this system is that a given lift pump requires a virtually constant force to drive it, irrespective of its speed of operation. Thus, the windmill produces a constant torque when driving a lift pump.

It has been shown that, if the windspeed at which the windmill just begins to drive the pump is "c" (the "cut-in" windspeed) , and the windspeed is Vw, then:

$$\text{Power} \propto c^2(Vw-c)$$

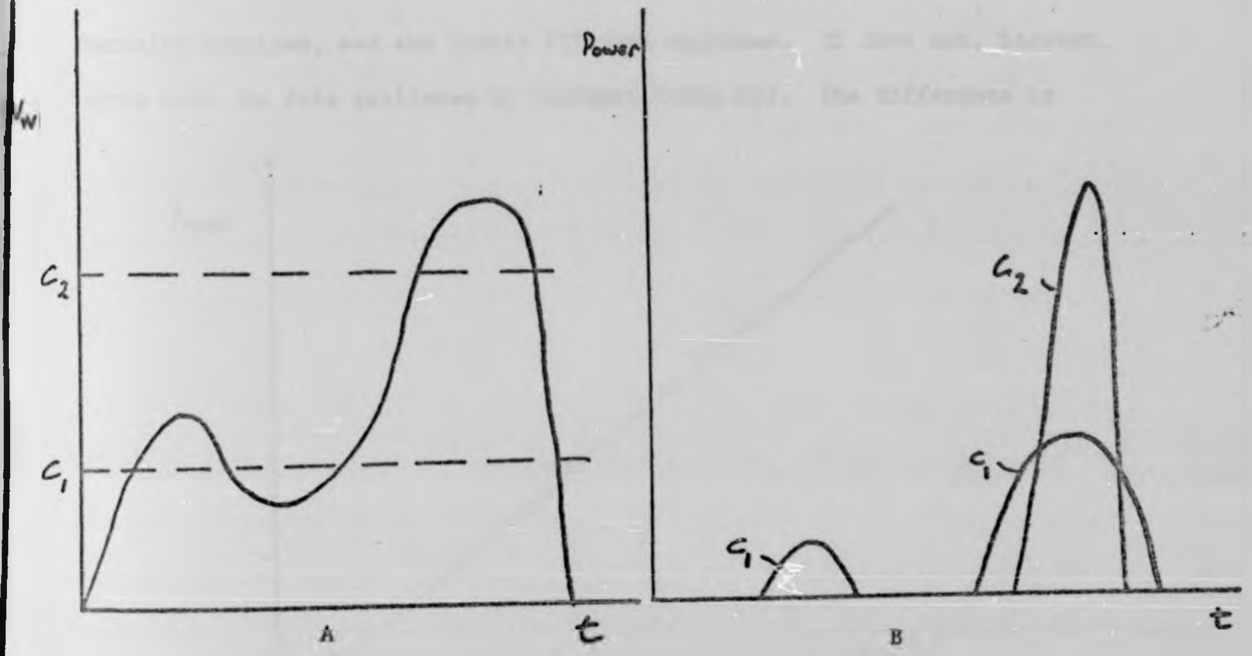


Figure 1: Power Output for Different Criteria Cut-in Wind Speeds as a Function or Wind Speed

Thus, the higher is "c" (the "cut-in" speed) the steeper is the increase in power for an increase in Vw, but if "c" is too high, the machine will operate slowly or not at all because (Vw-c) approaches zero.

This is illustrated in Figure 1. Given a wind distribution over time (A), a machine with a high value of "c" is idle for a large proportion of the time the wind is blowing, but produces a lot more power than the machine with low "c" for the period when the windspeed is high (B).

The theoretical relationship between windspeed and work rate for a slow speed windwheel driving a lift pump has been derived above. The form of this relationship agrees with the analysis of Golding (13), and the published performance data of the Lubing machines, the German Hercules machines, and the Sydney Williams machines. It does not, however, agree with the data published by Southern Cross Ltd. The difference is

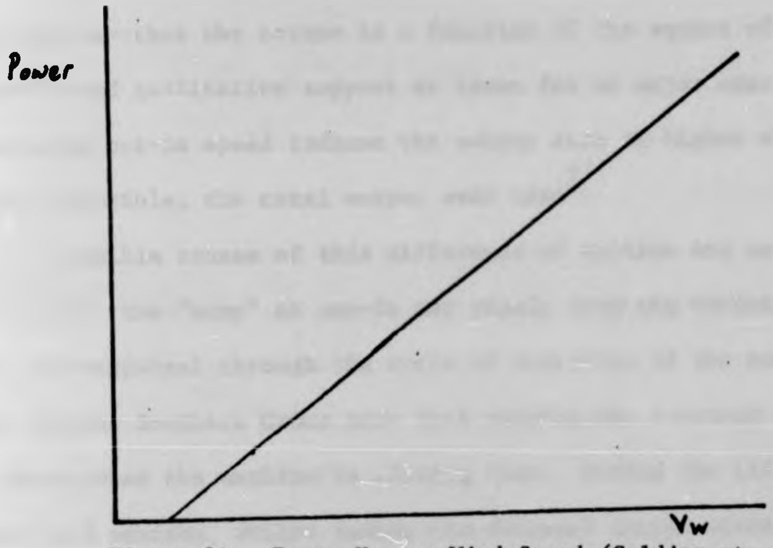


Figure 2A: Power Versus Wind Speed (Golding et. al.)

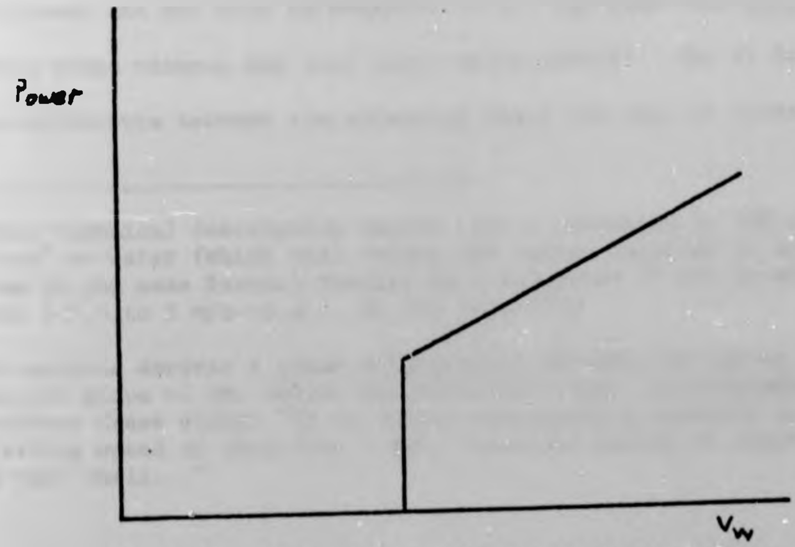


Figure 2B: Power Versus Wind Speed (Southern Cross) essentially that while Lubing, Sydney Williams Ltd., Golding and myself expect a linear increase in output with windspeed, along a line which does not intersect the origin, Southern Cross expect a virtual step increase from zero to 50% full capacity between the cut-in windspeed of 7-1/2 mph and 9 mph, followed by a linear increase in output beyond that along a line which does intersect the origin. Despite these fundamentally different conclusions, their data produces basic support for the only basic assumption in my analysis—that the torque is a function of the square of the windspeed[1/]—and qualitative support at least for my major conclusion—that reducing cut-in speed reduces the output rate at higher windspeeds, and hence, possible, the total output over time[2/].

Possible causes of this difference of opinion are as follows:

(1) the "step" at cut-in may result from the variation of the load on the windwheel through the cycle of operation of the pump. A clue to this is that Southern Cross note that pumping may continue at windspeeds below cut-in when the machine is slowing down. During the lifting stroke, the load is a maximum, whilst during the downward return stroke the load is a minimum, and may even be negative (i.e., the pump will pull the windwheel round without any wind power being needed). Now it is easy to see the difference between the situation where the mill is already in

---

[1/] Their technical description states that a reduction by 50% of the "head" of water (which will reduce the torque required to drive the pump by the same factor) results in a reduction of cut-in windspeed from 7-7.5 to 5 mph—i.e ., in the ratio 2:1.

[2/] My analysis derives a clear relationship between the cut-in speed and the slope of the output and windspeed line. In correspondence Southern Cross states "it is rarely economically feasible to have a starting speed of less than 4 mph, since the volume of water pumped is very small..."

operation, and, during the minimum load part of the cycle, it gathers momentum which carries it through the maximum load period (i.e., the average power imparted by the wind throughout the cycle is greater than the average power needed to derive the pump over the cycle) whereas at start up, the wind-power must overcome the peak cycle load without the benefit of any "stored" energy accumulated during the low demand period. Counterbalancing by use of weights could correct this variation, so that the torque requirement is constant;

(2) the difference in slope may result from the method of protecting the wind machine from overloading: a spring-loaded "tail" progressively causes the windwheel to be turned edge on to the wind, as the wind increases in strength. It may be that an over-sensitive mechanism can cause a reduction in the power output.

On balance theoretical considerations and the weight of evidence seem to favor the characteristic in Figure 1A, above, and this relationship has been used to predict outputs of water in conjunction with meteorological data.

It still remains, however, to estimate the peak efficiency of operation of the machine: the above analysis describes the variation in efficiency around the peak, but does not help in calculating the peak.

Vadot (14) has suggested an overall peak efficiency of a low-speed wind pump as 15-20%.

This would agree well with a windwheel efficiency of 25-30% and a pump efficiency of 50-60%, which might be expected.

Thus, for the analysis, peak overall efficiency of 20% has been used.

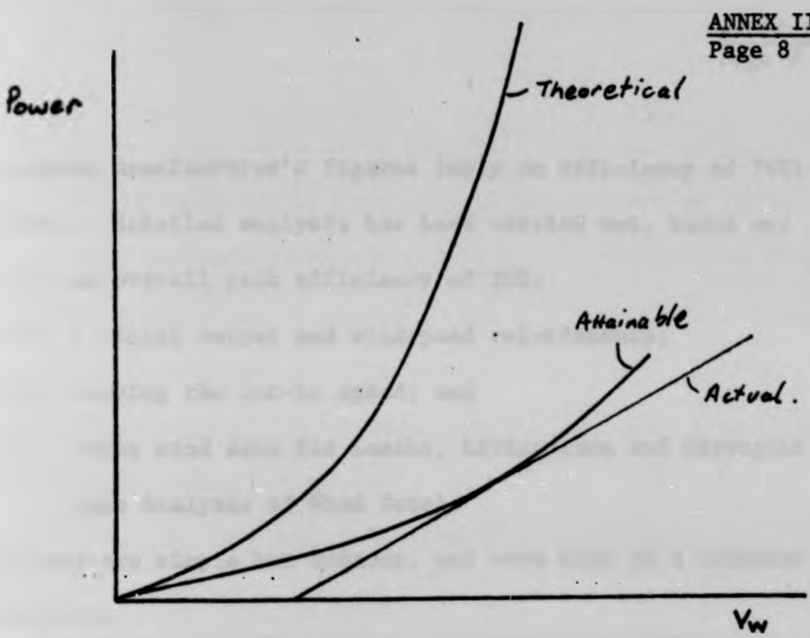


Figure 3: Theoretical, Attainable and Actual Power Derived from the Wind

What this means is shown in the figure: the efficiency limitation of 20% means that the attainable power and windspeed curve is equal to one-fifth of the theoretically available power at any windspeed.

The straight line output versus windspeed for an actual windmill/pump combination is tangential to this curve at one point, being everywhere else less efficient still than the 20% figure.

These points are crucial, since it is not possible as one might expect to simply read off performance from manufacturers data, for two reasons.

First, manufacturers data is usually only given for one windspeed, so that the variation of output with windspeed has to be calculated.

Secondly, some of the point data given seem to be grossly optimistic: one manufacturer quotes output rates which imply an overall efficiency of 54%—the maximum power obtainable from an airstream using a wind machine corresponds to 58% efficiency, and this excludes subsequent losses due to pump inefficiency.

Another manufacturer's figures imply an efficiency of 74%!

Thus, a detailed analysis has been carried out, based on:

(1) an overall peak efficiency of 20%;

(2) a linear output and windspeed relationship;

(3) varying the cut-in speed; and

(4) using wind data for Lusaka, Livingstone and Kazangula (see Analysis of Wind Data).

The calculations are simple but tedious, and were done on a computer in the following way.

First, the cut-in windspeed is defined (arbitrarily) as 2 meters/second. The computer then calculated the value of K in the equation:

$$\text{Power} = Kc^2 \; (Vw - c)$$

so that:

(1) peak efficiency (i.e., at $Vw = 1.5c$) is 20%; and

(2) power is in the units meter—liters of water per day.

Using this value of K, and the three-hourly wind data published by the Zambian Meteorological Office, a numerical integration is performed to find the total water output for a typical day in January (month 1), February (month 2), etc.

Then, the cut-in windspeed is increased to 2.5 meters per second, a new value of "K" is calculated, and the cycle repeated. This continues up to $c = 4$ meters/second. The output from this, using Lusaka wind data, is shown in Table I. In Table II, the output using Livingstone wind data is shown, while Table III is the output corresponding to the wind measurements I made during June 1973 at Kazungula in the area of the farm settlement. The data collected, and its analysis, is presented in Annex III.

It must be emphasized that the role of this data is solely to give a perspective of the wind regime at Kazungula in the context of Lusaka and Livingstone, for which reliable data are published. It would be dubious to draw any firm conclusions. Although a good deal of data was collected, it was collected when time allowed, and not regularly at fixed times. More important, the data for one month is not all that good a guide even to the "normal" wind regime of that month, let alone the whole year. It is very relevant that the largest wind machine ever built, the 1250kw a Grandpa's Knob, Vermont, was in fact built at the wrong site due to insufficient collection of wind data during the planning stage (13). Unfortunately, although the wind measuring device was left for the collection of further data, this was not done, so, on the basis of Tables I, II and III, it is assumed that the output from a wind machine at Kazungula will be an average of the output at Lusaka and that at Livingstone. Graph 1 shows data for the month of June only, and the Kazungula output is almost exactly mid-way between Lusaka and Livingstone. Thus, the full data for output at Kazungula is shown in Table IV, on the assumption that the relationship between Kazungula, Lusaka and Livingstone outputs holds true for the whole year.

GRAPH I

OUTPUT & CUT-IN SPEED
(MONTH OF JUNE)

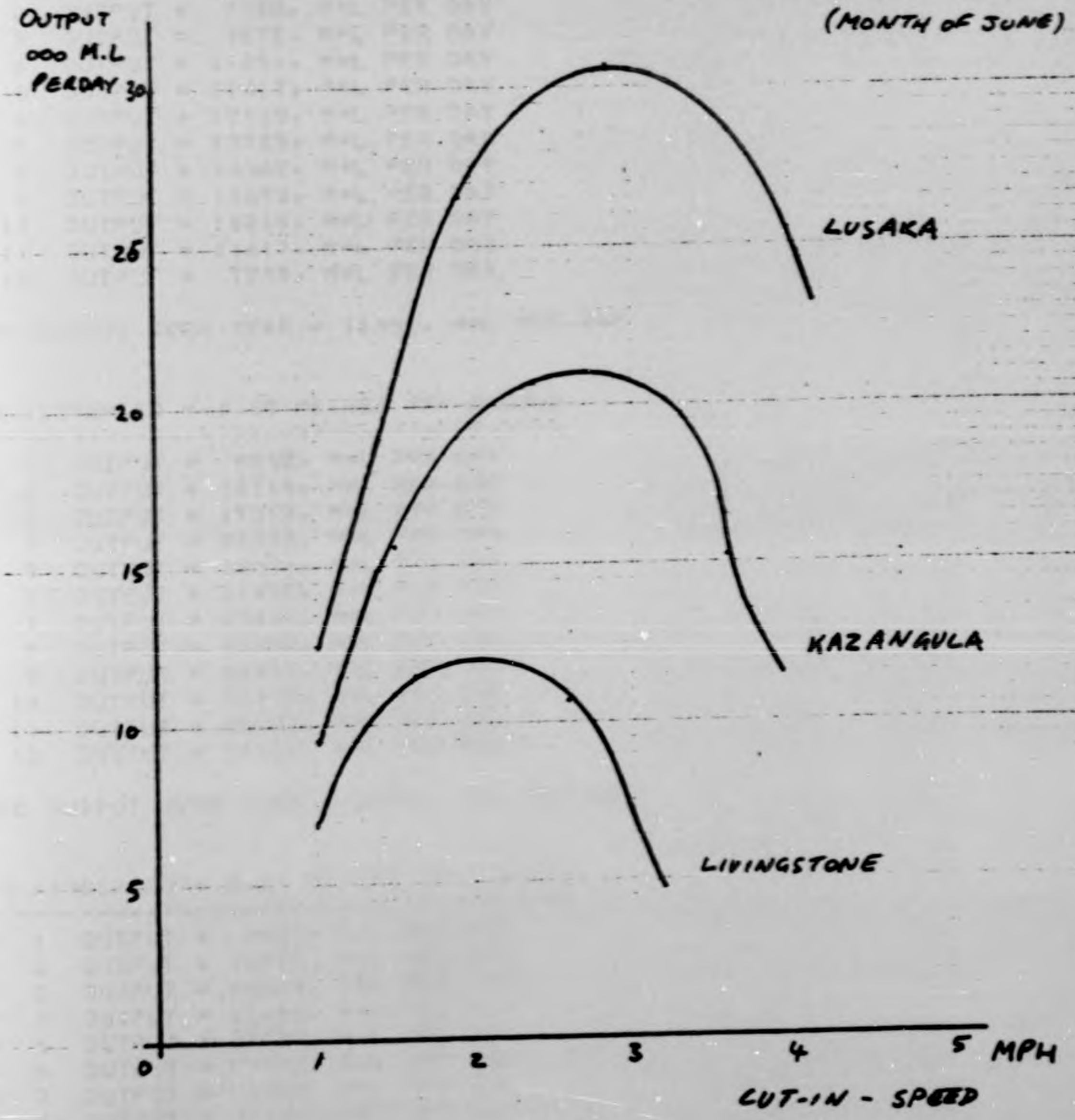


Table I - Output Based on Lusaka Winds

```
CUT-IN WINDSPEED = 1.00 METRES PER SECOND
-----------------------------------------
MONTH  1   OUTPUT =  5191. M*L PER DAY
MONTH  2   OUTPUT =  7382. M*L PER DAY
MONTH  3   OUTPUT =  9676. M*L PER DAY
MONTH  4   OUTPUT = 11651. M*L PER DAY
MONTH  5   OUTPUT = 11417. M*L PER DAY
MONTH  6   OUTPUT = 12119. M*L PER DAY
MONTH  7   OUTPUT = 13725. M*L PER DAY
MONTH  8   OUTPUT = 14562. M*L PER DAY
MONTH  9   OUTPUT = 16603. M*L PER DAY
MONTH 10   OUTPUT = 16269. M*L PER DAY
MONTH 11   OUTPUT = 11617. M*L PER DAY
MONTH 12   OUTPUT =  7200. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 11451. M*L PER DAY


CUT-IN WINDSPEED = 1.50 METRES PER SECOND
-----------------------------------------
MONTH  1   OUTPUT =  8292. M*L PER DAY
MONTH  2   OUTPUT = 13110. M*L PER DAY
MONTH  3   OUTPUT = 17310. M*L PER DAY
MONTH  4   OUTPUT = 20348. M*L PER DAY
MONTH  5   OUTPUT = 19821. M*L PER DAY
MONTH  6   OUTPUT = 21402. M*L PER DAY
MONTH  7   OUTPUT = 25016. M*L PER DAY
MONTH  8   OUTPUT = 26898. M*L PER DAY
MONTH  9   OUTPUT = 31491. M*L PER DAY
MONTH 10   OUTPUT = 30738. M*L PER DAY
MONTH 11   OUTPUT = 20273. M*L PER DAY
MONTH 12   OUTPUT = 11664. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 20530. M*L PER DAY


CUT-IN WINDSPEED = 2.00 METRES PER SECOND
-----------------------------------------
MONTH  1   OUTPUT =  9527. M*L PER DAY
MONTH  2   OUTPUT = 18093. M*L PER DAY
MONTH  3   OUTPUT = 24919. M*L PER DAY
MONTH  4   OUTPUT = 27468. M*L PER DAY
MONTH  5   OUTPUT = 25205. M*L PER DAY
MONTH  6   OUTPUT = 27620. M*L PER DAY
MONTH  7   OUTPUT = 34045. M*L PER DAY
MONTH  8   OUTPUT = 37391. M*L PER DAY
MONTH  9   OUTPUT = 45556. M*L PER DAY
MONTH 10   OUTPUT = 44217. M*L PER DAY
MONTH 11   OUTPUT = 26403. M*L PER DAY
MONTH 12   OUTPUT = 15416. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 27988. M*L PER DAY
```

Table I - Output Based on Lusaka Winds (Cont'd)

```
CUT-IN WINDSPEED = 4.00 METRES PER SECOND
-----------------------------------------
MONTH  1  OUTPUT =      0. M*L PER DAY
MONTH  2  OUTPUT =   4376. M*L PER DAY
MONTH  3  OUTPUT =  22091. M*L PER DAY
MONTH  4  OUTPUT =  22091. M*L PER DAY
MONTH  5  OUTPUT =  17808. M*L PER DAY
MONTH  6  OUTPUT =  25257. M*L PER DAY
MONTH  7  OUTPUT =  44043. M*L PER DAY
MONTH  8  OUTPUT =  49979. M*L PER DAY
MONTH  9  OUTPUT =  69253. M*L PER DAY
MONTH 10  OUTPUT =  56403. M*L PER DAY
MONTH 11  OUTPUT =  16784. M*L PER DAY
MONTH 12  OUTPUT =      0. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 27340. M*L PER DAY
```

Table 2 - Output Based on Livingstone Winds

```
CUT-IN WINDSPEED = 1.00 METRES PER SECOND
-----------------------------------------
MONTH  1  OUTPUT =  5542. M*L PER DAY
MONTH  2  OUTPUT =  4421. M*L PER DAY
MONTH  3  OUTPUT =  5610. M*L PER DAY
MONTH  4  OUTPUT =  4656. M*L PER DAY
MONTH  5  OUTPUT =  5158. M*L PER DAY
MONTH  6  OUTPUT =  6362. M*L PER DAY
MONTH  7  OUTPUT =  6345. M*L PER DAY
MONTH  8  OUTPUT =  7266. M*L PER DAY
MONTH  9  OUTPUT =  9175. M*L PER DAY
MONTH 10  OUTPUT = 10145. M*L PER DAY
MONTH 11  OUTPUT =  8305. M*L PER DAY
MONTH 12  OUTPUT =  5927. M*L PER DAY

AVERAGE OUTPUT OVER YEAR =  6576. M*L PER DAY


CUT-IN WINDSPEED = 1.50 METRES PER SECOND
-----------------------------------------
MONTH  1  OUTPUT =  8802. M*L PER DAY
MONTH  2  OUTPUT =  6937. M*L PER DAY
MONTH  3  OUTPUT =  7673. M*L PER DAY
MONTH  4  OUTPUT =  6184. M*L PER DAY
MONTH  5  OUTPUT =  7673. M*L PER DAY
MONTH  6  OUTPUT = 10459. M*L PER DAY
MONTH  7  OUTPUT = 10609. M*L PER DAY
MONTH  8  OUTPUT = 11948. M*L PER DAY
MONTH  9  OUTPUT = 15395. M*L PER DAY
MONTH 10  OUTPUT = 16960. M*L PER DAY
MONTH 11  OUTPUT = 13212. M*L PER DAY
MONTH 12  OUTPUT =  8953. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 10400. M*L PER DAY


CUT-IN WINDSPEED = 2.00 METRES PER SECOND
-----------------------------------------
MONTH  1  OUTPUT =  9794. M*L PER DAY
MONTH  2  OUTPUT =  7117. M*L PER DAY
MONTH  3  OUTPUT =  7653. M*L PER DAY
MONTH  4  OUTPUT =  6308. M*L PER DAY
MONTH  5  OUTPUT =  8852. M*L PER DAY
MONTH  6  OUTPUT = 12076. M*L PER DAY
MONTH  7  OUTPUT = 12873. M*L PER DAY
MONTH  8  OUTPUT = 14217. M*L PER DAY
MONTH  9  OUTPUT = 19175. M*L PER DAY
MONTH 10  OUTPUT = 21317. M*L PER DAY
MONTH 11  OUTPUT = 15294. M*L PER DAY
MONTH 12  OUTPUT = 10464. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 12095. M*L PER DAY
```

Table 2 - Output Based on Livingstone Winds (Conf'd)

```
CUT-IN WINDSPEED = 2.50 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =  8766. M*L PER DAY
MONTH  2  OUTPUT =  4165. M*L PER DAY
MONTH  3  OUTPUT =  5629. M*L PER DAY
MONTH  4  OUTPUT =  4728. M*L PER DAY
MONTH  5  OUTPUT =  7720. M*L PER DAY
MONTH  6  OUTPUT = 11275. M*L PER DAY
MONTH  7  OUTPUT = 13994. M*L PER DAY
MONTH  8  OUTPUT = 13849. M*L PER DAY
MONTH  9  OUTPUT = 19077. M*L PER DAY
MONTH 10  OUTPUT = 21232. M*L PER DAY
MONTH 11  OUTPUT = 14894. M*L PER DAY
MONTH 12  OUTPUT =  8202. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 11128. M*L PER DAY


CUT-IN WINDSPEED = 3.00 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =  3823. M*L PER DAY
MONTH  2  OUTPUT =   170. M*L PER DAY
MONTH  3  OUTPUT =  1375. M*L PER DAY
MONTH  4  OUTPUT =   943. M*L PER DAY
MONTH  5  OUTPUT =  5159. M*L PER DAY
MONTH  6  OUTPUT =  7568. M*L PER DAY
MONTH  7  OUTPUT = 11353. M*L PER DAY
MONTH  8  OUTPUT = 10449. M*L PER DAY
MONTH  9  OUTPUT = 17677. M*L PER DAY
MONTH 10  OUTPUT = 18450. M*L PER DAY
MONTH 11  OUTPUT = 11051. M*L PER DAY
MONTH 12  OUTPUT =  3954. M*L PER DAY

AVERAGE OUTPUT OVER YEAR =  7664. M*L PER DAY


CUT-IN WINDSPEED = 3.50 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =     0. M*L PER DAY
MONTH  2  OUTPUT =     0. M*L PER DAY
MONTH  3  OUTPUT =     0. M*L PER DAY
MONTH  4  OUTPUT =     0. M*L PER DAY
MONTH  5  OUTPUT =  1158. M*L PER DAY
MONTH  6  OUTPUT =  2317. M*L PER DAY
MONTH  7  OUTPUT =  4366. M*L PER DAY
MONTH  8  OUTPUT =  3137. M*L PER DAY
MONTH  9  OUTPUT = 12084. M*L PER DAY
MONTH 10  OUTPUT = 10854. M*L PER DAY
MONTH 11  OUTPUT =  3065. M*L PER DAY
MONTH 12  OUTPUT =     0. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 3081 M*L PER DAY
```

Table 3 - Output Based on Kazangula Winds (June Only)

```
CUT-IN WINDSPEED = 1.00 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT =  9241. M*L PER DAY

CUT-IN WINDSPEED = 1.50 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 14927. M*L PER DAY

CUT-IN WINDSPEED = 2.00 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 19170. M*L PER DAY

CUT-IN WINDSPEED = 2.50 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 20960. M*L PER DAY

CUT-IN WINDSPEED = 3.00 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 23990. M*L PER DAY

CUT-IN WINDSPEED = 3.50 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 16664. M*L PER DAY

CUT-IN WINDSPEED = 4.00 METRES PER SECOND
---------------------------------------------
MONTH  6  OUTPUT = 11337. M*L PER DAY
```

Table 4 - Assumed Kazangula Output

```
CUT-IN WINDSPEED = 1.00 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =  5366. M*L PER DAY
MONTH  2  OUTPUT =  5902. M*L PER DAY
MONTH  3  OUTPUT =  7643. M*L PER DAY
MONTH  4  OUTPUT =  8153. M*L PER DAY
MONTH  5  OUTPUT =  8287. M*L PER DAY
MONTH  6  OUTPUT =  9241. M*L PER DAY
MONTH  7  OUTPUT = 10035. M*L PER DAY
MONTH  8  OUTPUT = 10914. M*L PER DAY
MONTH  9  OUTPUT = 12889. M*L PER DAY
MONTH 10  OUTPUT = 13207. M*L PER DAY
MONTH 11  OUTPUT =  9961. M*L PER DAY
MONTH 12  OUTPUT =  6564. M*L PER DAY

AVERAGE OUTPUT OVER YEAR =  9013. M*L PER DAY


CUT-IN WINDSPEED = 1.50 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =  8547. M*L PER DAY
MONTH  2  OUTPUT = 10023. M*L PER DAY
MONTH  3  OUTPUT = 12492. M*L PER DAY
MONTH  4  OUTPUT = 13266. M*L PER DAY
MONTH  5  OUTPUT = 13747. M*L PER DAY
MONTH  6  OUTPUT = 15931. M*L PER DAY
MONTH  7  OUTPUT = 17813. M*L PER DAY
MONTH  8  OUTPUT = 19423. M*L PER DAY
MONTH  9  OUTPUT = 23443. M*L PER DAY
MONTH 10  OUTPUT = 23849. M*L PER DAY
MONTH 11  OUTPUT = 16742. M*L PER DAY
MONTH 12  OUTPUT = 10308. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 15465. M*L PER DAY


CUT-IN WINDSPEED = 2.00 METRES PER SECOND
------------------------------------------
MONTH  1  OUTPUT =  9660. M*L PER DAY
MONTH  2  OUTPUT = 12605. M*L PER DAY
MONTH  3  OUTPUT = 16286. M*L PER DAY
MONTH  4  OUTPUT = 16888. M*L PER DAY
MONTH  5  OUTPUT = 17028. M*L PER DAY
MONTH  6  OUTPUT = 19848. M*L PER DAY
MONTH  7  OUTPUT = 23459. M*L PER DAY
MONTH  8  OUTPUT = 25804. M*L PER DAY
MONTH  9  OUTPUT = 32366. M*L PER DAY
MONTH 10  OUTPUT = 32767. M*L PER DAY
MONTH 11  OUTPUT = 20849. M*L PER DAY
MONTH 12  OUTPUT = 12940. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 20042. M*L PER DAY
```

Table 4 - Assumed Kazungula Output (Cont'd)

```
CUT-IN WINDSPEED = 2.50 METRES PER SECOND
-----------------------------------------

MONTH  1  OUTPUT =  8347. M*L PER DAY
MONTH  2  OUTPUT = 12144. M*L PER DAY
MONTH  3  OUTPUT = 18209. M*L PER DAY
MONTH  4  OUTPUT = 18732. M*L PER DAY
MONTH  5  OUTPUT = 18209. M*L PER DAY
MONTH  6  OUTPUT = 20541. M*L PER DAY
MONTH  7  OUTPUT = 26847. M*L PER DAY
MONTH  8  OUTPUT = 29880. M*L PER DAY
MONTH  9  OUTPUT = 37577. M*L PER DAY
MONTH 10  OUTPUT = 37013. M*L PER DAY
MONTH 11  OUTPUT = 22946. M*L PER DAY
MONTH 12  OUTPUT = 12071. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 21876. M*L PER DAY


CUT-IN WINDSPEED = 3.00 METRES PER SECOND
-----------------------------------------

MONTH  1  OUTPUT =  3287. M*L PER DAY
MONTH  2  OUTPUT =  9375. M*L PER DAY
MONTH  3  OUTPUT = 16990. M*L PER DAY
MONTH  4  OUTPUT = 17828. M*L PER DAY
MONTH  5  OUTPUT = 17376. M*L PER DAY
MONTH  6  OUTPUT = 19032. M*L PER DAY
MONTH  7  OUTPUT = 27399. M*L PER DAY
MONTH  8  OUTPUT = 31013. M*L PER DAY
MONTH  9  OUTPUT = 40585. M*L PER DAY
MONTH 10  OUTPUT = 37508. M*L PER DAY
MONTH 11  OUTPUT = 21978. M*L PER DAY
MONTH 12  OUTPUT =  7588. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 20830. M*L PER DAY


CUT-IN WINDSPEED = 3.50 METRES PER SECOND
-----------------------------------------

MONTH  1  OUTPUT =     0. M*L PER DAY
MONTH  2  OUTPUT =  6657. M*L PER DAY
MONTH  3  OUTPUT = 14445. M*L PER DAY
MONTH  4  OUTPUT = 15639. M*L PER DAY
MONTH  5  OUTPUT = 13385. M*L PER DAY
MONTH  6  OUTPUT = 15604. M*L PER DAY
MONTH  7  OUTPUT = 25032. M*L PER DAY
MONTH  8  OUTPUT = 28685. M*L PER DAY
MONTH  9  OUTPUT = 40537. M*L PER DAY
MONTH 10  OUTPUT = 35003. M*L PER DAY
MONTH 11  OUTPUT = 15942. M*L PER DAY
MONTH 12  OUTPUT =  1604. M*L PER DAY

AVERAGE OUTPUT OVER YEAR = 17711. M*L PER DAY
```

Wind Readings Taken at Kazangula During June, 1973

Before installing a wind driven machine, it is obviously essential to have a sound knowledge of the local wind conditions—the more so because the energy is a function of the velocity cubed.

To gain this knowledge requires years of detailed observation, but in order to make some assessment of the potential of local conditions, a brief survey was carried out during June, 1973.

This was done using an anemometer supplied by the Intermediate Technology Development Group, who are interested in possible use of windpower in Zambia.

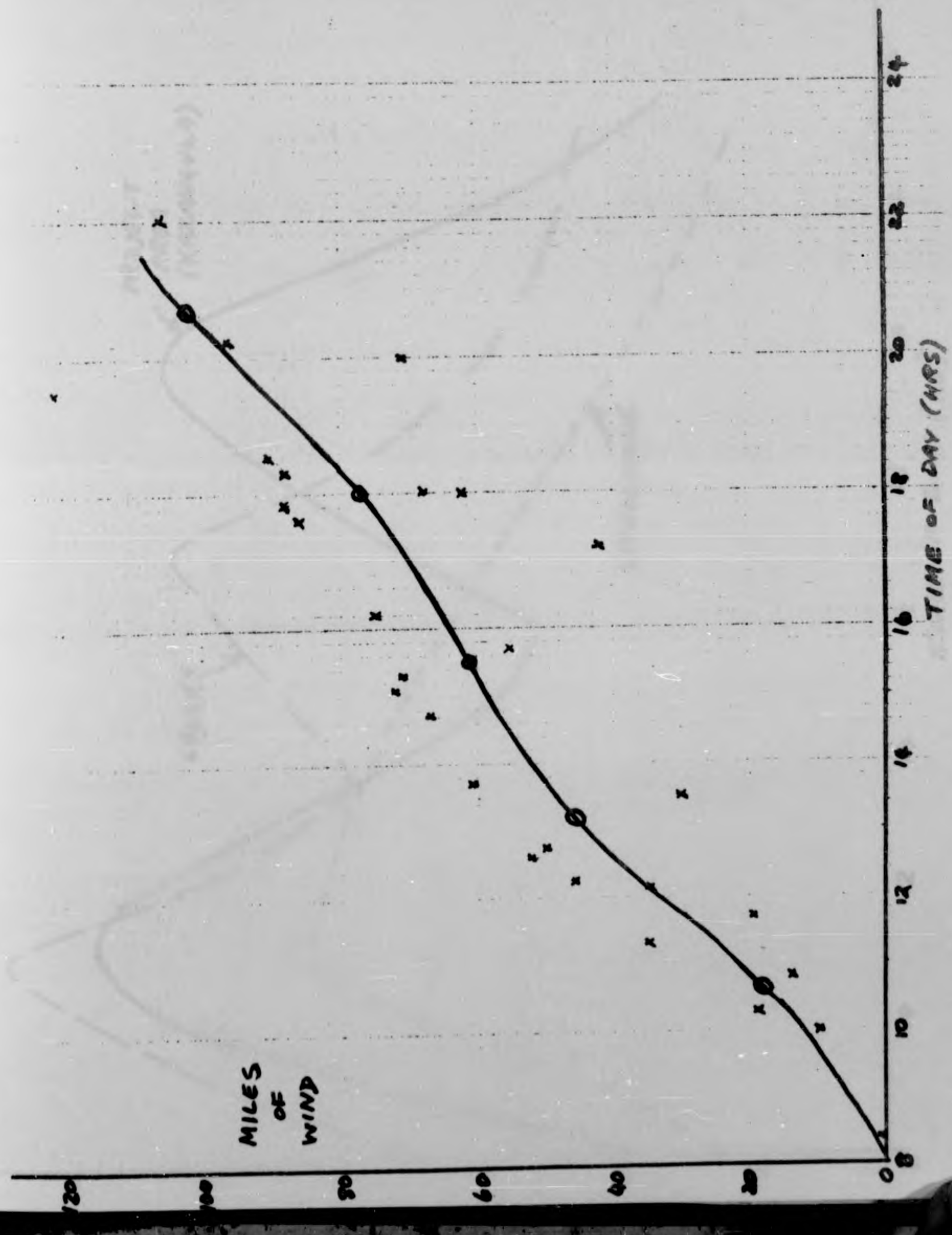
The instrument provided recorded miles of wind passing rather that windspeed, so some analysis of the data was required to produce a windspeed versus time graph. Also, since there were many other things to do during the survey period, readings were not taken at regular intervals—although three or four readings were taken on most days.

The method of analysis used was first of all to calculate a datum for the day at 8.00 am (usually a reading was taken around this time, if not the nearest reading was adjusted to its most likely value at 8.00 am). Then, all other readings for that day were expressible from that datum (e.g., if the 8.00 am reading was 156 miles, and the 11.15 am reading was 173 miles, the reading from the datum would be 3.25 hours, 17 miles). Thus, all readings could be plotted on one graph, and averaged in groups to give an estimate of the average wind during a June day. This distance versus time graph (Graph 1) was then converted to a velocity time graph (Graph 11) from which readings could be taken for calculating windmill outputs.

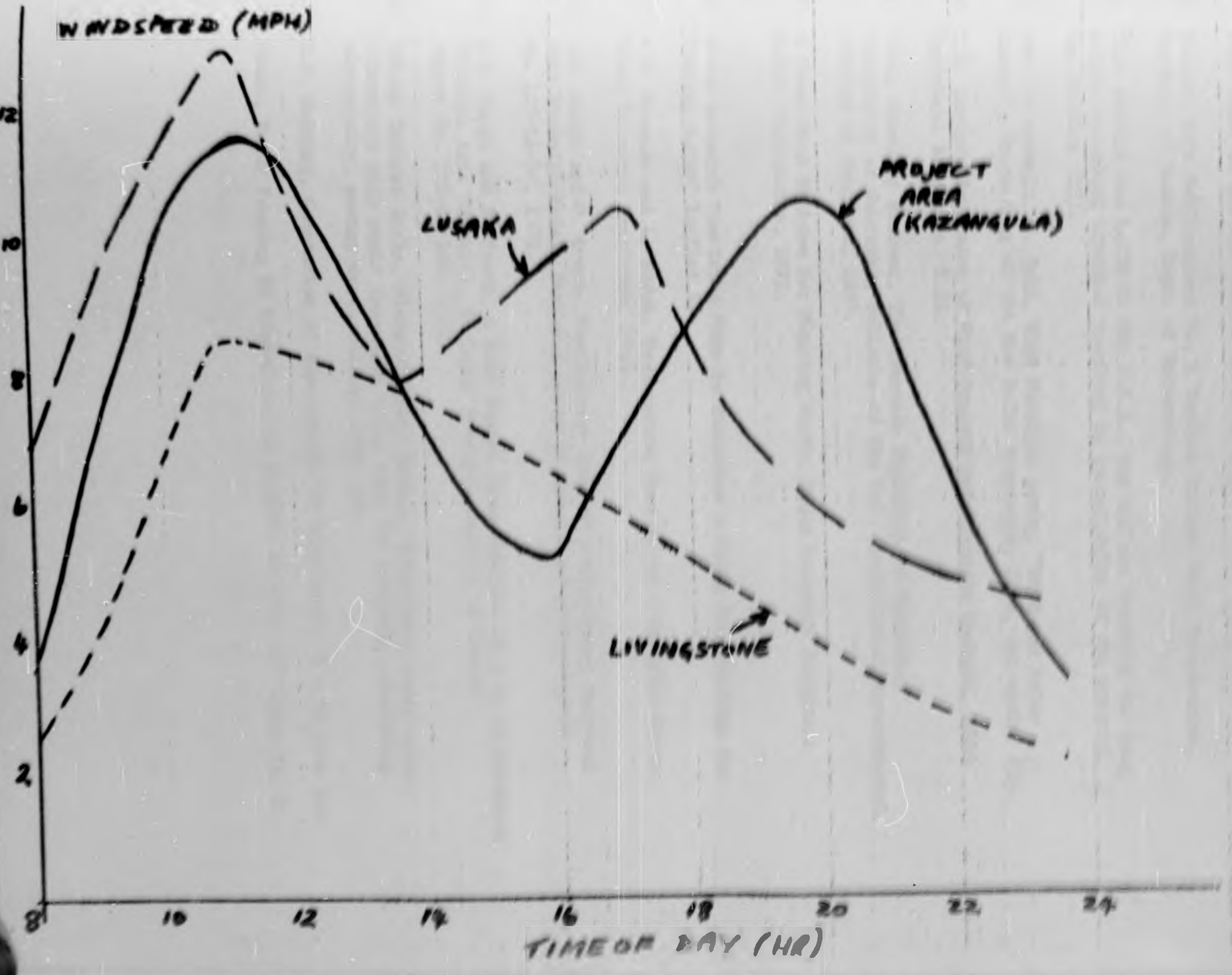
This method is simple and fairly crude, but it must be emphasized that this was not in any case a significant sample of data for one month, let alone a year, and especially since the readings were not continued when I left, it would overvalue the significance of the data to perform detailed statistical analyses.

The object is simply to gain a perspective of the wind regime in Karangula compared to other locations.

GRAPH I


MILES OF WIND
120
100
80
60
40
20
0
8
10
12
14
16
18
20
22
24
TIME OF DAY (HRS)

GRAPH II


WINDSPEED (MPH)
12
10
8
6
4
2
8
10
12
14
16
18
20
22
24
TIME OF DAY (HR)
LUSAKA
PROJECT AREA (KAZANGULA)
LIVINGSTONE

(1) New Sources of Energy and Economic Development Vol. 11.B.1, UN, Department of Ec. and Social Affairs, 1957.

(2) Climate Data Publications No. 1 Daytime Surface Wind Frequencies, Republic of Zambia, Depc. of Meteorology.

(3) This machine was built in the U.S.A., but did not function for long before technical troubles resulted in cancellation of the project. See Golding (13).

(4) See for example, J. Junl, Wind Machines paper, "Wind and Solar Energy", Proceeding of the New Delhi Symposium, 1956, and op.cit. (1).

(5) T.A. Lawand, Economics of Wind Powered Desalination Systems, Brace Technical Report No. T.36.

(6) Erwin Hinckley Barbour, The Homemade Windmills of Nebraska, University of Nebraska, Bulletin of the U.S. Agricultural Experimental Station of Nebraska, 1897.

(7) A Cheap Wind Machine for Pumping Water, Brace Research Institute, McGill University, 1973.

(8) Brace Research Institute "How to Construct a Cheap Wind Machine for Pumping Water" leaflet L5.

(9) M.M. Simonds and A. Bodek, Performance Testing of a Savonius Rotor, Brace Research Institute, 1964.

(10) R.S. Rangi and P. South, Preliminary Test of a High-Speed Vertical Axis Windmill Model, National Research Council of Canada Report No. LTR-LA-74, 1971.

(11) R.S. Rangi and P. South, A Wind Tunnel Investigation of a 14 ft Diameter Vertical Axis Windmill, National Research Council of Canada, Report No. LTR-LA-105, 1972.

(12) United Turbine Works, Niedersedlitz, Saxany, illustrate their sales literature with their fan-mills being used for pumping, generating electricity, sawing wood, milling corn, etc.

(13) E.W. Golding, Generation of Electricity by Wind Power, E & FN Spon Ltd.

(14) Vadot, Water Pumping by Windmills, La Mouille Blanche 12^e annee No. 2.

Chapter 5

Results of Analysis

Analysis of Data

Table 1 summarizes the cost data for each power source and farm size, as described in Chapter 4. The data fall into the two broad categories of initial costs and running costs. Columns 1-5 are initial costs, while columns 6-13 are recurring costs of running the equipment.

The two types of cost comprise the following elements:

Capital Cost –	(e.g., cost of plant and spares). These items are costed in pounds, and are the "border prices" as defined in the Little and Mirrlees' method;
Skilled Labor)) Artisan Labor)) Family Labor	Labor is costed in man days, and to convert to border prices the relevant Shadow Wage Rate must be used (as calculated in Chapter 3).

A time horizon of 30 years has been used as a basis for comparison, so all running costs are incurred annually for 30 years, while the initial costs are incurred once for a windmill (which has an expected life of 30 years or more), twice for a low speed diesel (expected life 15 years), etc.

Finally, rates of inflation, rates of increase of productivity, and the discount rate are included.

Rates of Inflation

Few things now are more speculative than inflation rates. However, it would be a considerable omission to exclude them completely. Obviously, if the price of a machine increases over time, then it is more advantageous to purchase a long-lived machine, and avoid at least the interim price increases paid when replacing a short-lived machine.[1/] Also, since the Shadow Wage Rate (SWR) of artisan and family labor is a direct function of the value of the output, then increases in commodity prices, and especially increases in agricultural commodity prices relative to capital goods prices will tend to change the relative costs of capital and labor over time.

Productivity Increases

If the productivity of farm labor increases over time, this has the same effect as increasing exported commodity prices relative to imported capital goods prices (assuming the machines considered here cannot be operated more efficiently as time goes by). The opportunity cost of labor, the SWR, increases, and the more capital intensive solutions, which free more time to agricultural work, become more attractive.

The Discount Rate

The analysis being performed is a cost effectiveness rather than a cost-benefit study. The investment will be undertaken, and it is of primary interest to find the minimum cost solution. The discount rate cannot therefore have the internal rate of return function—being allowed to vary to determine the highest yielding investment—but must be set in advance.

Values Used for the Analysis

Inflation Rates: Price indices for manufactured goods and exports from 1958 to 1972 are as follows:

	1958	1962	1965	1966	1967	1968	1969	1970	1971	1972
Manufactured Goods	97	99	103	106	107	107	110	117	124	135
Food	111	91	101	102	101	102	108	115	112	121

[1/] Provided that inflation rates exceed the financial cost of capital.

For both series, the average rate of increase since 1967 is about 5% p.a. and increasing (though manufactured goods have increased more stably). However, the effect of recent commodity price upheavals, particularly in the oil market, may well be to encourage harder, more organized bargaining by the developing countries, resulting in an improvement in their terms of trade.

The basic assumptions made in the data analysis, therefore, are that the prices of capital goods will increase 6% p.a. while the price of commodities (which here means the SWR and some other inputs such as diesel fuel and cement) will increase at 8% p.a.

Productivity Changes: The farmers in this area are good by Zambian and African standards, and have adapted readily to the use of fertilizers and draft power. It is therefore assumed that the productivity of the current farmer (as expressed through the SWR) will increase to equal the current productivity on the Magoye Unit Farm within 20 years—an increase rate of 4-1/2% p.a.

Discount Rate: The cost of capital is currently about 7% in Zambia, but the Central Projects Office[1] suggests that 10% would better reflect the scarcity of capital. By comparison with some developing countries, these rates are rather low (Little and Mirrlees' examples of calculations seem to use 10-15% as normal). In Zambia, however, thanks to the huge copper exports, finance is relatively plentiful—so 10% is taken as a base figure, though calculations are also done using 15% and 7%.

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[1] This information was received during discussions with the staff of the Government Project Planning Agency in Lusaka (April 1974).

Compilation of Costs

Given the SWR's, discount, inflation and productivity increase rates, the data in Table 1 can be converted to net present costs. The laborious nature of the repetitious calculations makes this a problem well suited to computer analysis, and a program has been written (see Appendix 1) to do this. The program functions as follows:

(a) the discount, inflation and productivity rates are read in, along with the SWRs;

(b) constants are calculated to convert the current cost of capital goods into their discounted (but inflated) replacement cost in 10, 15 and 20 years time, and similarly, for commodities and wage expenditures;

(c) constants are calculated to evaluate the annual expenditure on wages over a 30 year period in present value terms—again allowing for the discounting and increasing productivity effects;

(d) these constants are applied line by line to the data in the table, e.g., taking line 1, the life of a low speed diesel is 15 years, so the present cost of machinery is:

   i. the cost of a machine today (column 1) plus the cost of a machine in 15 years time, inflated at the capital goods rate of 6% and discounted to a present value;

   ii. the cost of material for building storage tanks (column 2);

   iii. the skilled labor cost of installation (column 3xSWR for skilled labor), plus the skilled labor cost of installation of a new machine in 15 years time, i.e., the present cost, inflated at the relevant rate for skilled labor and discounted to a present cost;

iv. the artisan labor cost of installation, multiplied by the relevant SWR;

v. the artisan labor cost of tank building, multiplied by the relevant SWR;

vi. the present value of the annual cost of replacement parts, inflated at the capital goods rate, and discounted;

vii. the present value of annual commodity usage (e.g., diesel fuel) inflated at the commodity inflation rate, and discounted;

viii. the present value of the annual skilled labor cost of repairs and maintenance, inflated as under item 3, and discounted;

ix. the present value of annual artisan labor costs inflated at the inflation rate for commodities and the increased productivity rate, and discounted;

x. the present value of annual inputs of family labor, at the lower SWR (e.g., child driving oxen), inflated and discounted as in ix. above.

xi. the present value of annual inputs of family labor at the higher SWR (equal to the artisan rate) inflated and discounted as under ix. above;

xii. the present value of annual capital costs of tank repairs, inflated at the commodity rate, and discounted; and

xiii. the present value of annual artisan labor on tank maintenance, at artisan SWR, inflated and discounted as under ix.

The total of items i.-xiii. is the net present cost of operating a given system for 30 years and is printed as the BASECOST. Finally, each item of cost input is increased by 10%, in turn, and the resulting percentage increase in the BASECOST calculated. This indicates the sensitivity of the total cost to each element of its composition.

The results of these calculations can be seen in Tables, 2, 3, and 4, where discount rates of 5% (at which finance is available), 10% (which was suggested by the Projects Office as being the correct rate) and 15% (to test the sensitivity of the solution) have been used.

The sensitivity of the solutions was further tested by considering the following four cases (see Tables 5-8):

(a) inflation rates for agricultural commodities and capital goods were both 7%;

(b) agricultural productivity increases more slowly than expected at 3% p.a;

(c) the skilled labor SWR was reduced by 20%;

(d) the artisan SWR was reduced by 20%.

These results have been summarized by system size in Tables 9-12. In each of these tables, the cost for each technology under the seven different sets of assumptions about inflation, wage rates, etc. is listed, together with the most significant component of the cost of the optimum solution, and the amount by which this element must change to cause a change in technology of the optimum solution, and the overall cost advantage of the best solution.

These tables were drawn up by rearranging the raw computer output shown in Tables 2-8, then:

(a) indicating the best solution under each set of assumptions by comparing the solutions;

(b) noting from the relevant table which cost component most affected the total cost;

(c) calculating the change in that component required to change the total cost enough to equal the second best solution;

(d) noting the overall advantage of the best solution over the second best.

For example, entries against the technologies in column one of Table 9 are the relevant (i.e., System size 1) results from the printout in Table 3.

Comparison of these figures shows that manpower, at E416, is the cheapest solution. From Table 3, the sensitivity tests in the manpower results for System 1 show that the most significant item is column 11 (Family Adult Labor) of the cost components (giving 6.35% change for a 10% change in the variable). The overall advantage of the solution over the second best solution (Wind) is 26% $((\frac{525}{416} \times 100) - 100)$; thus, to change the solution, the most significant component would have to change by $10 \times \frac{26}{6.35} = 40\%$. Of course, the number of ways and combinations in which the cost structure could change is endless, but the results tabulated give a reasonable impression of the sensitivity of the best solution to changes in the data.

Results by System Size

System Size 1: Under all sets of assumptions except one, manpower is the best solution for supplying the small requirements of this system. The single exception is when the low discount rate of 5% is used. This results in a shift from the high operating cost of manpower to the capital intensive, low running cost of wind power. Manpower is otherwise clearly optimal, with a substantial cost advantage.

System Size 2: At this level of demand, the results are not at all clearcut. Under three of the seven sets of assumptions, manpower is cheapest and under the other four sets, wind power is preferable. In any situation, small changes in the most significant cost elements (capital cost for wind power and family labor demand/cost for manpower) will alter the solution. It could well be that the optimal solution in this case is in fact animal power, which is also competitive, and is much more flexible than either wind power or manpower—i.e., if the demand level increases, this can easily be met by animal power. This conclusion is reinforced by the dominance of animal power as the best solution for the larger farm sizes.

Systems Sizes 3 and 4: Animal power is the optimum choice under all assumption for both these cases. The most interesting aspect of the results is that the margin by which it is preferable is considerably greater in the case of System 3, and the second best solution, which is wind in System 3, switches to diesel power for System 4. The implications of this are discussed below.

Results by Technology

Low Speed Diesel and Medium Speed Diesel: A low speed diesel engine was not competitive with other solutions at any of the output levels considered, and was invariably considerably more expensive than a medium speed diesel. Since the design of the higher speed unit is some 20-30 years more modern, it is not surprizing that this is a more economical solution, and only in uses where exceptional reliability is necessary could the low speed engine be considered—although the cost difference of 30 years operation (about £500) is enough to purchase a spare higher speed engine as a standby.

The higher speed diesel emerged from the analysis with considerable credit. Despite being very oversized for the levels of output required (it would only operate for a few minutes each day), the high speed diesel is competitive at the larger output levels, and would almost certainly be the best solution for an irrigation system, or other high demand. The ratio of costs between System 1 and System 4 for a diesel engine is only about 1.3:1, whereas for animal power, the ratio is 2:1. The total cost of a diesel system is heavily dependent on the initial capital cost (a 10% change in this alters the total cost by about 5%). Since the capital costs are known with considerable accuracy and the total cost is not particularly sensitive to changes in the other components (except the related servicing costs), the estimate shown should be fairly accurate.

Wind Power: Zambia is not a windy country and it is not surprizing that wind power is generally uncompetitive. It is disappointing that the experiments with a Savonius Rotor, which are currently underway in the area, are not very successful, and it does seem from this that in Zambia the use of wind power will be limited to those prepared to pay a premium for the advantages (such as unattended remote operation and extreme mechanical reliability) which wind power offers.

Methane: The methane powered solution is very difficult to evaluate. It is not competitive with the alternatives, but it is not completely uncompetitive so it is difficult to rule it out. The initial cost and cost of repairs are the two components to which the total cost is most sensitive, and these are also the two least known factors. Judgment on methane must therefore wait until some working units have been used in the field and some experience gained.

Animal Power: The results of the analysis show that animal power has a very definite role in the range of small scale power sources. The total system cost is not particularly sensitive to any component, capital cost and servicing being the main influences, but the estimates for these are fairly well based and, if anything, widespread use of animal power might lead to cheaper more efficient machines being available.

The tabulated results are based on the assumption that either:

(a) extra work oxen will not be kept just for water pumping; or

(b) if extra oxen are kept, the pasture thus committed to their consumption would not have been used for commercial rearing of beef.

Bearing in mind the attitude of the Tonga to cattle, the second assumption is almost certainly true, and it is also likely that the relatively small amount of work involved in water pumping can be done by the existing work animals.

In the description of the animal powered solution, the opportunity cost of pasture loss was calculated in full. If this figure is included in the calculation (i.e., neither assumption (a) or (b) above applies), then diesel power becomes the most economical solution. The crossover point is where about half the full opportunity cost is incurred. At this point, the cost of an animal powered solution, at 10% discount rate, is £1,711 for System 3 and £2,274 for System 4, compared with £1,732 and £2,069 respectively for diesel powered systems.

Man Power: As might be expected, manpower is an economical small scale source of power, and is an efficient choice for small scale farming. Man power rapidly becomes very expensive at higher output levels, however, and the economic advantages of using animal power are considerable.

General Conclusions

A study of one set of technologies applied in one specific area can hardly be regarded as a test case for Intermediate Technology. However, whilst recognizing these limitations and the fact that many more specific comparisons must be made and their results tested, it is of interest to see how clearly this set of results reflect the general assertions of Schumacher.

Animal power fits exactly Schumacher's notion of an Intermediate Technology. It is more capital intensive than current practice and yet far less capital intensive than "Western" solutions. It fits the local conditions, using available resources and skills. It is not "available". It will have to be reconstructed and modified from previously used technologies, and perhaps improved upon from current knowledge. Diesel power, the conventional "Western" solution, is inappropriate even to large farmers in this area, but if irrigation schemes were being designed, diesel power would probably be the best solution, so "high" technology may have an important role to play.

Man power might seem the obvious choice if the characteristics of Intermediate Technology (i.e., labor intensity) were being pursued, rather than the broader objectives. In fact, there seems to be a limited role for it, mostly because the relatively high productivity of the local farmers means that labor is better used in agriculture if water demand is above the minimum level.

Methane and wind power, two sources of power which are being tried in the area, may have a role to play. They are good examples of Intermediate Technologies, using local resources, but it seems in the case of wind at least that the local resources are not quite adequate and that in Zambia this will not be a competitive power source, particularly in its cruder forms.

Schumacher makes the assertion that Intermediate Technologies can be economically the best solution as well as socially. This is the case here. The economic analysis was carried out with little recourse to social criteria. Only in setting $S_0 = 1$ (see Chapter 3) and thus evaluating current consumption of the relatively poor as being as valuable as investment was such a bias included. Indeed, this may underestimate the economic effects if rural jobs have a multiplied effect on migration.

Necessary steps in selecting a technology for use in an unfamiliar setting are first to gain some understanding of the area, then to review all the technologies which will do the job.

Given the difference between the factor costs of developing countries compared to developed countries, it is likely that the "best" technology selected by any economic or social criteria will have some differences from that current in the developed world.

Table 1

COST SUMMARY

Power Source	System	INITIAL COST					RUNNING COST							
		Capital Cost (cif)		Installation Costs		Tank				Labor (mandays p.a.)			Tank (Repairs and Maintenance)	
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
		M'l E	Tank E	Skilled M.D.	Artesan M.D.	Artesan Tank	Capital Goods	Commodities	Skilled Labor	Artesan	Unskilled Child	Family Adult	(CAP)[3]	(LAB)[2]
Low Speed Diesel	1	809	10	3	32	26	10.80	.34	16.80	0	0	0	2	1
	2	831	19	3	32	49	10.80	1.00	16.80	0	0	0	3	2
	3	854	29	3	32	77	10.80	2.45	16.80	0	0	0	4	3
	4	854	70	3	32	182	10.80	6.46	16.80	0	0	0	10	7
Med. Speed Diesel	1	396	10	3	32	26	.34	14.75	14.75	0	0	0	2	1
	2	406	19	3	32	49	.98	14.75	14.75	0	0	0	3	2
	3	420	29	3	32	77	2.35	14.75	14.75	0	0	0	4	3
	4	420	70	3	32	182	6.32	14.75	14.75	0	0	0	10	7
Windmill	1	330	20	2	6	53	3.00 [1]	0.00	0.00	1	0	0	2	3
	2	494	62	2	6	165	5.00 [1]	0.00	0.00	1	0	0	6	9
	3	806	126	2	8	340	8.00 [1]	0.00	0.00	1	0	0	13	18
	4	2057	228	2	8	646	21.00 [1]	0.00	0.00	1	0	0	22	36
Methane/ Humphrey Pump	1	140	10	5	7	26	14.00	0.00	0.00	0	20	0	2	1
	2	140	19	5	7	49	14.00	0.00	0.00	0	25	0	3	2
	3	140	29	5	7	77	14.00	0.00	0.00	0	30	0	4	3
	4	164	70	5	7	182	16.00	0.00	0.00	0	40	0	10	7
Animal Power	1	200	10	1	20	26	20.00	62.00	0.00	10	13.5	0	2	1
	2	200	19	1	20	49	20.00	62.00	0.00	10	26.5	0	3	2
	3	200	29	1	20	77	20.00	62.00	0.00	10	55.5	0	4	3
	4	200	70	1	20	182	20.00	62.00	0.00	10	138.0	0	10	7
Manpower	1	59.50	10	0	3	26	.60	0.00	0.00	1	0	34.5	2	1
	2	59.50	19	0	3	49	.60	0.00	0.00	1	0	97.3	3	2
	3	59.50	29	0	3	77	.60	0.00	0.00	1	0	190.6	4	3
	4	64.00	70	0	6	182	.64	0.00	0.00	2	0	624.6	10	7
		CATA	CATA	CATB	CATC	CATC	CATA	CATD2	CATB	CATC	CATD1	CATD2	CATA	CATC

---

[1] 1% of windmill and pump costs.
[2] 4% of labor cost of building tanks.
[3] 15% of capital cost of building tanks.

Table 2

% CHANGE PER 10% CHANGE IN :-

SYSTEM SIZE	BASE COST	1	2	3	4	5	6	7	8	9	10	11	12	13
	DIESEL (LS)													
1	2005.9	6.22	0.45	0.24	0.08	0.06	1.51	1.55	0.04	0.	0.	0.	0.23	0.02
2	2102.0	6.10	0.09	0.23	0.08	0.12	1.44	1.48	0.11	0.	0.	0.	0.33	0.04
3	2195.0	6.00	0.13	0.22	0.07	0.18	1.38	1.42	0.26	0.	0.	0.	0.31	0.03
4	2559.1	5.15	0.27	0.19	0.16	0.36	1.18	1.21	0.58	0.	0.	0.	0.89	0.10
	DIESEL (HS)													
1	1542.3	5.44	0.06	0.44	0.10	0.08	1.72	1.78	0.05	0.	0.	0.	0.30	0.02
2	1621.9	5.28	0.12	0.42	0.10	0.15	1.64	1.69	0.14	0.	0.	0.	0.42	0.05
3	1732.4	5.11	0.17	0.40	0.09	0.22	1.53	1.58	0.31	0.	0.	0.	0.53	0.07
4	2069.0	4.28	0.34	0.33	0.08	0.44	1.28	1.32	0.70	0.	0.	0.	1.10	0.16
	WIND													
1	525.2	6.28	0.38	0.38	0.06	1.50	1.03	0.	0.	0.15	0.	0.	1.00	0.22
2	930.7	5.31	0.67	0.21	0.03	0.89	0.97	0.	0.	0.08	0.	0.	1.47	0.37
3	1643.5	4.90	0.77	0.12	0.02	1.03	0.88	0.	0.	0.05	0.	0.	1.01	0.42
4	3657.9	5.62	0.62	0.05	0.01	0.88	1.03	0.	0.	0.02	0.	0.	1.37	0.30
	METHANE													
1	1837.3	4.63	0.05	3.62	0.02	0.07	3.92	0.	0.	0.	0.42	0.	0.25	0.02
2	1962.7	4.45	0.14	0.58	0.02	0.12	3.85	0.	0.	0.	0.49	0.	0.35	0.04
3	2075.9	4.33	0.14	0.55	0.12	0.19	3.73	0.	0.	0.	0.55	0.	0.44	0.06
4	2360.1	3.31	0.30	o.48	0.01	0.39	0.28	0.	0.	0.	0.65	0.	0.97	0.11
	ANIMAL													
1	895.4	3.44	0.11	0.18	0.11	0.15	4.02	0.	0.	0.86	0.58	0.	0.51	0.04
2	992.4	3.11	0.19	0.16	0.19	0.25	3.62	0.	0.	0.77	1.02	0.	0.69	0.08
3	1154.2	2.67	0.25	0.14	0.09	0.33	3.12	0.	0.	0.66	1.84	0.	0.79	0.10
4	1716.4	1.84	0.41	0.10	0.36	0.53	2.10	0.	0.	0.45	3.08	0.	1.33	0.16
	MAN													
1	416.5	1.43	0.24	0.	0.04	0.31	0.26	0.	0.	0.18	0.	6.35	1.10	0.09
2	945.1	0.63	0.21	0.	0.02	0.26	0.11	0.	0.	0.08	0.	7.89	3.73	0.08
3	1711.1	0.35	0.17	0.	0.01	0.28	3.06	0.	0.	0.04	0.	8.54	0.53	0.07
4	5298.6	0.12	0.13	0.	0.11	0.17	0.02	0.	0.	0.03	0.	9.04	0.43	0.05

DISCOUNT RATE = 10.0%
CAPITAL GOODS INFLATION RATE = 6.0%
COMMODITY INFLATION RATE = 8.3%
PROD. INCREASE RATE = 4.5%
SKILLED LABOUR SWR = 10.0 POUNDS/DAY
ARTISAN LABOUR SWR = 0.5 POUNDS/DAY

Table 3

```
BASECOST          % CHANGE PER 10% CHANGE IN :-

            1    2    3    4    5    6    7    8    9   10   11   12   13

DIESEL (LS)
 3171.3  5.51 0.13 0.22 0.35 0.04 1.85 1.92 0.35 0.   0.   0.   0.39 0.02
 3326.5  5.41 0.35 0.21 0.35 0.07 1.76 1.83 0.15 0.   0.   0.   0.44 0.04
 3471.2  5.32 0.18 0.20 0.35 0.11 1.69 1.75 0.34 0.   0.   0.   0.42 0.04
 4134.4  4.47 0.17 0.17 0.34 0.22 1.42 1.47 0.76 0.   0.   0.   1.17 0.12

DIESEL (HS)
 2643.3  5.41 0.14 0.42 0.36 0.05 1.94 2.03 0.16 0.   0.   0.   0.37 0.03
 2776.6  4.86 0.17 0.40 0.16 0.09 1.85 1.93 0.17 0.   0.   0.   0.52 0.05
 2968.6  4.71 0.11 0.37 0.15 0.13 1.73 1.81 0.33 0.   0.   0.   0.65 0.07
 3571.5  3.91 0.20 0.31 0.14 0.25 1.44 1.50 0.95 0.   0.   0.   1.35 0.14

WIND
  651.0  5.08 0.31 0.31 0.35 0.41 1.61 0.   0.   0.21 0.   0.   1.71 0.32
 1312.3  4.11 0.52 0.17 0.12 0.69 1.45 0.   0.   0.12 0.   0.   2.41 0.52
 2172.2  3.71 0.58 1.49 0.02 0.73 1.28 0.   0.   0.06 0.   0.   2.89 0.58
 4691.5  4.31 0.49 0.14 0.01 0.69 1.56 0.   0.   0.03 0.   0.   2.26 0.54

METHANE
 3191.7  4.21 0.33 0.58 0.01 0.04 4.37 0.   0.   0.   0.44 0.   0.30 0.02
 3415.7  4.05 0.06 0.54 0.01 0.07 4.29 0.   0.   0.   0.51 0.   0.43 0.04
 3597.6  3.95 0.08 0.51 0.01 0.11 4.16 0.   0.   0.   0.58 0.   0.54 0.06
 4173.7  3.43 0.17 0.45 0.01 0.22 3.67 0.   0.   0.   0.68 0.   1.18 0.12

ANIMAL
 1522.9  2.84 0.07 0.15 0.07 0.09 4.58 0.   0.   0.92 0.62 0.   0.63 0.05
 1649.5  2.56 0.11 0.14 0.06 0.15 4.12 0.   0.   0.83 1.10 0.   0.86 0.08
 1971.3  2.19 0.15 0.12 0.05 0.20 3.53 0.   0.   0.71 1.97 0.   0.98 0.11
 2950.6  1.46 0.24 0.08 0.03 0.31 2.36 0.   0.   0.47 2.26 0.   1.63 0.17

MAN
  734.3  0.84 0.14 0.   0.02 0.12 0.30 0.   0.   0.23 0.   6.94 1.37 0.10
 1657.2  0.36 0.11 0.   0.01 0.15 0.13 0.   0.   0.18 0.   8.20 0.97 0.09
 3139.5  0.21 0.11 0.   0.00 0.13 0.07 0.   0.   0.05 0.   8.76 0.64 0.07
 7033.6  0.07 0.07 0.   0.00 0.13 0.02 0.   0.   0.03 0.   9.15 0.51 0.05

DISCOUNT RATE =    5.0 %
CAPITAL GOODS INFLATION RATE =  6.0 %
COMMODITY INFLATION RATE =  8.0 %
PROD. INCREASE RATE =  4.5 %
SKILLED LABOUR SWR =  10.0 POUNDS/DAY
ARTISAN LABOUR SWR =   1.5 POUNDS/DAY
```

BASECOST	% CHANGE PER 10% CHANGE IN :-												
	1	2	3	4	5	6	7	8	9	10	11	12	13
DIESEL (LS)													
1496.8	6.72	0.07	0.26	0.11	0.09	1.26	1.28	0.10	0.	0.	0.	0.18	0.02
1569.2	6.58	0.12	0.25	0.10	0.16	1.20	1.22	0.08	0.	0.	0.	0.25	0.03
1641.1	5.47	0.18	0.24	0.10	0.23	1.15	1.17	0.20	0.	0.	0.	0.24	0.03
1893.2	5.61	0.37	0.20	0.08	0.48	0.99	1.01	0.45	0.	0.	0.	0.70	0.09
DIESEL (HS)													
1068.9	5.74	0.09	0.46	0.15	0.12	1.55	1.58	0.04	0.	0.	0.	0.25	0.02
1126.3	5.56	0.17	0.43	0.14	0.22	1.47	1.50	0.12	0.	0.	0.	0.35	0.04
1205.5	5.37	0.24	0.44	0.13	0.32	1.37	1.40	0.26	0.	0.	0.	0.44	0.06
1441.4	4.49	0.49	0.34	0.11	0.63	1.15	1.17	0.58	0.	0.	0.	0.92	0.12
WIND													
475.1	6.93	0.42	0.42	0.06	0.56	0.71	0.	0.	0.10	0.	0.	0.64	0.16
[illegible]24.7	5.99	0.75	0.24	0.04	1.00	0.68	0.	0.	0.06	0.	0.	0.97	0.27
1433.2	5.60	0.88	0.14	0.03	1.10	0.62	0.	0.	0.03	0.	0.	1.20	0.31
3254.2	6.32	0.70	0.06	0.01	0.99	0.72	0.	0.	0.02	0.	0.	0.90	0.28
METHANE													
1257.2	4.95	0.08	0.65	0.03	0.10	3.56	0.	0.	0.	0.40	0.	0.21	0.02
1345.3	4.75	0.14	0.60	0.03	0.19	3.50	0.	0.	0.	0.46	0.	0.30	0.04
1427.3	4.61	0.20	0.57	0.02	0.27	3.37	0.	0.	0.	0.53	0.	0.37	0.05
1635.5	4.02	0.43	0.50	0.02	0.56	2.94	0.	0.	0.	0.61	0.	0.81	0.11
ANIMAL													
631.2	3.94	0.16	0.20	0.16	0.21	3.55	0.	0.	0.79	0.53	0.	0.42	0.04
7[illegible]	3.55	0.27	0.18	0.14	0.35	3.20	0.	0.	0.71	0.95	0.	0.57	0.07
[illegible]12.2	3.36	0.36	0.16	0.12	0.47	2.76	0.	0.	0.62	1.71	0.	0.65	0.09
12[illegible]1.6	2.37	0.58	0.11	0.08	0.76	1.06	0.	0.	0.42	2.87	0.	1.10	0.15
PV													
297.2	2.01	0.34	0.	0.05	0.44	0.23	0.	0.	0.17	0.	5.80	0.89	0.08
547.4	1.92	0.29	0.	0.02	0.38	0.19	0.	0.	0.10	0.	7.51	0.62	0.08
1153.6	1.52	0.25	0.	0.01	0.33	0.16	0.	0.	0.04	0.	8.26	0.46	0.06
3517.6	1.10	0.21	0.	0.01	0.25	0.12	0.	0.	0.03	0.	8.88	0.39	0.05

DISCOUNT RATE = 15.0 %
CAPITAL GOODS INFLATION RATE = 6.0 %
COMMODITY INFLATION RATE = 8.0 %
PROD. INCREASE RATE = 4.5 %
SKILLED LABOUR SWR = 10.0 POUNDS/DAY
ARTISAN LABOUR SWR = 0.5 POUNDS/DAY

Table 5

```
BASECOST               % CHANGE PER 10% CHANGE IN :-

            1     2     3     4     5     6     7     8     9    10    11    12    13

DIESEL (LS)
2193.4    6.31  0.05  0.23  0.08  0.06  1.62  1.40  0.03  0.    0.    0.    0.19  0.02
2167.2    6.21  0.09  0.22  0.07  0.11  1.55  1.34  0.09  0.    0.    0.    0.28  0.04
2278.0    6.12  0.13  0.22  0.07  0.17  1.49  1.29  0.22  0.    0.    0.    0.27  0.03
2613.0    5.34  0.27  0.19  0.06  0.35  1.30  1.12  0.50  0.    0.    0.    0.77  0.10


DIESEL (HS)
1623.1    5.59  0.06  0.42  0.10  0.38  1.83  1.59  0.04  0.    0.    0.    0.25  0.02
1690.8    5.45  0.11  0.40  0.09  0.14  1.75  1.52  0.12  0.    0.    0.    0.36  0.05
1846.4    5.30  0.16  0.38  0.09  0.21  1.65  1.43  0.26  0.    0.    0.    0.45  0.05
2116.5    4.53  0.33  0.32  0.08  0.43  1.41  1.22  0.60  0.    0.    0.    0.95  0.13


WIND
 525.7    6.28  0.38  0.38  0.06  0.50  1.15  0.    0.    0.15  0.    0.    0.88  0.22
 925.7    5.34  0.67  0.22  0.03  0.89  1.09  0.    0.    0.28  0.    0.    1.31  0.37
1626.6    4.96  0.77  0.12  0.02  1.05  0.99  0.    0.    1.05  0.    0.    1.61  0.42
3645.8    5.64  0.63  0.05  0.01  0.89  1.16  0.    0.    0.02  0.    0.    1.22  0.38


METHANE
1990.6    4.63  0.05  0.57  0.02  0.07  4.06  0.    0.    0.    0.39  0.    0.20  0.02
2119.7    4.47  0.09  0.54  0.02  0.12  4.00  0.    0.    0.    0.45  0.    0.29  0.04
2234.5    4.35  0.13  0.51  0.02  0.17  3.89  0.    0.    0.    0.51  0.    0.36  0.05
2512.8    3.89  0.28  0.46  0.01  0.36  3.47  0.    0.    0.    0.61  0.    0.81  0.11


ANIMAL
 952.4    3.43  0.11  0.17  0.11  0.14  4.24  0.    0.    0.80  0.54  0.    0.42  0.04
1146.7    3.12  0.18  0.16  0.10  0.23  3.86  0.    0.    0.73  0.97  0.    0.58  0.07
1215.9    2.71  0.24  0.14  0.08  0.32  3.35  0.    0.    0.64  1.76  0.    0.67  0.10
1752.1    1.86  0.40  0.09  0.06  0.52  2.34  0.    0.    0.44  3.02  0.    1.15  0.15


MAN
 412.5    1.44  0.24  0.    0.04  0.32  0.29  0.    0.    0.19  0.    6.41  0.98  0.09
 530.5    0.63  0.20  0.    0.02  0.25  0.13  0.    0.    0.08  0.    7.95  0.65  0.08
1701.9    0.35  0.17  0.    0.01  0.23  0.07  0.    0.    0.05  0.    8.59  0.47  0.07
5273.5    0.12  0.13  0.    0.01  0.17  0.02  0.    0.    0.03  0.    9.08  0.38  0.05


DISCOUNT RATE =  10.0 %
CAPITAL GOODS INFLATION RATE =  7.0 %
COMMODITY INFLATION RATE =  7.1 %
PROD. INCREASE RATE =  4.5 %
SKILLED LABOUR SWR =  10.0 POUNDS/DAY
ARTISAN LABOUR SWR =   0.5 POUNDS/DAY
```

Table 6

```
BASECOST             % CHANGE PER 10% CHANGE IN :-

              1     2     3     4     5     6     7     8     9    10    11    12    13

DIESEL (LS)
1941.4     6.30  0.15  0.25  0.08  0.07  1.53  1.44  0.14  0.    0.    0.    0.20  0.02
2076.1     6.17  0.09  0.24  0.08  0.12  1.46  1.38  0.11  0.    0.    0.    0.30  0.03
2158.7     6.07  0.13  0.23  0.07  0.18  1.39  1.32  0.26  0.    0.    0.    0.32  0.03
2530.3     5.20  0.28  0.19  0.06  0.36  1.19  1.13  0.58  0.    0.    0.    0.90  0.09


DIESEL (HS)
1519.9     5.52  0.07  0.45  0.11  0.09  1.75  1.66  0.35  0.    0.    0.    0.30  0.02
1598.1     5.35  0.12  0.43  0.10  0.15  1.66  1.58  0.14  0.    0.    0.    0.40  0.04
1709.0     5.10  0.17  0.40  0.09  0.23  1.55  1.47  0.31  0.    0.    0.    0.50  0.06
2043.5     4.33  0.34  0.33  0.08  0.45  1.30  1.23  0.71  0.    0.    0.    1.12  0.11


WIND
 522.6     6.31  0.38  0.38  0.06  0.51  1.33  0.    0.    0.13  0.    0.    1.01  0.19
 925.0     5.34  0.67  0.22  0.03  0.89  0.97  0.    0.    0.07  0.    0.    1.48  0.02
1633.2     4.93  0.77  0.12  0.02  1.04  0.88  0.    0.    0.04  0.    0.    1.82  0.07
3636.4     5.65  0.63  0.05  0.01  0.89  1.04  0.    0.    0.02  0.    0.    1.08  0.03


METHANE
1826.5     4.66  0.05  0.62  0.02  0.07  3.94  0.    0.    0.    0.36  0.    0.25  0.02
1948.9     4.49  0.10  0.59  0.02  0.13  3.88  0.    0.    0.    0.43  0.    0.35  0.03
2058.9     4.37  0.14  0.55  0.02  0.19  3.76  0.    0.    0.    0.48  0.    0.44  0.05
2335.9     3.85  0.30  0.49  0.01  0.39  3.31  0.    0.    0.    0.57  0.    0.98  0.10


ANIMAL
 877.6     3.51  0.11  0.19  0.11  0.15  4.10  0.    0.    0.76  0.51  0.    0.52  0.04
 967.4     3.19  0.20  0.17  0.10  0.25  3.72  0.    0.    0.69  0.91  0.    0.71  0.07
1113.9     2.77  0.26  0.15  0.09  0.35  3.23  0.    0.    0.60  1.65  0.    0.82  0.09
1631.6     1.89  0.43  0.14  0.06  0.56  2.20  0.    0.    0.41  2.81  0.    1.40  0.14


MAN
 379.5     1.57  0.26  0.    0.04  0.34  0.28  0.    0.    0.17  0.    6.04  1.20  0.09
 843.1     0.71  0.23  0.    0.02  0.29  0.13  0.    0.    0.19  0.    7.66  0.81  0.08
1512.6     0.39  0.19  0.    0.01  0.25  0.07  0.    0.    0.14  0.    8.37  0.60  0.07
4651.1     0.14  0.15  0.    0.01  0.20  0.02  0.    0.    0.10  0.    8.82  0.49  0.05


DISCOUNT RATE =  10.0 %
CAPITAL GOODS INFLATION RATE =  6.0 %
COMMODITY INFLATION RATE =  8.0 %
PROD. INCREASE RATE =  3.0 %
SKILLED LABOUR SWR =  10.0 POUNDS/DAY
ARTISAN LABOUR SWR =   0.5 POUNDS/DAY
```

Table 7

```
BASECOST            % CHANGE PER 10% CHANGE IN :-

             1    2    3    4    5    6    7    8    9   10   11   12   13

DIESEL (LS)
1933.8    6.45 0.05 0.20 0.08 0.07 1.56 1.29 0.04 0.   0.   0.   0.24 0.02
2030.0    6.31 0.09 0.19 0.08 0.12 1.49 1.22 0.11 0.   0.   0.   0.34 0.04
2122.5    6.20 0.14 0.18 0.08 0.18 1.42 1.17 0.26 0.   0.   0.   0.32 0.04
2486.7    5.80 0.28 0.16 0.06 0.37 1.21 1.00 0.59 0.   0.   0.   0.92 0.11

DIESEL (HS)
1473.8    5.69 0.07 0.37 0.11 0.09 1.80 1.49 0.05 0.   0.   0.   0.31 0.03
1552.5    5.51 0.12 0.35 0.10 0.16 1.71 1.41 0.14 0.   0.   0.   0.44 0.05
1664.0    5.32 0.17 0.33 0.10 0.23 1.59 1.32 0.32 0.   0.   0.   0.55 0.07
2100.5    4.42 0.35 0.27 0.08 0.45 1.33 1.09 0.72 0.   0.   0.   1.14 0.13

WIND
 521.2    6.33 0.38 0.31 0.06 0.51 1.04 0.   0.   0.15 0.   0.   1.01 0.22
 926.7    5.33 0.67 0.17 0.03 0.89 0.97 0.   0.   0.08 0.   0.   1.48 0.37
1639.5    4.92 0.77 0.10 0.02 1.04 0.88 0.   0.   0.05 0.   0.   1.81 0.42
3653.9    5.63 0.62 0.34 0.01 0.88 1.03 0.   0.   0.02 0.   0.   1.38 0.38

METHANE
1814.4    4.69 0.06 0.50 0.02 0.07 3.96 0.   0.   0.   0.42 0.   0.25 0.02
1939.9    4.51 0.10 0.47 0.02 0.13 3.89 0.   0.   0.   0.49 0.   0.35 0.04
2153.0    4.38 0.14 0.44 0.02 0.19 3.77 0.   0.   0.   0.56 0.   0.45 0.06
2337.3    3.85 0.30 0.39 0.01 0.39 3.31 0.   0.   0.   0.66 0.   0.98 0.11

ANIMAL
 392.1    3.46 0.11 0.15 0.11 0.15 4.03 0.   0.   0.86 0.58 0.   0.51 0.04
 939.1    3.12 0.19 0.13 0.10 0.25 3.64 0.   0.   0.78 1.03 0.   0.69 0.08
1154.9    2.68 0.25 0.11 0.09 0.33 3.13 0.   0.   0.67 1.85 0.   0.79 0.10
1713.1    1.84 0.41 0.08 0.06 0.53 2.10 0.   0.   0.45 3.09 0.   1.03 0.16

MAN
 416.5    1.43 0.24 0.   0.04 0.31 0.26 0.   0.   0.18 0.   6.35 1.10 0.09
 945.1    0.63 0.20 0.   0.02 0.26 0.11 0.   0.   0.08 0.   7.89 0.73 0.08
1711.1    0.35 0.17 0.   0.01 0.23 0.06 0.   0.   0.04 0.   8.54 0.53 0.07
5290.6    0.12 0.13 0.   0.01 0.17 0.02 0.   0.   0.03 0.   9.04 0.43 0.05

DISCOUNT RATE =  10.0 %
CAPITAL GOODS INFLATION RATE =  6.0 %
COMMODITY INFLATION RATE =  8.0 %
PROD. INCREASE RATE =  4.5 %
SKILLED LABOUR SWR =   8.0 POUNDS/DAY
ARTISAN LABOUR SWR =   0.5 POUNDS/DAY
```

Table 8

```
BASECOST              % CHANGE PER 10% CHANGE IN :-

              1    2    3    4    5    6    7    8    9   10   11   12   13

DIESEL (LS)
1999.2     6.24 0.05 0.25 0.06 0.05 1.51 1.55 0.04 0.   0.   0.   0.23 0.02
2092.3     6.12 0.09 0.23 0.06 0.09 1.44 1.49 0.11 0.   0.   0.   0.33 0.03
2182.1     6.04 0.13 0.22 0.06 0.14 1.38 1.42 0.26 0.   0.   0.   0.31 0.03
2531.9     5.20 0.28 0.19 0.05 0.29 1.19 1.23 0.58 0.   0.   0.   0.90 0.08

DIESEL (HS)
1535.7     5.46 0.07 0.45 0.08 0.07 1.73 1.78 0.05 0.   0.   0.   0.30 0.02
1611.3     5.31 0.12 0.42 0.08 0.12 1.65 1.70 0.14 0.   0.   0.   0.43 0.04
1719.2     5.05 0.17 0.40 0.07 0.18 1.54 1.59 0.31 0.   0.   0.   0.53 0.05
2042.2     4.33 0.34 0.34 0.06 0.36 1.30 1.34 0.71 0.   0.   0.   1.12 0.11

WIND
 515.4     6.40 0.39 0.39 0.05 0.41 1.05 0.   0.   0.12 0.   0.   1.02 0.18
 935.1     5.46 0.68 0.22 0.03 0.73 0.99 0.   0.   0.07 0.   0.   1.51 0.30
1593.4     5.06 0.79 0.13 0.02 0.85 0.90 0.   0.   0.04 0.   0.   1.86 0.35
3563.4     5.77 0.64 0.06 0.01 0.73 1.06 0.   0.   0.02 0.   0.   1.41 0.31

METHANE
1817.9     4.68 0.06 0.63 0.02 0.06 3.96 0.   0.   0.   0.34 0.   0.25 0.02
1936.4     4.52 0.10 0.59 0.01 0.10 3.90 0.   0.   0.   0.40 0.   0.35 0.03
2042.2     4.41 0.14 0.56 0.01 0.15 3.79 0.   0.   0.   0.45 0.   0.45 0.05
2305.2     3.90 0.30 0.49 0.01 0.32 3.35 0.   0.   0.   0.53 0.   0.99 0.09

ANIMAL
 864.3     3.57 0.12 0.19 0.09 0.12 4.16 0.   0.   0.71 0.48 0.   0.53 0.04
 948.3     3.25 0.20 0.17 0.08 0.21 3.79 0.   0.   0.65 0.86 0.   0.72 0.06
1184.3     2.84 0.27 0.15 0.07 0.28 3.32 0.   0.   0.57 1.57 0.   0.84 0.08
1569.7     1.96 0.45 0.10 0.05 0.46 2.29 0.   0.   0.39 2.70 0.   1.46 0.14

MAN
 358.4     1.66 0.28 0.   0.03 0.29 0.30 0.   0.   0.17 0.   5.90 1.27 0.09
 787.7     0.76 0.24 0.   0.02 0.25 0.14 0.   0.   0.08 0.   7.58 0.87 0.08
1407.0     0.42 0.21 0.   0.01 0.22 0.08 0.   0.   0.04 0.   8.31 0.65 0.07
4313.7     0.15 0.16 0.   0.01 0.17 0.03 0.   0.   0.03 0.   8.89 0.53 0.05

DISCOUNT RATE =  10.0 %
CAPITAL GOODS INFLATION RATE =  6.0 %
COMMODITY INFLATION RATE =  8.0 %
PROD. INCREASE RATE =  4.5 %
SKILLED LABOUR SWR =  10.0 POUNDS/DAY
ARTISAN LABOUR SWR =   0.4 POUNDS/DAY
```

Table 9

SYSTEM SIZE 1

	"Best Estimate" Values	Variable(s) Changed and New Value(s)					
Discount Rate (%)	10	5	15				
Cap. Goods Inflation Rate (%)	6			7			
Com. Inflation Rate (%)	8			7			
Prod. Increase Rate (%)	4.5				3		
Skilled Labor SWR (pounds/day)	10.0					8	
Artisan SWR (pounds/day)	0.5						0.4
Diesel (LS)	2,006	3,171	1,497	2,093	1,980	1,934	1,999
Diesel (HS)	1,542	2,643	1,069	1,623	1,520	1,474	1,536
Wind	525	650	476	526	523	521	515
Methane	1,837	3,192	1,257	1,991	1,827	1,814	1,818
Animal	895	1,523	631	952	878	892	864
Man	416	704	297	412	380	417	358
Most Sensitive Cost Element of Best Solution	11	1	11	11	11	11	11
% Change in Above Needed to Change Optimum Solution	40	12	87	42	60	39	74
% Overall Cost Advantage Over Next Best Solution	26	8	71	28	38	25	44

Table 10

SYSTEM SIZE 2

	"Best Estimate" Values	Variable(s) Changed and New Value(s)					
Discount Rate (%)	10	5	15				
Cap. Goods Inflation Rate (%)	6			7			
Com. Inflation Rate (%)	8			7			
Prod. Increase Rate (%)	4.5				3		
Skilled Labor SWR (pounds/day)	10.0					8	
Artisan SWR (pounds/day)	0.5						0.4
Diesel (LS)	2,102	3,326	1,569	2,187	2,076	2,030	2,092
Diesel (HS)	1,620	2,777	1,126	1,699	1,598	1,552	1,611
Wind	931	1,202	825	926	925	927	905
Methane	4,962	3,409	1,345	2,120	1,949	1,940	1,936
Animal	992	1,689	700	1,047	967	989	948
Man	945	1,657	647	939	843	945	788
Most Sensitive Cost Element of Best Solution	1	1	11	1	11	1	11
% Change in Above Needed to Change Optimum Solution	2.5	63	34	2.5	13	3.5	16
% Overall Cost Advantage Over Next Best Solution	1.5	38	8	14	10	2	15

SYSTEM SIZE 3

	"Best Estimate" Values	Variable(s) Changed and New Value(s)					
Discount Rate (%)	10	5	15				
Cap. Goods Inflation Rate (%)	6			7			
Com. Inflation Rate (%)	8			7			
Prod. Increase Rate (%)	4.5				3		
Skilled Labor SWR (pounds/day)	10.0					8	
Artisan SWR (pounds/day)	0.5						0.4
Diesel (LS)	2,195	3,470	1,641	2,278	2,169	2,123	2,182
Diesel (HS)	1,732	2,969	1,206	1,806	1,709	1,664	1,719
Wind	1,644	2,172	1,438	1,627	1,633	1,640	1,593
Methane	2,076	3,598	1,427	2,235	2,059	2,053	2,042
Animal	1,154	1,971	812	1,206	1,114	1,151	1,084
Man	1,711	3,039	1,154	1,702	1,513	1,711	1,407
Most Sensitive Cost Element of Best Solution	6	6	41	6	6	6	11
% Change in Above Needed to Change Optimum Solution	135	29	138	105	111	135	89
% Overall Cost Advantage Over Next Best Solution	42	10	49	35	36	42	30

Table 11

SYSTEM SIZE 4

	"Best Estimate" Values	Variable(s) Changed and New Value(s)					
Discount Rate (%)	10	5	15				
Cap. Goods Inflation Rate (%)	6			7			
Com. Inflation Rate (%)	8			7			
Prod. Increase Rate (%)	4.5				3		
Skilled Labor SWR (pounds/day)	10.0					8	
Artisan SWR (pounds/day)	0.5						0.4
Diesel (LS)	2,559	4,130	1,893	2,613	2,530	2,487	2,532
Diesel (HS)	2,069	3,541	1,442	2,117	2,043	2,000	2,042
Wind	3,658	4,691	3,254	3,646	3,638	3,654	3,563
Methane	2,360	4,079	1,636	2,503	2,336	2,337	2,305
Animal	1,716	2,959	1,202	1,752	1,632	1,713	1,570
Man	5,299	9,534	3,518	5,274	4,651	5,299	4,314
Most Sensitive Cost Element of Best Solution	10	10	10	10	10	10	10
% Change in Above Needed to Change Optimum Solution	66	116	69	69	89	54	111
% Overall Cost Advantage Over Next Best Solution	21	21	20	21	25	17	30

Table 12

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TIGHTLY
BOUND

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